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Patterns and drivers of regional crop production in Chad

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LUND UNIVERSITY

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Abstract

Agriculture constitutes the largest economic sector and professional occupation in Chad, and is undergoing rapid changes due to processes of population increase, institutional reforms, conflicts in neighbouring countries, increasingly globalized trade networks, and environmental changes. But despite their importance for livelihoods and economic growth, the specific patterns and drivers of change in the agricultural sector are however poorly understood. This has mostly been a result of low data availability and a lack of comprehensive research programs to address the agricultural changes of various spatial scales. By analysing crop statistics on a level of detail that have not been done before, this thesis has been able to show how the agricultural production is changing over time and between the different administrative regions in Chad.

In general it found that the harvested area has been increasing faster than the yield, and that a majority of the changes have happened under abrupt rather than gradual changes. By using this detailed understanding of the patterns of change, and by combining numerous kinds of relevant datasets on hydrology, demographics, international aid, market prices, conflicts, and agricultural practices, this thesis has evaluated potential factors of these changes with an extent and detail that have not been done before. This evaluation have showed that variations in hydrological conditions, market prices, and food security conditions can be linked to the variability in crop production. By looking at descriptions of livelihood conditions in agricultural areas, factors such as material and technical farm support have been linked to abrupt changes in the crop production for specific areas. Also, the differences in long term change between the administrative regions in Chad have been explained by differences in demographic factors and amount of international aid received.

These and similar results are relevant to increase the understanding of how agricultural societies evolve in Chad, and how strategies and interventions can be developed to assist local communities in their objectives. More specifically, the results can be used to evaluate the effects of certain events or policies, and to improve seasonal predictions for crop production and food availability. Beyond Chad, the results and methods developed for this thesis are relevant for application in the wider Sahel, where the agro-ecological and institutional conditions share some key characteristics.

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Abstract

Agriculture constitutes the largest economic sector and professional occupation in Chad, and is undergoing rapid changes due to processes of population increase, institutional reforms, conflicts in neighbouring countries, increasingly globalized trade networks, and environmental changes. But despite their importance for livelihoods and economic growth, the specific patterns and drivers of change in the agricultural sector are however poorly understood. This has mostly been a result of low data availability and a lack of comprehensive research programs to address the agricultural changes of various spatial scales. By analysing crop statistics on a level of detail that have not been done before, this thesis has been able to show how the agricultural production is changing over time and between the different administrative regions in Chad. In general it found that the harvested area has been increasing faster than the yield, and that a majority of the changes have happened under abrupt rather than gradual changes. By using this detailed understanding of the patterns of change, and by combining numerous kinds of relevant datasets on hydrology, demographics, international aid, market prices, conflicts, and agricultural practices, this thesis has evaluated potential factors of these changes with an extent and detail that have not been done before. This evaluation have showed that variations in hydrological conditions, market prices, and food security conditions can be linked to the variability in crop production. By looking at descriptions of livelihood conditions in agricultural areas, factors such as material and technical farm support have been linked to abrupt changes in the crop production for specific areas. Also, the differences in long term change between the administrative regions in Chad have been explained by differences in demographic factors and amount of international aid received. These and similar results are relevant to increase the understanding of how agricultural societies evolve in Chad, and how strategies and interventions can be developed to assist local communities in their objectives. More specifically, the results can be used to evaluate the effects of certain events or policies, and to improve seasonal predictions for crop production and food availability. Beyond Chad, the results and methods developed for this thesis are also relevant for application in the wider Sahel, where the agro-ecological and institutional conditions share some key characteristics.

Populärvetenskaplig sammanfattning

Jordbruk utgör den största ekonomiska sektorn och har den högsta sysselsättningsgraden i Tchad. Samtidigt så genomgår den hastiga förändringar på grund av populationsökning, institutionella reformer, konflikter i grannländerna, ökande globaliserade handelsnätverk, samt miljöförändringar. Men trots dess betydelse för lokala uppehällen och ekonomisk tillväxt, så är de specifika förändringsmönstrena och deras drivkrafter i jordbrukssektorn dåligt förstådda. Detta är främst ett resultat av den låga datatillgången och en avsaknad av omfattande forskningsprogram som angriper förändringarna i jordbrukssektorn på olika spatiala skalor. Genom att analysera jordbruksstatistik på en förbättrad detaljnivå så har den här avhandlingen kunnat visa hur jordbruksproduktionen förändras över tid samt mellan regionerna i Tchad. Den visar att jordbruksarealen har förändrats snabbare än skörden per areal, samt att förändringarna främst har realiserats genom abrupta processer, istället för gradvisa. Genom att använda den ökade detaljförståelsen för förändringsmönstrena, och med hjälp av en kombination av relevanta dataregister över hydrologi, demografi, utvecklingsbistånd, marknadspriser, konflikter, samt jordbrukstekniker, så har den här avhandlingen utvärderat potentiella förändringsfaktorer med en omfattning och detalj som inte har gjorts innan. Denna utvärdering har visat att variation i hydrologi, marknadspriser, samt matsäkerhet kan kopplas till variationer i jordbruksproduktionen. Genom att gå igenom beskrivningar av lokala jordbrukssamhällen, så har faktorer som materiellt och tekniska jordbruksstöd kunnat kopplas abrupta förändringar i jordbruksproduktionen i specifika områden. Skillnader i långtgående förändringar mellan de olika regionerna har förklarats genom skillnader i demografiska faktorer och erhållet utvecklingsbistånd. Dessa och liknande resultat är relevant för en ökad förståelse för hur jordbrukssamhällen i Tchad förändras, och hur strategier och interventioner kan utformas för att bättre assistera de lokala samhällena i deras mål. Mer specifikt så kan metoderna användas för utvärdera särskilda händelser eller strateger, och för att förbättra säsongsbaserade förutsägelser om jordbruksproduktion och mattillgänglighet. Förutom i Tchad så är resultaten även relevanta i stora delar av Sahel, där agronomiska, ekologiska och samhällsekonomiska förhållanden delar många grundläggande faktorer.

Papers

Appended papers

I. **Nilsson, E**. Hochrainer-Stigler, S., Mochizuki, J. & Uvo, C. B. 2016. Hydro-climatic variability and agricultural production on the shores of Lake Chad. *Environmental Development*, 20, 15-30. doi: 10.1016/j.envdev.2016.09.001

II. **Nilsson, E**., & Uvo, C. B (2018). Nonlinear dynamics in agricultural systems in Chad. *African Geographical Review*. doi: 10.1080/19376812.2018.1485585

III. **Nilsson, E**., Uvo, C. B., Becker, P., & Persson, M. (2018). Drivers of regional crop variability in Chad. *Agricultural Systems* (Submitted 2018-06-30)

IV. **Nilsson, E**., Becker, P., & Uvo, C. B.(2018). Drivers of abrupt and gradual changes in agricultural systems in Chad. (Manuscript)

Author's contribution appended papers

I. The author collected all the data from field studies in Chad and online databases, developed the scope and the statistical analysis together with supervisors at IIASA and TVRL, did all the statistical analysis and summary of the results, and wrote the full paper, except a subsection in the introduction, with minor reviews from supervisors on the overall structure.

II. The author collected all the data from field studies in Chad and online databases, developed the idea and scope together with supervisors at TVRL, developed the statistical analysis with occasional assistance from supervisors at TVRL, did all the statistical analysis and summary of the results, and wrote the full paper with minor reviews from supervisors at TVRL.

III. The author collected all the data from field studies in Chad and online databases, developed the idea and scope together with supervisors at TVRL, developed the statistical analysis with occasional assistance from supervisors at TVR, built a categorized and searchable database of food security reports to be used for the analysis, developed a methodology to combine the broad set of databases used in the study, did all the statistical analysis and summary of the results, and wrote the full paper with minor reviews from supervisors at TVRL

IV. The author collected all the data from field studies in Chad and online databases and developed the idea and scope together with supervisors at TVRL. This paper uses part of the same statistical analysis, databases and results from paper 2 & 3, which the author developed with occasional assistance from supervisors at TVRL. The author did all the analysis to draw connections between the different databases and results. and wrote the full paper with reviews and minor writing contribution from supervisors at TVRL

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1 Introduction

1.1 Thesis background

This PhD thesis project started in 2013 with a focus on water management in Chad and its relationship to the varying surface area of Lake Chad. Stemming from previous research on the role of climate variability in water availability in the Lake Chad basin, a multidisciplinary project was launched at Lund University to address the hydrological, sociological, climatological, and managerial components of sustained water availability in the basin. To set up achievable and relevant research goals within this broad and complex scope, initial efforts were directed towards reviewing previous research with similar and related scopes, as well as assessing the underlying data availability. Early conclusions pointed out that the academic literature was mostly focused on the hydrological aspects, covering hydrological models, inter-basin water transfers, impacts of climate projections, and recreation of historical hydrological conditions (e.g. Bader, Lemoalle, & Leblanc, 2011; Bastola & Francois, 2012; Lemoalle et al., 2012). The academic coverage of the demographic, sociological, economical, and political aspects of water management was on the other hand largely missing. By expanding the initial research review beyond the academic literature, it became clear however that such topics were addressed by various international development organizations present in Chad, which covered events related to livelihoods and health conditions within their objectives and program locations. While the practical orientation of these monitoring efforts are suitable for short-term decision making within these organizations and their partners, they often lack an analytical emphasis on the spatially broad and long-term scales. This gap in data collection and analysis on the sub-national level was thus picked up as a key research objective, to complement the monitoring efforts by development actors, and to capitalize on the multidisciplinary and exploratory perspective granted by the original research funding. Following field studies in N'Djamena in 2014, the research objectives were further specified to centre on the extensive records of agricultural statistics collected by government bodies in Chad, which, despite their extent and level of detail, had to my knowledge never been included in any sub-national analysis of agricultural developments. Meetings with the statistical branch of the Chadian government added access to a range of demographic and health oriented surveys, carried out in Chad over the past three decades. By taking in the analytical potential offered by

the agricultural statistics and the demographic censuses, and combining it with the continuous livelihood monitoring from development organizations, a novel data coverage had been created under a promising research objective. With a clear focus on the agricultural sector, a limited research scope in a data rich environment had been established, while satisfying the initial focus on water resource management from a multidisciplinary and policy relevant perspective. The methodology that followed was directed to evaluate and establish relationships of interest between the acquired data, tailored towards advancing the state of knowledge on the patterns and drivers of change in the agricultural systems in Chad. While the acquired data provided plenty of new research opportunities, they also served as effective limits to the research scope, in both detail and topic. The agricultural statistics as collected from the Direction de la Production et de la Statistique Agricoles (DPSA) in N'Djamena covered each of the 16 administrative regions, as presented in Fig. 1 together with the main ecological zones. This set a suitable spatial level of analysis, by being able to distinguish agricultural dynamics within the country, while being assessable within the time frame set by a PhD thesis. Additionally, this spatial level of analysis served as a compliment to the continuous, and often region specific, food security monitoring provided by development organizations. The earliest acquired agricultural statistics were from 1983, with more consistent reporting from 1990, which served as the main temporal limitations for the research scope.

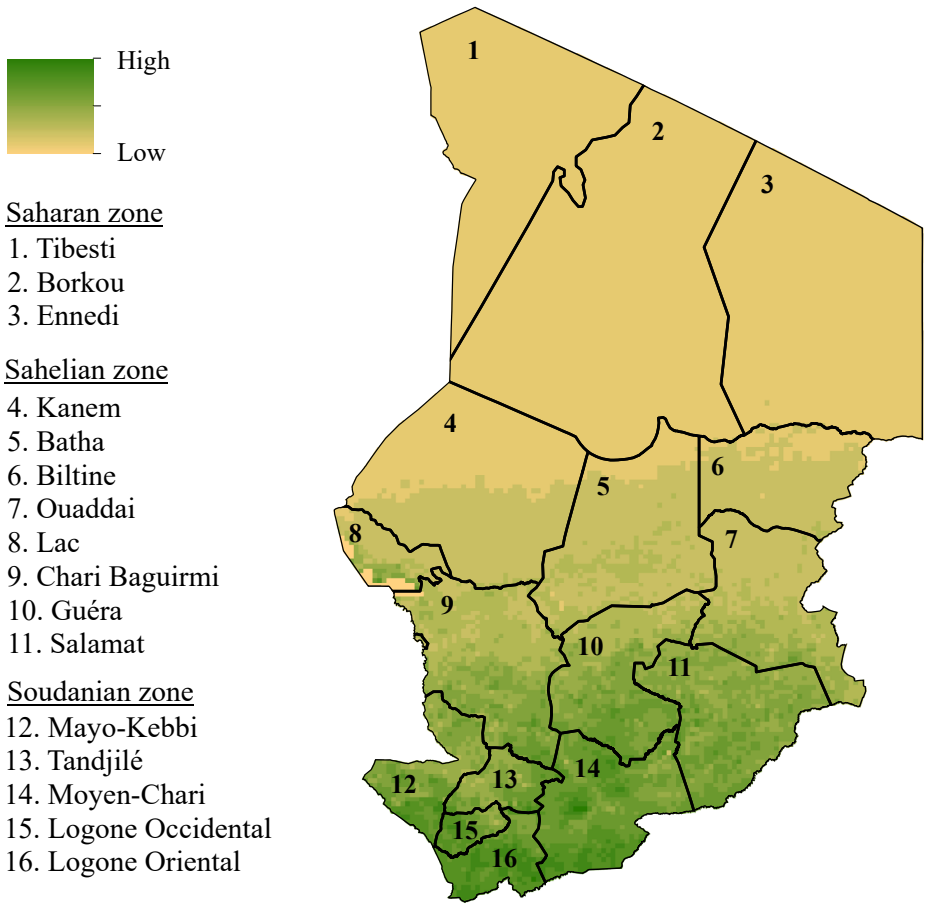

Fig. 1 *– Administrative division and main ecological zones in Chad, with NDVI index for July 2000 (NDVI data from Pinzon and Tucker 2014). Note that this is not the current administrative regional division in Chad*

1.2 Research objective

While the acquired data and the subsequent analysis focused on Chad, the overarching theme for this thesis has been to develop methodologies that could be applied to generic regions in the Sahel, where a combination and analysis of already

existing datasets could complement ongoing research and development activities. Within this overarching theme, the research has been directed to be relevant for efforts to improve the living conditions of communities directly and indirectly dependent on the agricultural sector. As notions of improved living conditions are specific to cultures and even individuals, and ridden with contradictory and conflictual goals on various scales, some generalizations were needed for practical purposes. Following the extensive efforts of international development organizations, donors, and the government of Chad to increase the agricultural production and productivity, the research objectives were directed to enhance any such efforts. Acting under these motives, and with the limitations set out by the funding of the research project and the data availability, the research focus on the *Patterns and Drivers of Regional Crop Production in Chad* was established. Following the acquired datasets, the connection to the overarching theme in practice became a matter of improving the evaluative and predictive capacity to the agricultural output on a regional level of analysis. Both the evaluative and predictive capacities are recognized as limitations for general development efforts in Chad (République du Tchad, 2017), which are reflections of the low institutional capacities, and lack of relevant data under conditions of volatile patterns of change in the agricultural sector. A low evaluative capacity means that the effects of interventions in the agricultural sector, such as development projects and national strategies, are difficult to evaluate. This effectively limits the potential of learning from previous interventions, and improving their effectiveness. And as funding for development projects and investment plans strongly hinge on their expected and measurable impacts, the lack of evaluative capacity is foundational for a range of interventions in any economic sector. Similar connections are seen to the predictive capacity, but where the outcome is that agricultural outlooks on both seasonal and long term scales lack precision, which limits the potential of both early responses and long term strategies. The research objectives and their potential applications are summarized in Fig. 2.

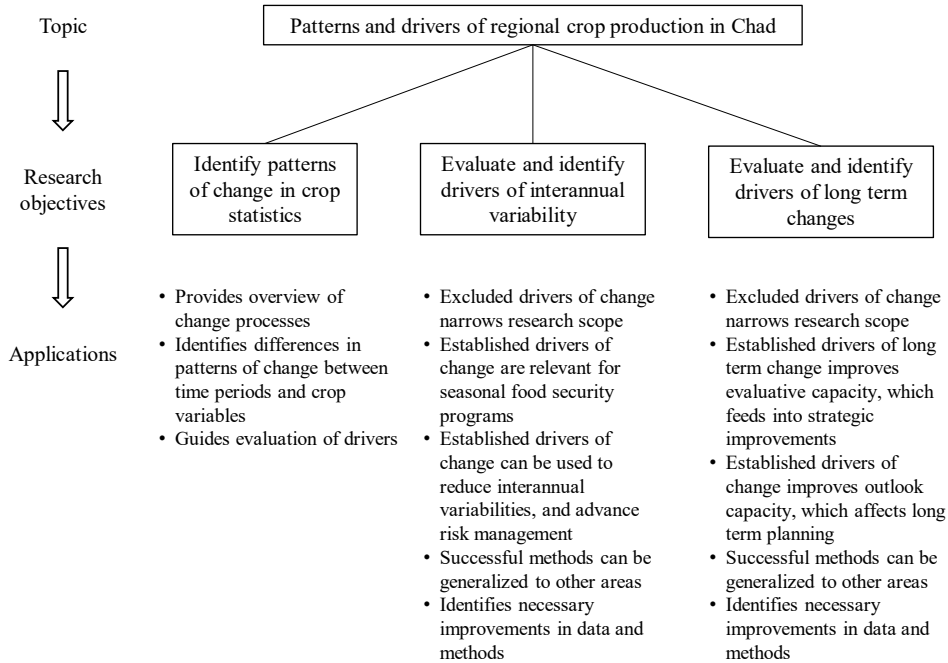

Fig. 2 *– Summary of research objectives and potential applications*

1.3 Summary structure

The following sections of the summary give detailed accounts of the research components covered by this thesis. The research output has been structured into four research papers, out of which two are published, one is under review, and one is to be submitted, at the time of printing of this thesis. The first paper, **Hydro-climatic variability and agriculture on the shores of Lake Chad** (Nilsson, Hochrainer-Stigler, Mochizuki, & Uvo, 2016)**,** mainly served as an introduction to the research topic, and in terms of results only plays a marginal role in the thesis and subsequently this summary. The following three papers, **Nonlinear dynamics in agricultural systems in Chad** (Nilsson & Uvo, 2018)**, Drivers of regional crop variability in Chad,** and **Drives of abrupt and gradual changes in agricultural systems in Chad,** all follow the research objectives as presented in Fig. 2, and build directly on each other in this order. The structure of this summary follows the development of these three papers, and presents an overview of all the included research components in a thematically developing manner. As such, large parts of this summary are identical to sections in the last three papers, and no crucial information is presented in the papers that is not included in this summary.

The Theoretical Background presents the current status of this field of research, generally confined within the academic disciplines of geography, water resource engineering, and development studies. It is limited by scopes and applications that were considered to be of direct relevance to the study of the current agricultural systems in Chad, and serves as a justification of the methodological frame set out by the data coverage and analytical methods. It is followed by a section on the agricultural sector in Chad, which gives an introduction to the main components behind its ongoing changes. The Data section presents the extent, detail, and quality of the datasets related to this field of research, and gives an overview of the potential and limitations for research on agricultural system in Chad. The Methods section elaborates on the qualitative and quantitative research methods employed to optimize the explanatory capacity from the selected datasets towards the set research objectives. With volatile patterns of agricultural change, methods were developed to address patterns and drivers of change to both the interannual variability and long term changes. The Results section presents a visualization of the patterns of change in the crop statistics, as well as the evaluation of the potential drivers of change related to the harvested area, yield, and production in the administrative regions. It points out where the evaluated datasets and methods have been fruitful, and where more detailed data and analyses are needed to establish useful relationships. This distinction serves as a basis to discuss the practical implications and potential of this research in the final section, which also sets out objectives and strategies of how to improve the potential and influence of this kind of research in Chad, and its implications for countries in similar socio-ecological conditions.

2 Theoretical background

2.1 Background to agricultural systems in the Sahel

Across the Sahelian countries, the agricultural sector is often the largest economic sector in terms of occupation rates and contribution to GDP (FAO, 2018a). It thus figures prominently in national development strategies, as a key component to drive economic growth, address poverty, and to ensure food security (Binswanger-Mkhize & McCalla, 2010; World Bank, 2013b). The agricultural sector in the Sahelian countries are further undergoing foundational changes, which broadly are explained by rapid population increase, institutional reforms, technological changes, international aid, foreign investments, and migration patterns responding to both employment opportunities and security threats (Ickowicz et al., 2010; IMF, 2015; Jayne, Chamberlin, & Headey, 2014; Nin Pratt, 2015). While a range of such key drivers of change have been pointed out, their specific effects and dynamics remain elusive (Fuglie & Rada, 2013). Notwithstanding the prominence given to the agricultural sector by national governments and influential foreign donors, the lack of detail in these relationships is largely a result of the complexity of the agricultural sector under conditions of low institutional capacities and data availability. With a high degree of small-scaled subsistence farmers engaging in diverse cropping systems, disentangling the dynamics of the agricultural systems on aggregated spatial scales requires extensive and detailed datasets, as well as an understanding of the cultural context of local decision making. Any evaluation of Sahelian agricultural systems on spatial scales above the farm level thus require substantial generalizations and simplifications to be useful. From a policy relevant standpoint, the key factors affecting agricultural systems as seen on a national and sub-national level of analysis can broadly be conceptualized as in Fig. 3.

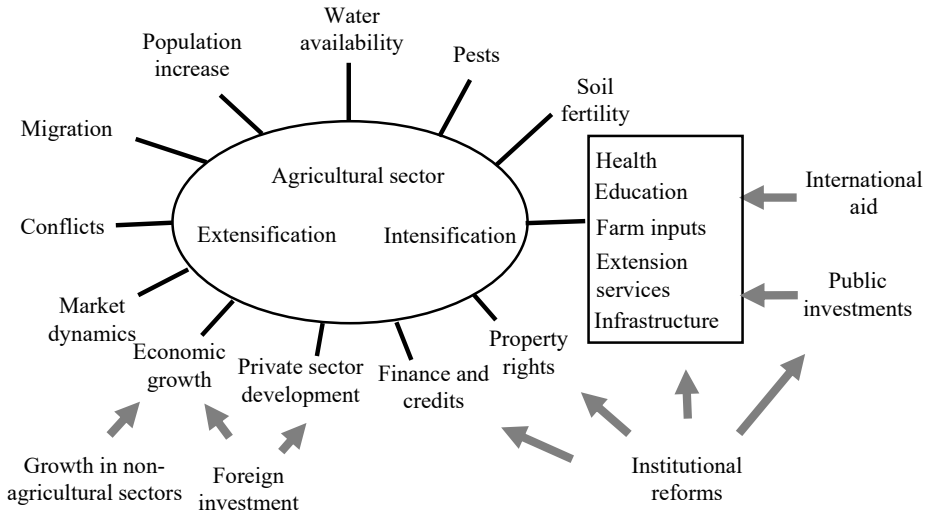

Fig. 3 *– Overview of drivers of agricultural change in the Sahel*

The responses in the agricultural sector to the effects of these components can be distinguished between processes of extensification or intensification, defined as the amount of land dedicated to agriculture, and the amount of agricultural output per input (see e.g. Nin Pratt, 2015). Common input measures behind the intensification estimate are land, labour, fertilizers, and machinery. Under national development objectives of increased agricultural production and productivity, both extensification and intensification are of strategic interest. As they play different roles in local livelihoods and the wider economy, and respond to different drivers, they exhibit distinct patterns of change. Fig. 4 gives an aggregated overview of these developments for cereals in Sahelian countries (Burkina Faso, Cameroon, Central African Republic, Chad, Eritrea, Mali, Niger, and Nigeria), where the harvested area can be seen to clearly outgrow the yield. Over this time period, these annual average growth rates are equivalent to a 164% increase in the harvested area, compared to a 26% increase in the yield, and as a result, production increases have largely been driven by extensification processes. The rates of change are however visibly different over this time period, with unstable patterns in the yield, and a notable reduction in extensification after the mid-90s.

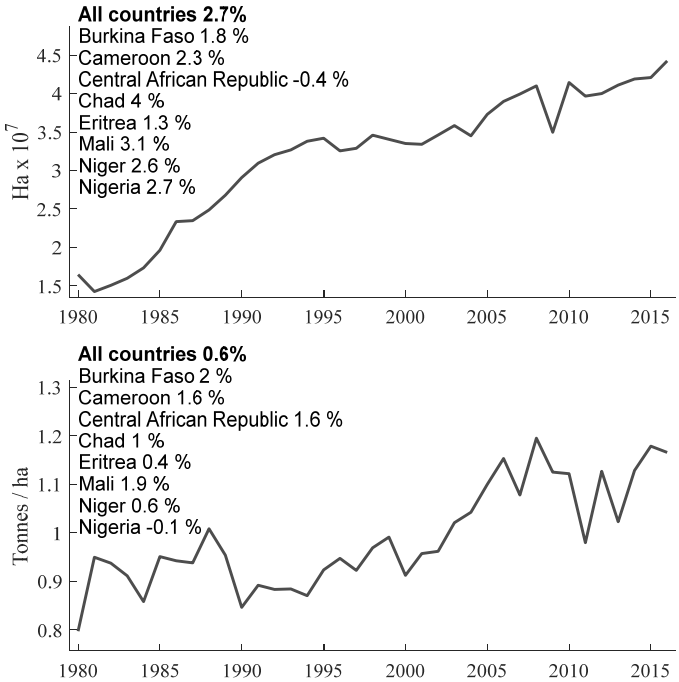

Fig. 4 *– Aggregated harvested area and yield, and annual average growth rates, for cereals in Sahelian countries in 1980-2016 (data from FAO, 2017)*

Despite a clear increase in the yield, agricultural productivity in the Sahel have in comparison to other regions remained notoriously low over the past decades (T. E. Epule & Bryant, 2015; FAO & AfDB, 2015; OECD, 2013; Yengoh, 2013). Moreover, a review of agricultural growth across Sub-Saharan Africa concluded that yield increases like these mainly are a result of additional resources, rather than improved efficiencies in the resource use (Fuglie & Rada, 2013). And contrary to the rather smooth patterns seen on the multinational scale in Fig. 4, variations in the intensity of the agricultural drivers often results in nonlinear and volatile output patterns on the national and sub-national level (Bachewe, Berhane, Minten, & Taffesse, 2015; Ebanyat et al., 2010; Hentze, Thonfeld, & Menz, 2017; Mutoko, Hein, & Bartholomeus, 2014). This is also reflected by pronounced interannual variabilities, which generally are attributed to the small-scaled and low input agricultural systems' dependence on seasonal rainfall (FAO, 2016a; Leroux et al., 2016). With a high degree of uncertainty in the agricultural output, both farmers and potential investors face considerable risks, which effectively limits their potential and willingness to invest in productivity increases (World Bank, 2015). Together with the high land availability in many Sahelian countries, the agricultural systems' response to increasing population and market demand have favoured expansive over intensive processes. Additionally, the rates of extensification in the Sahel have been

linked to migration patterns and market dynamics, through liberalization policies, devaluation of the Central African Franc in 1994, and infrastructure improvements (Dorosh, Rashid, & Asselt, 2016; OECD, 2013).

While extensification has been an accessible way for the increasing rural population to establish their livelihoods, it poses issues for land use management, and does not push for the specialization needed to reach higher levels of economic growth and poverty reduction. Consequently, decreased land availability has been identified as a driver of productivity increases (Boserup, 1965; OECD, 2013), although this relationship varies considerably (Demont, Jouve, Stessens, & Tollens, 2007; Muyanga & Jayne, 2014). The lack of further agricultural intensification, which in a global historical context has been the key driver of productivity increases, is thus a foundational issue, and since long a focus of a wide range of research activities and development efforts. Beyond population density, previous studies have identified a couple of key drivers behind increased intensification, such as: subsidized fertilizers and seeds (Yengoh, 2013; Yengoh & Ardo, 2014), water availability and rainfall patterns (Elagib, 2014; Mohamed, 2011), irrigation (Emmanuel, Kow, & Popoola, 2016), soil quality (Yengoh & Ardo, 2014), market incentives (Nin Pratt, 2015), and investment in agricultural research (Fuglie & Rada, 2013). While low intensification primarily can linked to the use of fertilizers and improved seeds by farmers, as well as irrigation schemes, the causes behind their uptake are intertwined with several of the components listed in Fig. 3, such as: farmers' purchasing power, level of education and willingness to adopt new technologies and practices, farmers' propensity to engage in cooperatives, access to finance and insurance, property rights and investment stability, risks in return on investment, institutional capacities and extent of public support provided to farmers, private sector development, and terms of trade for agricultural products (see e.g. Fuglie & Rada, 2013; Jayne et al., 2014; World Bank, 2013a; Yengoh, 2013). A comprehensive understanding of the uptake of improved farm inputs and general agricultural intensification thus requires a socio-economic analysis beyond the farm level of analysis.

To analyse patterns and drivers of change in agricultural systems in the Sahel under these conditions, crop statistics play a key role. Although crop statistics are collected extensively on various spatial levels by rural and agricultural government bodies across the Sahel, their accessibility is sparse, with most research activities using the national aggregates as available from FAOSTAT. While a national level of analysis can be instructive for international comparisons, its potential to identify patterns and drivers of change in agricultural systems within countries is limited. Given the size and population of most of the Sahelian countries, where agro-ecological and socio-economic conditions display considerable sub-national diversity (FEWS NET, 2011b, 2012, 2014), a national level of analysis might even be misleading. Examples of sub-national data agricultural gathering include the now abandoned Agro-maps

(FAO, 2006), and global crop land databases such as the Earthstat dataset (Monfreda, Ramankutty, & Foley, 2008) and the IIASA-IFPRI cropland map (Fritz et al., 2015). To complement the national aggregates and the data provided by these global datasets, collaborations with country based government statistics offices are however required, which might be out of reach for certain research projects.

2.2 Patterns of change in Sahelian crop statistics

While the use of sub-national crop statistics in the Sahel certainly do occur, studies that specifically address the patterns and drivers of agricultural production in are rare. A review of studies and reports using longitudinal crop statistics from Chad and its neighbouring countries in the Sahelian-Soudanian ecological zones (Central African Republic, Cameroon, Nigeria, Niger, and Sudan) over the past three decades showed that there are no studies with the explicit aim of analysing and understanding the patterns of crop statistics. But trend analyses of crop data is sometimes found in related applications, such as when establishing annual growth rates for agricultural variables (Abdelrahman, 1998; Chauvin, Mulangu, & Porto, 2012; Dorosh et al., 2016; FAO & AfDB, 2015; OECD, 2013; Ojiako, Asumugha, & Ezedinma, 2008), comparing trends between variables and periods (Akinyoade, Dietz, Foeken, & Klaver, 2013; Oyekale, 2010), and extrapolating established trends into future scenarios (Betru & Kawashima, 2010; Maikasuwa & Ala, 2013; Tahir, 2014). The trend analyses employed in these studies almost exclusively rely on linear or exponential trends by ordinary least-square (OLS) regressions over the full time series. They usually use national level data from FAOSTAT, with only a few using sub-national level data from national data providers (see e.g. (Elagib, 2014; Larsson, 1996; Maikasuwa & Ala, 2013). Crop production as presented in these studies commonly show patterns of large interannual variations and varying degrees of positive linear trends in either part or all of the sample. Depending on the application of the analysis, using full sample linear trends on agricultural variables with varying nonlinear patterns risk establishing trends with low accuracy, and perpetuates an assumption that changes to the agricultural systems happen in continuous and smooth processes. Linear trends can namely easily be found to be statistically significant as long as one part of the data deviates from the rest of it, which does not guarantee that the overall progression in the data is linear. This can further lead to a misrepresentation of the drivers behind the patterns in the data by attempting to identify drivers that match these trends. Misidentified trends also pose direct issues for extrapolation methodologies. A few of the reviewed studies increase the complexity by separating the time series into periods, usually by following established notions of influential government programs, such as the Structural Adjustment Programs or agricultural support programs, to compare the linear trends between these periods (Akinyoade et al., 2013; Elagib, 2014; Ojiako,

Ifeanyi, Ezedinma, Asumugha, & Uzokwe, 2007; Sanusi, 2014). Although analysing structural breaks in data series has a long history in the statistical sciences (e.g. Chow 1960; Watt 1979) and with an extensive range of applications, the reviews conducted for this thesis indicates that such patterns often are neglected in studies of agricultural systems in Sub-Saharan Africa. Despite covering a wide range of applications, most of the reviewed examples could benefit from more detailed analyses and understandings of the trends and patterns in the crop statistics beyond full sample regression analyses. The lack of refined statistical approaches is probably due to a mix of data availability, statistical capacity, and research scope, but also due to an assumption of continuous and smooth progressions in the studied systems.

2.3 Regional agricultural systems

As alluded to previously, a common approach to the analysis of crop production in Sahelian countries is simply to work with the aggregated data and treat it as a unified whole. While this results in a practical simplification and summary, a considerable amount of information is lost. And as sub-national agricultural dynamics are likely to be distinct, a national crop dataset risk attenuating these divergences. To avoid this, and yet retain the analytical advantages that come on larger spatial scales, research methods applicable to large sets of crop variables are required. Approaching a national agricultural system as a combination of connected sub-national systems, rather than a unified single systems, acknowledges this, but in return has to contend with the added complexity it brings. Beyond the analytical advantage, there are also distinct policy features connected to the spatial level of analysis of agricultural systems. Besides directly feeding in to the policy developments on the national and global level, the regional (sub-national) level of analysis is commonly the level where land use, economic planning, and environmental management is conducted (J. W. Jones et al., 2016). For the Sahel specifically, agricultural dynamics on the regional scale is crucial for a range of food security metrics and operational tools employed by national ministries, AGRHYMET, the Food and Agriculture Organization of the United Nations (FAO), the Famine Early Warning Systems Network (FEWS NET), the World Food Programme (WFP), and others (FEWS NET, 2011b; IPC Global Partners, 2012; A. Jones, Ngure, Pelto, & Young, 2013). A lack of relevant and precise data on agricultural and rural dynamics on this level of analysis is a clear limitation for much of these efforts (European Commission, 2016). And as knowledge on this level of analysis further feeds in to rural strategies, specific interventions, and impact evaluations, the lack of the necessary datasets effectively limits their precision and potential (European Commission, 2016). Ongoing data gathering efforts are actively

addressing this, both through the development of institutional capacities (World Bank, 2017), as well as point specific food security monitoring and data collection by various development organizations (CILSS, 2018; FEWS NET, 2011b, 2014; Food Security Cluster, 2018; WFP, 2013). A review of the statistical capacities and data usage in selected studies across the Sahel however make it clear that large sections of sub-national data availability have been unaddressed (see e.g. Elagib, 2014; Larsson, 1996; Maikasuwa and Ala, 2013; Mohammed et al., 2010), where data compilation efforts and widened research scopes are needed. However, the qualitative and diverse nature of much of this data can render comparisons over extended time periods difficult. Coupling socio-economic data from these and other sources with quantitative environmental data in studies of regional agricultural dynamics thus faces several methodological issues. Partly due to this, studies on both the farm and national scales have received more attention than regional ones (Andrieu, Descheemaeker, Sanou, & Chia, 2015; Hoffman, Kemanian, & Forest, 2018; Jahel et al., 2016; Whitfield, Dixon, Mulenga, & Ngoma, 2015; Yengoh, 2013), based on either detailed data from field studies in specific areas, or nationally aggregated datasets. As a result of the lack of data compilation and research scopes on the disaggregated sub-national level of analysis, the widely reported patterns in Sahelian crop statistics of long term extensification trends and pronounced interannual variabilities are only explained in broad terms. Looking ahead, several indications show that the statistical capacity and data availability in the Sahel generally is increasing (World Bank, 2018b), which calls for a concurrent development of methods to appropriate the increased complexity and analytical potential this entails.

2.4 Assessing interannual variabilities in agricultural output

The interannual variabilities in Sahelian crop statistics is a reoccurring focus for both development strategies and research efforts, due to its strong links to food security and general risk management in the agricultural sector. And although these patterns are not understood to any predictable degree, they are often ascribed to seasonal variations in soil water availability (Bautista, 2012; LCBC, 2015). Methods to analysis these relationships usually focus on statistical correlations between crop yields and remote sensing atmospheric and soil variables (Badolo & Somlanare, 2014; Habtemariam, Abate Kassa, & Gandorfer, 2017; Kamali, Abbaspour, Lehmann, Wehrli, & Yang, 2018; Lobell, 2010; McNally et al., 2015; Sultan et al., 2013; Traoré et al., 2011; Webber, Gaiser, & Ewert, 2014). However, such studies usually leave a large part of the crop variability unexplained (Kamali et al., 2018; McNally et al., 2015; Traoré et al., 2011). Although the processes of crop growth

are well understood, estimating the crop response to seasonal atmospheric and soil conditions on spatial scales above the farm level are mired with uncertainties. Added to the difficulty of capturing the complex relationships between water availability, nutrients, and crop growth under changing agro-ecological conditions and with imprecise dataset, the limited explanatory capacity is commonly explained by a lack of data on additional factors that are relevant for crop variability (Louise, Christian, Danny, Agnes, & Seydou, 2015). Examples of such factors are pests, technological innovations, fertilizers, farm incomes, labour and land availability, development projects, political programs, conflicts, population dynamics, and market prices (Hazell & Wood, 2008; Mertz et al., 2010; Nelson, Zak, Davine, & Pau, 2016; Ouédraogo et al., 2017; van Vliet, Reenberg, & Rasmussen, 2013). Besides an overall lack of data on these factors, another reason for the omission of these factors is the dominance of climate change agendas and climate models in setting agricultural research priorities (Whitfield et al., 2015), with its allure of providing results over extended spatio-temporal scales. Purely climate driven analyses do however not add much of value for agricultural management in the Sahel in near-time periods, where decision makers are concerned with tangible productivity improvements, and where combinations of socio-economic, political, and climate variability factors are the prime drivers of change. Moreover, the influences of these factors are strongly connected to the spatial scale of the analysis, and the socio-economic complexity that goes with it (Jahel et al., 2016; Whitfield et al., 2015). Addressing these shortcomings in the knowledge of the drivers of interannual variability in the Sahel, on any spatial scale, initially requires a widening of the included datasets beyond the purely agronomical, as well as added detail in the data. Additionally, comprehensive methods need to be developed to appropriate the widened data coverage, which are likely to require combinations of qualitative and quantitative methods drawn from various academic disciplines.

2.5 Assessing long term changes in agricultural output

By extending the driver analysis from the short term interannual variabilities to the long term patterns of agricultural change, a diverse set of methods become relevant. By reviewing the use of such methods as applied across agricultural systems in Sub-Saharan Africa over the past 15 years, the following three main groups were identified: household surveys, focus groups or interviews in areas where changes had been identified (Nin-Pratt & McBride, 2014; Ouedraogo, Mbow, Balinga, & Neufeldt, 2015; Ouédraogo et al., 2017; Valbuena, Groot, Mukalama, Gérard, & Tittonell, 2015; Wood, Jina, Jain, Kristjanson, & DeFries, 2014); quantitative correlation to potential factors (Abro, Alemu, & Hanjra, 2014; Bachewe et al., 2015; E. T. 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 socio-economic factors (Berakhi, Oyana, & Adu-Prah, 2014; Kamwi, Kaetsch, Graz, Chirwa, & Manda, 2017; Mbow, Mertz, Diouf, Rasmussen, & Reenberg, 2008; Sandstrom & Juhola, 2017). These three groups of methods together draw from various academic disciplines, and deliver diverse knowledge outputs. Given the extended time periods, complexity and generally low data availability in studies of long term changes in agricultural systems above the farm level, an evaluation of drivers of change will be forced to contend with high levels of uncertainties and speculations. Consequently, a comprehensive analysis will need to draw from all possible data sources and research methods, to validate assumptions and arrive at relevant conclusions. This requires flexible but reliable analytical frameworks, which are not commonly found within the confines of any of the traditional academic disciplines. Wide analytical frames are however commonly found within the strategies and operations of organizations engaged in food security and rural development, but whose temporal scopes usually are focused on current events. And while the use of panel datasets are enabled by occasional surveys of the rural sector (see e.g. Houssou & Chapoto, 2014; Josephson, Ricker-Gilbert, & Florax, 2014), data that tracks the evolution of farming systems over time is generally limited to the national scale (see e.g. Binswanger-Mkhize & McCalla, 2010; FAO & AfDB, 2015; Fuglie & Rada, 2013; Nin Pratt, 2015). Several ongoing monitoring initiatives across the Sahel are addressing this, either with this specific aim in focus, or indirectly through general monitoring of the rural geographies and economies (CILSS, 2018; FAO, 2016b, 2018b; FEWS NET, 2018b; Food Security Cluster, 2018; Traore et al., 2014). Despite this increasing data availability, attributing drivers to agricultural changes is often confined to statistical analysis on national scales or qualitative assessments in specific areas, while methodological and spatial combinations of the two are rare (see e.g. Muyanga & Jayne, 2014). Due to the multitude of actors involved in the data collection efforts, with various agendas, comprehensive research methods that combine the existing datasets are needed to establish more precise relationships.

Moreover, advancing the analytical potential in long term changes to agricultural systems can initially be achieved by having a detailed understanding of the patterns of change, which is crucial to guide the driver identification not only spatio-temporally, but also to provide information on the characteristics of the driver. For instance, periods with different degrees of gradual change, as well as points of abrupt changes, might be distinguishable in the given context. In cases of attribution by quantitative correlation, an accurate trend estimation is necessary to distinguish the trends from the interannual variabilities. In a similar way, qualitative attributions are likely to be based on the identification of differences in trends between periods, as well as points of abrupt changes.

3 The agricultural sector in Chad

Over the past three decades Chad has been undergoing widespread socio-economic transformations, due to processes of population increase, urbanisation, democratization, public investment in social services, economic and financial reform, oil exports, conflict based migrations, and foreign aid (INSEED, 2012; World Bank, 2015). The rural sector forms the backbone of the Chadian economy, both in rates of occupation and economic output, and has thus directly been affected by these processes. The extent of changes to the Chadian economy and its main subsectors are illustrated by Fig. 5, which displays a distinct increase to the GDP, total population, and GDP per capita, as well as a high ratio of aid dependence.

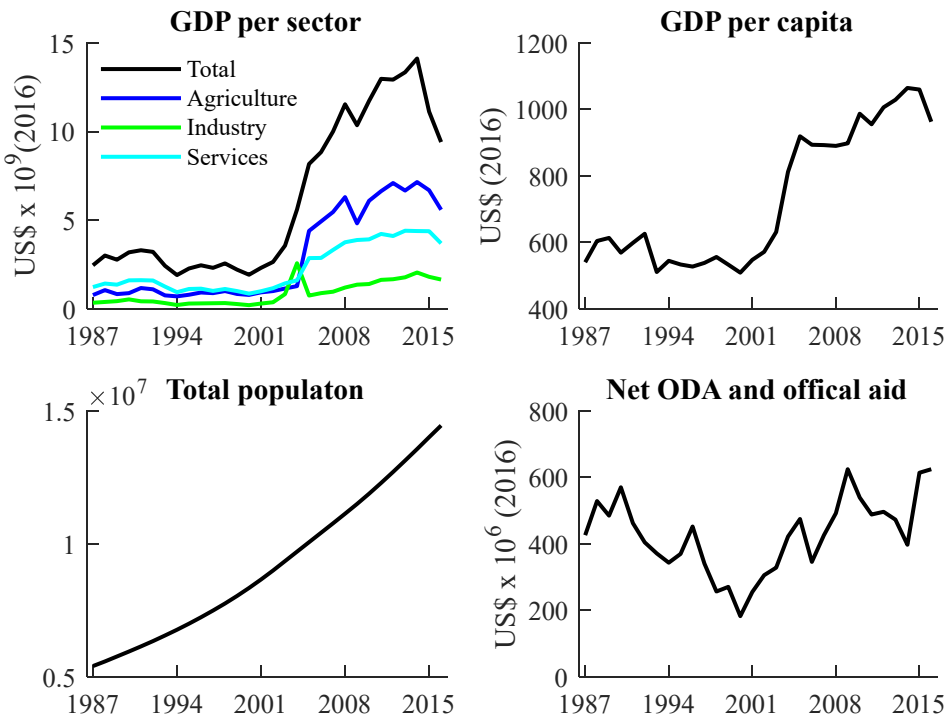

Fig. 5 *– Changes to GDP, population, and Net ODA over the last three decades (data from World Bank, 2018c)*

The jump in GDP and GDP per capita after 2003 is due to the extraction and export of oil which started in 2001, and triggered unprecedented rates of foreign direct investment and subsequently became a priority for the government's growth strategy (Ministry of Planning Develoment and Cooperation, 2003). Although the strong economic growth over the past decade largely has been due to the export of oil, its stock limits have made recent growth strategies actively seek to reduce the economy's dependence on the oil sector, partly through investments in the agricultural sector (République du Tchad, 2017). Within these strategies, an increased and stabilized crop production are two of the governments' main objectives, which mainly are to be realized through further expansions and by the creation of industry scaled agricultural systems (République du Tchad, 2017). While the conceived issues behind rural and agricultural development in Chad have received considerable attention (Lemoalle & Magrin, 2014; World Bank, 2013a), the factors of growth in the agricultural sector are still elusive and not established to any applicable degree, which is especially true for sub-national levels of analyses. Identifying these drivers of change plays a crucial role in creating influential interventions, and can provide a necessary complement to the issue based analyses.

The lack of further understanding of how the agricultural systems change is partly due to the complexity stemming from the agricultural sector's small-scaled agricultural and pastoral livelihoods, with low levels of specialization and industrialization (FAO, 2018a; FEWS NET, 2011b). Added to this, the public investments and interventions in the rural sector lack detailed evaluations and impact assessments, stemming from institutional constraints of lack of capital resources, technical capacities, corruption, and low data availability (World Bank, 2014). Moreover, there is a multitude of development organizations involved in the rural sector in Chad, which can also be seen in the high amounts of aid received in Fig. 5, which makes up around 75% of public capital expenditures in the rural sector and 5% of the annual GDP (World Bank, 2014). The influence of the various projects and agendas of these organizations, under conditions of inefficient public management and low data availability, further add complexities to the evaluations and impact assessments in the agricultural sector. The following section provide additional background to the main factors underlying these developments in Chad.

3.1 Agricultural practices

As the agricultural sector is the largest economic sector by occupation, and stretches over diverse ecological conditions, the agricultural livelihoods have some distinct differences within the country. The crop production in Chad can initially be separated between food crops and cash crops. The main food crops are millet, sorghum, rice, maize, and wheat, while the main cash crops are cotton, sugarcane,

peanuts, and sesame (République du Tchad, 2014). National food crop production is by itself generally insufficient to cover the nutritional requirements, which due to the livelihoods' dependence on these crops results in high and chronic food insecurity with strong seasonal patterns (République du Tchad, 2014; WFP, 2015). The food crop production is the most common agricultural orientation and has the largest contribution to the agricultural economy, while the cash crop production plays a larger role in exports (Ministry of Agriculture and Irrigation, 2013; République du Tchad, 2014). Both orientations are thus crucial points in rural development strategies, but this thesis however only covers the food crop production component, based on its more detailed and extensive data availability. Key distinctions in the agricultural systems have been laid out by FEWSNET's livelihood profiles (FEWS NET, 2005, 2011b), as presented in Fig. 6.

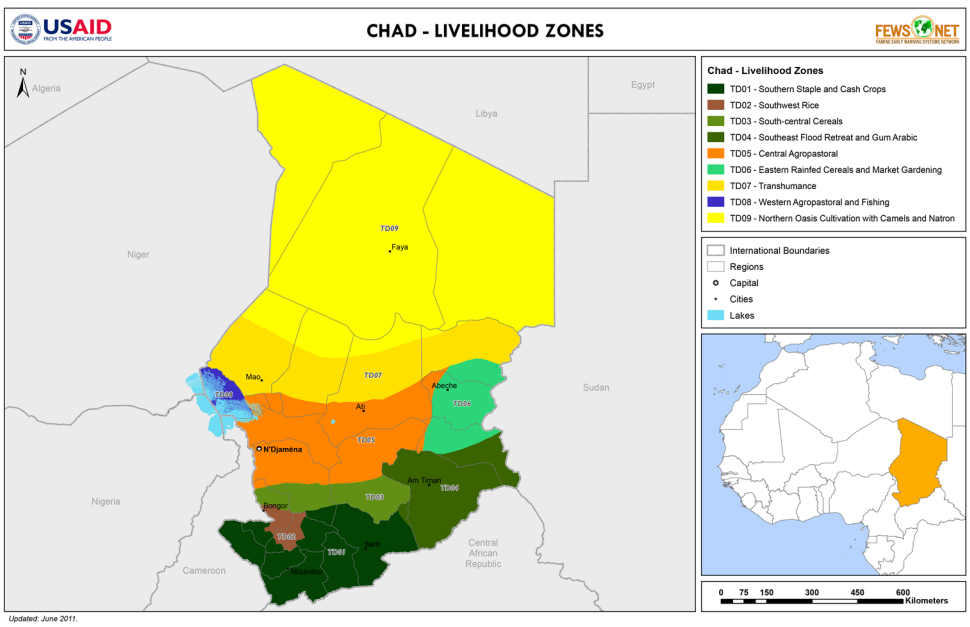

Fig. 6 *– FEWSNET livelihood profiles in Chad (FEWS NET, 2011b)*

Broadly described, the agricultural livelihoods follow the ecological north-south ecological and precipitation gradient, with increased levels of pastoral and transhumant livelihoods in the dry north, and more intense farming in the more humid south (FEWS NET, 2011b). A comparison with the previous livelihood profile assessment by FEWSNET in 2005 shows that the only distinct changes have been a slight movement to the south of the Sahelian vegetation, and a removal of a lake specific flood-retreat and fishing livelihood group around Lake Fitri, due to its reduced lake size and fish population (FEWS NET, 2005, 2011b). The Sahelian zone, stretching from Transhumance zone to the Southern Staple and Cash Crops

zone, is generally marked by mixtures of rainfed farming and transhumant pastoralism (République du Tchad, 2010). The Soudanian zone covers the area south of the Sahelian zone, where the production systems commonly are mixtures of different crops, combined with low levels of livestock, where the specifics of each area responds to local conditions of water availability, soil fertility, market connections, and access to non-agricultural revenues (République du Tchad, 2010). Additionally, the role of the cotton industry, which has been a focal point of industrialization strategies for the agricultural sector, is deeply engrained within the Soudanian livelihoods (République du Tchad, 2010).

Flood recession farming is prevalent in the Soudanian zone, which recently has become the focus of large scale hydro-agricultural developments (République du Tchad, 2014). Similar infrastructure projects have been launched in the mountainous regions of Ouaddai, Biltine, Guéra, and Mayo-Kebbi, to retain water and reduce erosion (République du Tchad, 2014). Improved agricultural water availability through groundwater and river extractions are confined to certain regions and the few large scale farms, with current estimates of irrigated land at around 43,000 ha, mainly around Lake Chad and certain parts in the Soudanian regions, while national strategies are aiming for a doubling by 2020 (Moussa, 2013; République du Tchad, 2014). Groundwater availability, and its related irrigation potential, is high but barely exploited, with annual storage levels varying between 263 and 455 billion m^3 and an annual recharge rate of around 26 billion m^3 (République du Tchad, 2014).

Table 1 summarizes the main differences in agricultural practices between the administrative regions in Chad, which primarily shows the extent of the small-scaled and low input production systems in both the Sahelian and Soudanian zones. Differences between the zones are mainly in the rate of improved seeds and chemical fertilizer use, and partly in the use of traditional hoe and storage facilities, where the Soudanian zone displays higher levels of intensification in all measures. Rates of pesticide use and rates of pastoral livelihoods are on the other hand similar between the two zones, which challenges the division of pastoral livelihoods between the Sahelian and Soudanian zones as described by other sources (FEWS NET, 2011b; République du Tchad, 2010). Average amount of cultivated area per household are almost identical between the two zones, at 3.5 ha in Sahel and 3.2 in Soudan, but which can mask distinct distributions.

Table 1 *– Agricultural practices in % of villages in the administrative regions in Chad (data from (Republic of Chad, 2009)*

	Improved seeds	Chemical fertilizer	Pesticide use	Traditional hoe	Pastoral	Storage facility
SAHEL						
Batha	1	1	4	74	80	20
Biltine	2	2	23	80	40	23
Chari B	5	4	5	64	56	12
Guéra	4	1	10	65	54	56
Kanem	12	4	8	62	60	12
Lac	3	1	3	56	40	0
Ouaddai	3	8	5	52	57	29
Salamat	1	0	1	69	26	20
Average	*3.9*	*2.6*	*7.4*	*65*	*52*	*22*
SOUDAN						
Mayo Kebbi	14	17	10	51	76	20
Tandjilé	11	10	8	57	58	32
Logone Occidental	4	5	2	68	40	37
Logone Oriental	16	17	9	62	45	29
Moyen Chari	5	6	10	49	38	51
Average	*10*	*11*	*7.8*	*57.4*	*51.4*	*33.8*

3.2 Processes of change

In the short term, agricultural production in Chad is known to be highly fluctuating, which is usually ascribed to the high ratio of rainfed and low-input farming in dry growing conditions (World Bank, 2015). Besides the generally dry growing conditions, the agricultural systems in Chad are subject to gradually increasing temperatures and occurrences of extreme events in term of droughts, floods, and heatwaves (République du Tchad, 2017). Hydro-climatic changes have been extensive since the 1960s, which is most apparently displayed by altered surface area of Lake Chad, where the annually maximum area has varied from 25,000 km^2 to a minimum of 1,800 km^2 in the 1980s, after which it increased to its current level of around 10,000 km^2 (Bader et al., 2011; Lemoalle et al., 2012; WMO & LCBC, 2005). With 80-90% of its inflow coming from the Chari-Logone River (Akan, Abbagambo, Chellube, & Abdulrahman, 2012), this reflects hydro-climatic conditions in the whole country. Ascribing agricultural variability solely to water

availability and ecological conditions are however bound to miss crucial drivers. With the currently low agricultural productivity levels, combined with the ongoing rural transformations, and potentially disruptive events such as pests, conflicts, and altered economic opportunities, crop production variability is likely to hold more complexity than what a purely ecological focus will capture. The uncertain production conditions are further linked to the low rates of specialization and yields in the agricultural sector, which together with a lack of financing, insurance, transportation, and storing facilities results in a situation where intensifying farming strategies pose a high risk, have low expected returns and market reach, and are difficult to finance (World Bank, 2015). These factors have been linked to the spread 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).

3.3 Structural reforms and markets

Structural reforms have liberalized the Chadian economy since the 1990s, by privatizing public companies, and by removing import and export licenses, monopolies, minimum wages, and price limits (IMF, 1999). Seen across Africa, these structural reforms have been particularly beneficial for agricultural growth in Chad (Ousmane, 2011). But despite efforts to reduce the state's involvement in the economy, the presence of the private sector in the agricultural sector is notoriously low (Ministry of Planning Develoment and Cooperation, 2003; Moussa, 2013). This is partly reflected by the Doing Business ranking of Chad at 183 of 189 countries (World Bank Group, 2016), and the corruption ranking at 165 of 180 (Transparcency International, 2018), which sets considerable institutional obstacles for both private and public investments. The private sector is however active in the commercialization and trade of agricultural products, but due to transport limitations, and the low levels of: competition among the private actors, storage and transformation capacities, market information, and purchasing powers, the market dynamics cause large differences in market prices and food security within the country (République du Tchad, 2010). This also creates distinct seasonal patterns in market prices, as most agricultural products are sold to local markets at the end of the growing season (Brown, 2014). Food markets in Chad are furthermore largely dependent by national, and to some extent regional, market supplies, with little integration with international markets (Brown, 2014). Advancing the commercialization of the whole rural sector has thus been set as one of the key national strategies for rural development, with a focus on developing transformation and storage facilities for agricultural products, to be able to satisfy national market demands in all seasons (République du Tchad, 2014, 2017).

Processes of agricultural intensification are further highly dependent on the availability of financing and credits. With no national institution charged with providing credit and finance for the rural sector in Chad, agricultural producers are dependent on the few commercial banks located in the main cities, which generally show little interest for the rural sector beyond industry scaled cotton sector (République du Tchad, 2010). Although funding schemes have been set up for specific development projects, the low financial capacity of farmers means that they generally lack the means to invest in improved inputs and equipment (République du Tchad, 2010).

3.4 Demography

These market dynamics mean that demand for agricultural products largely is driven by national demand, which is directly connected to the high levels of annual population growth at around 2%, making it one of the world's highest (World Bank, 2018c). On top of population and market integration, demand is driven by the purchasing power, which is marked by inequalities and evolving with a strong urban-rural divide in monetary poverty (World Bank, 2013c). Despite progress in poverty reduction, mainly attributed to urbanisation and oil-driven economic growth, the high population increase resulted in a 15% increase in the total number of monetary poor between 2003 and 2011 (World Bank, 2013c). Moreover, with a predominantly young population, leading to high dependency ratios, the cohort of population in working age is growing rapidly, from around 3.7 million in 2003 to 5.8 million in 2012 (INSEED, 2006a, 2013). As agriculture is the most common occupation in the country (INSEED, Ministère de la Santé Publique, & ICF International, 2016), demographic changes like these are affect the agricultural sector through various channels beyond market demand. And as demographic changes within the country are driven by urbanisation and other migration factors, following droughts (République du Tchad, 2017), employment opportunities, or security threats (INSEED, 2012), the rates of change are likely to differ considerably between the regions. While responding to these factors, the effects of population growth on the agricultural sector will depend on the education levels, and the livelihood complexity and social organization it enables. Chad has one of the world's lowest literacy rates, which in 2013 stood at 47.4% for men and 29.1 % for women, who make up the majority of the agricultural work force (République du Tchad, 2010, 2017). The relatively low educational and technical capacities affect the agricultural sector through a range of socio-economic facets, such as: uptake rates of new technologies, access and use of information related to weather and market conditions, technical advises and training from public extension officers, evaluation of interventions, and organizational complexities on both an institutional

and community level. Low education levels further imply that additional investments in education, due to ongoing economic growth and international aid, are likely to have widespread societal effects. While commonly theorized and emphasized as factors of agricultural change, and complex in their details, the cost and organizational efforts required to collect demographic data mean that these relationships often are unexplored. Crude measures of education levels such, such as literacy rates and educational attainment, can still pick up on the general tendencies of these relationships, and need to be included in assessments of agricultural change. The demographic data availability in Chad, and its application in this thesis, are presented in the Data section (section 0).

3.5 Public investments and governance

Improving education levels and agricultural growth are main targets for public investments in Chad (République du Tchad, 2017). The amount of public investments in the these sectors are however directly dependent on the state of the general economy, whose growth constraints commonly are linked to security problems in its neighbouring countries, dependence on volatile oil revenues, and inefficient public financial management (IMF, 2013). Moreover, there are range of public actors involved in rural and agricultural development (see République du Tchad, 2014), which have been undergoing reforms and structural adjustments since the 1990s (IMF, 1999). The efficiency of this systems and its public investments is however hindered by a highly centralized political system, where transfers of resources and competence to local branches often are insufficient (République du Tchad, 2017). The sheer size of the country and limited communications and transportation capacity further increases the gap between central and local government branches (Ministry of Planning Develoment and Cooperation, 2003). On top of this, the discrepancy between budgeted and realized expenses are thought to be considerable, with pronounced annual variations in the budgetary execution rates (IMF, 2013; République du Tchad, 2014; World Bank, 2014). To reach the objective of annual economic growth in the agricultural sector of 6%, current public spending is estimated to require an increase by 8.0% per year (République du Tchad, 2014). Four key components to realize this growth have been identified as: access to inputs and farm equipment, reduction of post-harvest losses, conservation and transformation facilities, and improved and diversified seeds (République du Tchad, 2014). A review of public expenditures over the period from 2002 to 2012 found that public spending in the agricultural sector has increased more than the sector's contribution to GDP, indicating a priority of agricultural development from the government's side (World Bank, 2014). This commitment is also displayed through recent public strategies and development programs (Ministry of Agriculture and

Irrigation, 2013; République du Tchad, 2003, 2014, 2017). With variations in annual economic growth levels, a heavy centralization of the public administration, and overwhelming budget rates directed to wage expenses, public spending in the agricultural sector has however had low proportions of its budget directed to operational activities in this time period, which at 4 % is below the national budget average of 9 % (World Bank, 2014). This lack of sufficient operational resources adds to the low managerial capacities within the ministries and public institutions, which seriously limits the implementation and efficiency of development programs and projects in the agricultural sector (World Bank, 2014). One key outcome of this, in combination with the low level of private sector involvement and financing, is that there is a general lack of fertilizers and seeds adapted to the specific growing conditions (République du Tchad, 2014). The effects of public investments are furthermore difficult to evaluate, due to a lack of systematic evaluation and monitoring procedures in place, stemming from the complexity of the agricultural sector under conditions of low data availability and limited operational resources (IFAD, 2011; World Bank, 2014). Additionally, distinguishing the effects of interventions in the agricultural sector is complicated by the pronounced interannual output variabilities, which despite their fundamental influence on food security mostly remain unexplored.

An additional ongoing institutional development relevant for agricultural change is the often conflictual jurisdictions between property rights in customary and statutory laws (République du Tchad, 2017), a conflict which balances between the recognition and respect for traditional cultures, and the strive for a modernized and efficient economic sector. Aspects of property rights are also foundational to the management of areas with combined agro-pastoral activities, which due to the transhumant pastoral livelihoods and the expansive agricultural livelihoods commonly lead to conflicts of access to land (Krätli, Monimart, Jallo, Swift, & Hesse, 2014). While being a recognized institutional issue, finding sustainable solutions have proven difficult, adhering to issues of rapid demographic changes, an obsolete institutional frame dating from the colonial era, and a lack of normalization of the customary laws (République du Tchad, 2017). With ongoing demographic, cultural, institutional, and economic changes, additional pressures are likely to mount on the need for a regulatory frame which reconciles the various notions and objectives of property and development.

3.6 International aid

Public expenditure on agricultural and rural development is furthermore dependent on foreign funding and aid programs, with a recent review estimated to make up around 75% of public capital expenditures the rural sector (World Bank, 2014). At

the same time, total international aid per inhabitant in Chad is at $17 per year and inhabitant generally 2-3 times lower than other Sahelian countries (Swiss Agency for Development and Cooperation, 2016). To understand and evaluate the impact of public programs, the role of international aid and foreign investments thus provides an additional important source of analysis. Several of the main development actors, such as the World Bank, the European Commission, and the African Development Bank, provide detailed information about the projects they operate, which gives added potential to evaluate their effects. However, the same issues of uncertain impact evaluations and pronounced interannual output variabilities as for the public expenditure and programs persists here (Herdt, 2010; IRAM-ADE, 2016), which is further complicated by the multitude of development actors involved. This multitude of actors also results in conflictual development agendas, requiring considerable coordination efforts (IRAM-ADE, 2016). More information on the amount and focus of international aid in Chad is provided in the aid specific Data and Methods sections (4.5 & 5.5.2.3).

3.7 Conflicts, refugees, and security

Situated between Nigeria, Cameroon, the Central African Republic, Sudan, and Libya, Chad has over the past decades constantly been involved in regional conflicts to various degrees. Recently, the Boko Harm insurgency that originated in Nigeria and Cameroon has spread into Chad, mainly around the Lake Chad region. After a couple of years of violent attacks and insecurity, this situation has lately been successfully constrained (République du Tchad, 2017), although the overall security threat still remains. Maintaining security within the country has thus been a key priority for the Chadian government's development strategy, which have come at odds with other non-security related development efforts (New York Times, 2008). On top of the competition over public funds, and the reduced priority of long term agricultural development, the impacts on the agricultural sector due to this situation are many. Most urgently, violent attacks, and the fear thereof, have forced farmers to abandon certain agricultural areas (WFP, 2016). Additionally, the ongoing conflicts in the neighbouring countries have made Chad into one of the countries with the highest amount of refugees in the world (UNHCR, 2018b). Although generally addressed by refugee camps established and funded by international aid organizations within its borders, the reception of refugees and returnees put additional strains on the natural resources and social services of the rural host communities (FEWS NET, 2007; USAID, 2017). The intensity and unpredictability of conflict related impacts thus adds complexity to agricultural development, and the understanding of its patterns and drivers of change.

3.8 Knowledge gaps

Although the main drivers of agricultural growth as presented in the previous sections commonly are mentioned, their combined dynamics and effects on the agricultural sector are yet to be specified and explained. This applies both to the patterns and drivers of change, in both the short and long term. Several previous studies have collected data and described the differences in agricultural practices between the administrative regions in Chad (FEWS NET, 2005, 2011b; Republic of Chad, 2009; WFP, 2013; World Bank, 2010), although no comparative analysis of the patterns and drivers of agricultural output between the regions have been conducted prior to this thesis. With important regional differences within the country (World Bank, 2015), this is a limiting factor for development initiatives, and more precisely for seasonal and long term planning for food security, which often takes place on sub-national levels of analysis. Lack of further analysis on patterns and drivers of crop production the sub-national levels can be explained both by a limited access to sub-national longitudinal crop data, joint with the complexity of crop production on this level of analysis. Added to this, a considerable part of the reports and studies on the agricultural sector in Chad come from development organizations in the country, whose research scopes usually are limited to current events, and thus might not engage in analyses with more extensive scopes. Moreover, regional crop statistics and market prices form the basis of much of the operative food security work, but has prior to this thesis yet to be combined over extended time series to evaluate patterns of covariation and quantified causalities.

4 Data

4.1 Data availability in the agricultural sector in Chad

Although all the main drivers of agricultural change as presented in Fig. 3 are relevant for a comprehensive analysis of the dynamics in the agricultural sector in Chad, the data availability effectively limits any such analysis into a manageable scope. While some of the identified drivers can be covered adequately by online data sources, extensive and quantitative data on most of the socio-economic drivers require collaborations with Chadian institutions. Several of data gathering institutions in Chad have a long running tradition of data collection, most of which is not readily accessible online. The Chadian Institute for Statistics, Economic Studies and Demographics (INSEED, previously DSEED), has the overall responsibility for statistics in the country and has been established since 1969, but with interruptions to its activities due to violent conflicts between 1979-1989 and in 1990 (INSEED, 2006c). Agricultural statistics has been collected by the Direction de la Production et de la Statistique Agricoles (DPSA) and the Office National de Développement Rural (ONDR), both under the Ministry of Agriculture (INSEED, 1994, 2006b). ONDR was established in 1969, and have since been releasing reports with high level of detail from at least the mid-80s (e.g. INSEED, 2006b; ONDR, 1988, 1984). Besides the agricultural surveys used to acquire estimates of annual production, harvested area, and yields, they also collect data on food market prices (DPSA, 1994; INSEED, 2006b). A prominent issue is that several of these data collection functions depend on external and project specific funding, and as a consequence publications have sometimes been irregular and discontinuous (INSEED, 2006b). Furthermore, collection of agricultural data besides crop statistics has been lacking, and there are reoccurring issues with inconsistent data collection methodologies for these data categories (DPSA, 1994; FAO, 2013; INSEED, 2006b; Ministry of Agriculture, 2005). Recently, authorities and development organizations in the country have been addressing the lack of detailed socio-economic data through demographic censuses in 1993 and 2009 (INSEED, 1993, 2012), and with an increasing amount of food security related surveys and assessments (FEWS NET, 2005, 2011b; INSEED, 2013; INSEED, UNFPA Tchad, & UNICEF Tchad, 2011; Republic of Chad, 2009; WFP, 2005, 2009, 2013). To strengthen the statistical capacity in the country, the Système d'Information sur la Sécurité Alimentaire et d'Alerte Précoce (SISAAP) has recently been created, with

the purpose of supporting data collection, coordinating the actions of all the food security actors in the country, and establishing a comprehensive and unified information system for food security (FAO, 2013). An overview of the drivers that were covered to various degrees by the data used in this thesis are summarized in Fig. 7, as related to the main drivers of change as identified in Fig. 3, and are presented in detail in the following sections.

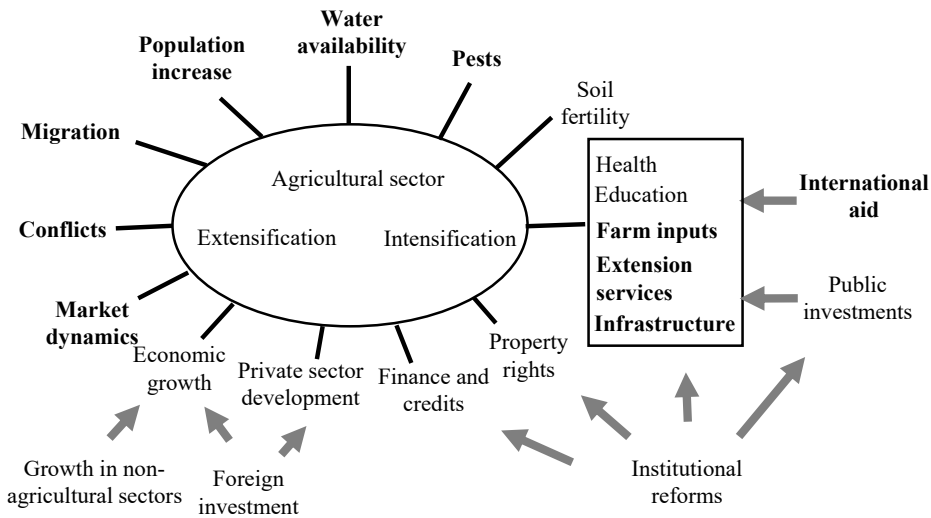

***Fig. 7** – Overview of data coverage (in bold) of main drivers of change in the agricultural sector*

4.2 Agricultural data

Through collaborations with the DPSA and INSEED, detailed and extensive datasets on cereal crop statistics were acquired on the regional level, i.e. first administrative level under the national level. 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. The only exception to this was the crop statistics acquired for the Lac region from SODELAC for 1988-2013, which had coverage down to the village level. 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 (DPSA, 2017), with eight Sahelian regions: Batha, Biltine, Chari Baguirmi, Guéra, Kanem, Lac, Ouaddai, and Salamat; and five Soudanian regions: Mayo-Kebbi, Tandjilé,

Logone Occidental, Logone Oriental, and Moyen-Chari. The location of the cultivated areas in each region were taken from the Earthstat dataset (Monfreda et al., 2008), which gives the average fraction of hectares under cultivation between 1997-2003 for each crop and grid cell (at 0.1°). Fig. 8 presents the areal distribution of cultivated areas together with the administrative division used.

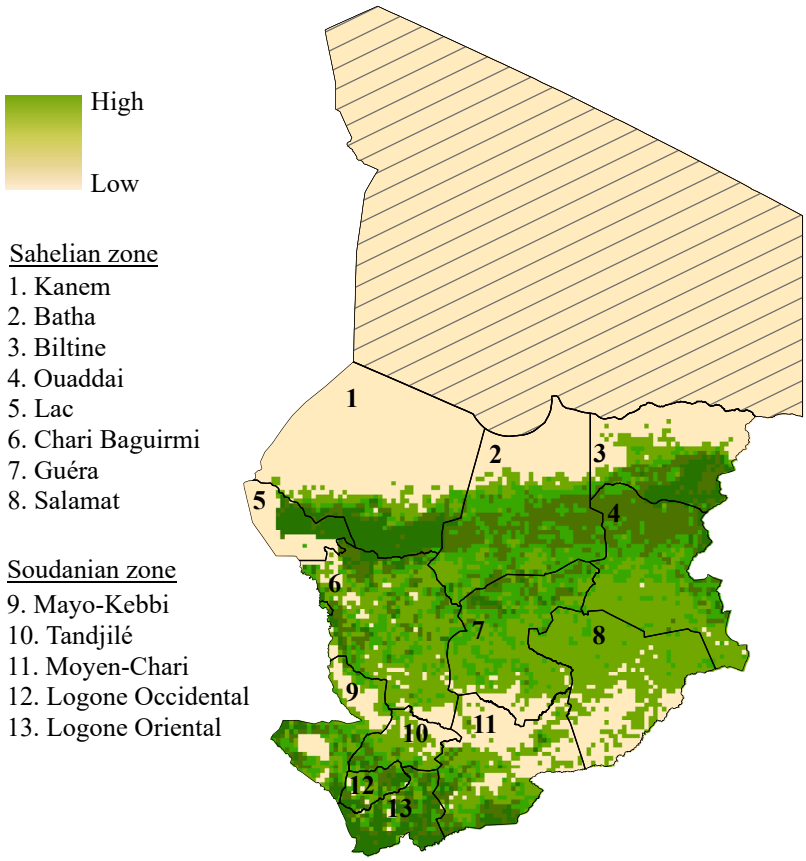

Fig. 8 *– Distribution of maize, millet, and sorghum crops as given in the Earthstat dataset (Monfreda et al., 2008), together with the regional divisions used in this study. Note that this is not the current administrative regional division in Chad*

All regional data originate from the ONDR and its data branch DPSA, but were acquired from FAO's Agro-MAPS database for 1983-1995 (FAO, 2006), INSEED for 1993-1997 (INSEED, 1994, 1997), and DPSA for 1998-2016 (DPSA, 2017). Despite their extent and detail, these crop statistics have not been available online prior to this thesis except as in national aggregates through the FAOSTAT database (FAO, 2018a). The crop data collection is based on surveys and aggregation on village, departmental, and regional levels over the country (INSEED, 2006b). One

assessment on the statistical capacities by the Chadian institutions have concluded that the agricultural data collected by DPSA and ONDR have proceeded without major issues (INSEED, 2006b). In the early phases of the agricultural data collection, the block-like structure of the small-scaled agricultural areas were identified as facilitating agricultural surveys, while a complicating feature was the varying mix of crops grown within these blocks (ONDR, 1984). This introduces an uncertainty in the precision of crop-level data, while it strengthens the reliability of the data on the total crops per area. Other sources have however cautioned about errors and inconsistencies in the crop statistics (FAO, 2013; INSEED, 2006b; Ronelyambaye, 2015; World Bank, 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.

4.2.1 Data verification

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. Crop variables whose total production over the full sample were < 1 % of the total production for each region were excluded, as were initial periods in variables with corresponding production levels of < 1 ton / 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 zero could result in extremely high yields. The maximum yield level was set to 5 ton / ha, which was considerably higher than the normally reported yield of around 1 ton / ha (FAO, 2018a). An outlier filter set to three standard deviations from the five-year moving average was applied to exclude unrealistic values within each variable. This resulted in 52 region specific crops for the 13 administrative regions, with 29 in the Sahelian zone and 23 in the Soudanian zone, with three crop variables analysed for each crop (harvested area, yield, and production). 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. Moreover, from at least the year 2000 onwards the crop data from the DPSA has 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).

4.3 Data for crop-water relationships

The environmental impact on the agricultural production was assessed based on precipitation, crop evapotranspiration, and crop water deficits over each growing season. With considerable uncertainties in the datasets and appropriate methods, as well as lack of information on specific crop and growing conditions, a range of potentially influential variables were created to be evaluated against the crop data. Crop evapotranspiration, crop water deficits, and subsequent effects on the crops were estimated based on FAO's methods for yield response to water (Allen, Pereira, Raes, & Smith, 1998; Doorenbos & Kassam, 1979; Steduto, Hsiao, Fereres, & Raes, 2012). Crop specific coefficients needed for these calculations were taken from (Allen et al., 1998; Doorenbos & Pruitt, 1977). Crop characteristics will however vary according to the specific crop variety used in the different regions of Chad, but such detailed data were not acquired for this study. Seasonal precipitation, crop evapotranspiration and crop water deficits per region and crop were calculated as weighted averages based on a 0.1° spatial resolution and relative weights according to the previously described crop maps in Fig. 8. Due to ongoing transformations in the agricultural systems across Chad, the extent and location of cultivated areas have changed over the studied time period. However, as such expansions are likely to occur adjacent to current areas, the atmospheric conditions are likely to remain similar. A combination of remotely sensed, modelled, and re-analysis datasets were used for the environmental data needed for these calculations (Table 2). For datasets with different spatial resolutions than 0.1°, the nearest grid cell was selected, thus assuming homogeneity within each grid cell irrespective of resolution.

Table 2 *- Data for seasonal water availability estimates*

Variable	Dataset	Spatial resolution (°)	Temporal resolution (h)	Temporal coverage	Source
Precipitation	ARC2	0.1	24	1983 - 2016	(Novella & Thiaw, 2013)
Soil moisture	ESA CCI SM v03.2	0.25	24	1978 - 2015	(EODC, 2017; Liu et al., 2011, 2012; Wagner et al., 2012)
Temperature, Wind speed, Dew temperature	ERA Interim	0.7	6	1979 - 2016	(Berrisford et al., 2009)
Solar radiation	NCEP/NCAR reanalysis	1.9	24	1979 - 2016	(Kalnay et al., 1996)
Soil water holding capacity, Hydraulic conductivity	Global Soil Hydraulic Properties	0.25	-	2014	(Hengl et al., 2014; Montzka, Herbst, Weihermüller, Verhoef, & Vereecken, 2017; Schaap, Leij, & van Genuchten, 2001)
Elevation	GMTED2010	0.5	-	2011	(Danielson & Gesch, 2011)
Crop location	Earthstat	0.1	-	1997 - 2003	(Monfreda et al., 2008)

Two data sources were used to drive the crop water availability calculations: precipitation from ARC2 (Novella & Thiaw, 2013), and satellite based soil moisture estimates from ESA CCI SM v03.2 (EODC, 2017; Liu et al., 2011, 2012; Wagner et al., 2012). The ARC2 dataset was developed specifically for the operational use of FEWS NET in Africa, while its high resolution and extensive coverage period also makes it suitable for research activities (Novella & Thiaw, 2013). The ESA CCI SM v03.2 have shown promising validation results (Liu et al., 2012), and improvements over atmospherically driven soil water estimates related to crop

yields in the Sahel (McNally et al., 2015). A potential advantage with measured soil moisture data is that they include all sources of water input to the soil, e.g. runoff and irrigation, which are usually neglected in the atmospherically driven estimates, while shortcomings, on top of measurement uncertainties, mostly stem from them only estimating soil moisture in the topsoil (EODC, 2017). The precipitation, relative humidity and temperature datasets were verified against monthly observations stations in Chad from the Direction des Ressources en Eau et de la Météorologie (DREM) for the period 1998-2013 (DREM, 2014), with 8 stations for precipitation and 3 stations for temperature and relative humidity. The average Spearman correlation coefficient to the nearest four grid cells of each observation station was 0.88 for the ARC2 data, 0.89 for ERA Interim Temperature, and 0.95 for ERA Interim Relative Humidity, which were acceptable validations of the remote sensing atmospheric data.

4.4 Livelihood data

To assess the role of socio-economic factors to changes in the crop production, data from food security reports from FEWS NET were included. These reports are available on a monthly basis since the year 2000 (FEWS NET, 2018a), and cover events and conditions relevant for the operational activities of food security actors in Chad. For the Lac region, the FEWSNET reports were complemented by the annual reports from SODELAC, which provides added detail to the developments to this region specifically (SODELAC, 2014). Aspects covered by these reports generally include: food security conditions, market prices, conflicts both in Chad and in neighbouring countries, population movements, trade flows, employment opportunities, pests, and political developments. The extent, detail, and temporal consistency in these reports provide a wealth of information about livelihood changes in Chad. The reporting is mostly qualitative in nature, with few quantifiable parameters, and differs noticeably across the studied time period, both in coverage and detail. Initially, information from the food security reports with 2-3 months of separation for 2000-2016 were sorted according to the region, month, and livelihood factor they concerned. The information in the reports is given on different spatial scales, and to accurately relate the information to the relevant regions, all information within each livelihood zone (Fig. 6), and region (Fig. 8) were assigned to the respective region used in the study, while information on broader spatial scales than this was excluded. This initial sorting and categorization of the reports was done in MAXQDA, and later imported as a database to MatLab for further analysis. Nine different topics were created to categorize the information, which are presented in Table 3. This categorization of information into topics, locations, and growing seasons from a large set of reports into a searchable database provided an

easily accessible overview of all relevant livelihood factors for each growing season and location. The analytical potential of this database is however limited by the large spatial units used in the reports, as well as the qualitative and inconsistent nature of the information, where the detail, focus, and style varies over time. Added to this, the reports are biased towards crises and events with high levels of food insecurity, with less reporting on factors driving crop production in food secure areas.

Table 3 *- Categories used to organize the information from FEWSNET's food security reports*

Livelihood topics	**Coverage**
Agricultural production	Production, yield, planted & harvested areas
Conflict	Armed conflicts, refugees
Market	Market prices, market supplies, food security reserves
Pastoral	Livestock health, movements, and numbers
Employment & health	Income, employment availability, health conditions, food access
Weather & Environment	Precipitation, soil moisture, temperature, drought, NDVI
Development projects	Time and space specific development interventions
Policies	Price caps, subsidies, trade regulations, fiscal policies
Pest	Locusts, elephants, soil borne diseases
Food security classifications	Classes of food security (from 1 – 5), set by FEWSNET

4.5 Aid data

Data on international aid received in Chad was mainly taken from the International Aid Transparency Initiative (IATI) datastore (IATI, 2018b) and its explorer of geocoded data, d-portal (IATI, 2018a). As IATI only compiles and provides the data supplied through their reporting system by donors, with no data validation on its own, the quality and reliability of the data is ultimately up to each donor to uphold. As reporting to IATI also is voluntary, several donor organizations hold more detailed and extensive project information in their respective project databases. For the main donor organizations, the IATI data was thus complemented with donor specific project databases, which are presented in Table 4. AidData also provides geocoded data from selected donor organizations, which in the case of Chad only is available for the World Bank and the Global Environment Facility (Goodman, Benyishay, & Runfola, 2016). To evaluate the effect of aid on regional agricultural growth, data was extracted from each project on: project period, project budget, target location, aid category according to OECD's Development Assistance Committee (DAC) (OECD, 2018b), and project descriptions. All project budgets were converted to US$ and deflated to 2016 price levels by using the Consumer

Price Index of the World Bank (World Bank, 2018d). For projects with no disbursement data available, the project budget was set to the committed amounts, and distributed equally over the full project period on an annual level. 3-digit DAC5 sector categories were used (OECD, 2018b), which gave sufficient detail to be able to distinguish between the main types of aid, and enabled an acceptable categorization accuracy of projects without given DAC categories based on their project descriptions.

Besides the general difficulty of impact evaluations for development projects in Chad (IFAD, 2011; IRAM-ADE, 2016), the main limitation with the aid data is that the target location often is lacking from project entries, or only given broad descriptions. This is especially true for earlier projects, while recent data provision initiatives, such as AidData and IATI's d-portal, actively are addressing this by providing geocoded locations to projects. For the majority of projects in Chad not included in AidData or d-portal, project locations were ascribed to specific regions in Chad by using a search algorithm that compared texts in the project titles and project descriptions to location names in Chad. A comprehensive list of location names were built from a lists of all cities in Chad (MaxMind, 2018), all districts and regions (INSEED, 2008), refugee camps from UNHCR and FEWSNET reports (e.g. FEWS NET, 2015; UNHCR, 2018a), as well as a list of general location identifiers created by the authors (e.g. North Chad, Northern Chad) in English and French. Target locations were then ascribed to regions according to the location names identified in the project texts, and split equally according to the number of locations identified in each region. As Chad is receiving large amounts of aid directed to humanitarian projects for refugees, target locations for project texts mentioning refugees without any location names were ascribed according to the location of refugees in Chad for the project period. The number and location of refugees for each year were estimated based on UNHCR's population statistics (UNHCR, 2018b), which provide data on country of origin for all refugees reported in Chad. As no specific data is given on the location of the refugees in Chad, refugee locations were set to the region or regions in Chad bordering their country of origin. Project budgets for such entries were then split over all regions hosting refugees, weighted according to the estimated number of refugees in each region. Although this is bound to misrepresent the target locations for individual refugee projects, it is likely to give an accurate estimate of target locations and budget attributions over a large set of projects.

Table 4 *– List of sources used for donor specific project databases on international aid*

Donor organization	**Source**	**Time coverage***
United States Agency for International Development (USAID)	(USAID, 2018)	1961 - 2018
European Commission	(European Commission, 2018)	1992 - 2018
International Fund for Agricultural Development (IFAD)	(IFAD, 2018)	1991 - 2018
World Bank	(AidData, 2017; World Bank, 2018a)	1975 - 2018
Global Environment Facility	(AidData, 2018; Globel Environment Facility, 2018)	1995 - 2018
African Development Bank	(African Development Bank, 2018)	1975 - 2018
Germany Agency for International Cooperation (GIZ)	(GIZ, 2018; KfW, 2018; OECD, 2018a)	1995 - 2018
French Development Agency (AFD)	(AFD, 2018; OECD, 2018a)	1993 - 2018
Arab Bank for Economic Development in Africa (BADEA)	(BADEA, 2018b, 2018a)	1974 - 2018
OPEC Fund for International Development (OFID)	(OFID, 2018)	1989 - 2018
Kuwait Fund for Arab Economic Development (KFAED)	(KFAED, 2018)	1995 - 2018
Swiss Agency for Development and Cooperation (EDA)	(EDA, 2018)	2008 - 2018
Islamic Development Bank (IsDB)	(IsDB, 2018; OECD, 2018a)	1995 - 2018
United Nations Development Programme (UNDP)	(FAO, 2018c; OECD, 2018a)	1984 - 2018
Food and Agricultural Organization of the United Nations (FAO)	(FAO, 2018c, 2018d)	1989 - 2018

** Time coverage is the earliest and latest year of projects reported in Chad for the respective organization*

4.6 Demographic data

The demographic data stems from the only two nationwide demographic censuses conducted in Chad, in 1993 and 2009 (INSEED, 1993, 2012), complemented with surveys on consumption and the informal sector in 2003 and 2011 (INSEED, 2006a, 2013), rural food security in 2013 (WFP, 2013), and rural occupations and livelihoods in 2014 (INSEED & ICF International, 2016). The demographic variables included in this study are listed in Table 5, where the low sample rates for all but the nationwide demographic censuses introduce uncertainties in the data. And while being based on extensive surveys, which enables detail panel data analysis, their sparse temporal data availability limits the potential to evaluate any detailed relationships to the agricultural sector, where data only was acquired once per year and region. Instead, only broad comparisons can be made to the agricultural output of the regions over the points in time specified in Table 5.

Table 5 *– Demographic data*

Variable	Definition	Time	Sample rate (%)	Source
Total population	-	1993, 2009	100, 100	(INSEED, 1993, 2012)
Agricultural population	Main occupation during the 12 months preceding the survey	1993, 2009, 2014	100, 100, 9	(INSEED, 1993, 2012; INSEED et al., 2016)
Poor population	Member of household with income below set annual poverty threshold	2003, 2013	5, 15	(INSEED, 2006a; WFP, 2013)
Non-poor population	Member of household with income above set annual poverty threshold	2003, 2013	5, 15	(INSEED, 2006a; WFP, 2013)
Literacy population	Individual with the ability to read or write a simple phrase in any language	1993, 2009	100, 100	(INSEED, 1993, 2012)
Mean income	Mean income per household	2003, 2011	5, 11	(INSEED, 2006a, 2013)
Income inequality	Rate of highest to lowest household income quintile	2003, 2011	5, 11	(INSEED, 2006a, 2013)

4.7 Summary of data availability

Table 6 gives an overview of the type and temporal coverage of all of the included datasets.

Table 6 *– Time coverage for data types*

Data type	Time coverage
Crop statistics	1983 - 2016
Soil moisture	1983 – 2016
Demographic data	1993, 2003, 2009, 2011, 2014
Aid data	1961 – 2016*
Livelihood data	2000 - 2016

** Earliest and latest year of projects reported in Chad*

5 Methods

5.1 Overview of methods

The methods were developed to take full use of the compiled datasets to advance the knowledge of the patterns and drivers of agricultural change on a sub-national level in Chad. Several previous studies had reported on the pronounced interannual variabilities in the production patterns, while a few had presented its long term increasing trends on a national level (World Bank, 2013c), although no prior study had analysed the agricultural statistics with the level of detail as presented here. These broad descriptions of pronounced interannual variability and long term increases in the agricultural statistics were confirmed by early evaluations, which then formed the basis of the methodological framework, as summarized in Fig. 9.

Due to the unique extent and detail of the agricultural statistics, summarizing the patterns of change was set an initial instrumental, as well as intrinsic, research objective **(see Paper 2)**. This showed that the long term patterns in the data often did not follow continuous or linear trends, which required an application of non-linear statistical methods. By identifying the patterns of change in the agricultural statistics, the trend levels could be distinguished from the patterns of interannual variability. After the interannual variabilities and the trend levels had been satisfyingly identified, both datasets were analysed separately to identify the drivers of change for their respective patterns **(Paper 3 & 4).** This required use of different sets of data and methods. The analysis of drivers of interannual variability served to identify the best estimate of soil water availability, which was then applied to the analysis of trend levels as well. The identified drivers were finally combined to present a comprehensive picture of the explanatory capacity of these datasets and the develop methods to the patterns and drivers of change in regional agricultural production in Chad. Finally, the data, methods, and results as applied in the case of Chad, were generalized as a proposal for evaluation of patterns and drivers of change in agricultural systems in the wider context in the Sahel. The following sections presents the methods applied for these research steps.

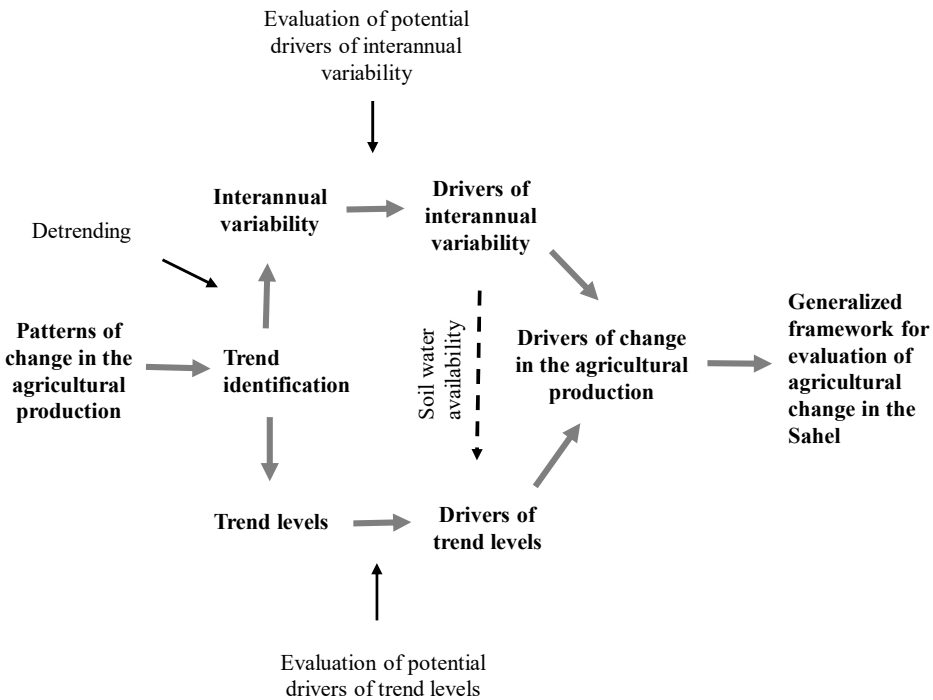

Fig. 9 *– Methodological framework*

5.2 Regression analysis

To identify key relationships and potential causalities between the full set of quantitative data collected, various forms of regression analyses were applied. All regression estimators can be described as the function, p, which minimizes the residual function, r, through the coefficient estimates, β, according to Eq. 1:

$$\min[\sum_{i=1}^{n} p(r_i), \beta], \; r_i = (y_i - x_i\beta) \quad (\boldsymbol{Eq.\,1})$$

$$y_i = dependent\ variable, x_i = independent\ variable$$

In a statistical sense, the focus was to identify single or groups of variables, x, with distinct relationships to the patterns of change in the crop statistic, y, as well to give reliable estimates of those relationships, β. As most of the collected quantitative data had not been compared on this level of analysis before, both single variable effects and total model explanatory capacities were of interest for the statistical evaluations. Under ideal data conditions and stable system dynamics, regressions analysis is an

effective and flexible tool to evaluate and establish relationships between quantitative datasets. In the case of the regional agricultural sector in Chad, several factors are however complicating the applicability and reliability of regression analyses. Although the compiled datasets provided unprecedented extent and detail about the agricultural sector in Chad, the number of observations were in terms of statistical applications arguably small. The full crop dataset covered 37 crop seasons (1983-2016), but could only be considered to be reliable for 27 (1990-2016). For a volatile system dependent on a multitude of factors, 27 observations is a clear analytical limitation. And in certain cases, panel data methods were used to evaluate differences between the administrative regions within the country and within each ecological zone, which limited the number of observations to 13, 8, and 5 respectively. At these observation ranges, only the most parsimonious model assumptions and the strongest variable effects can be evaluated. Moreover, given the large spatial scale of analysis and the ensuing low precision in the datasets, uncertainties and errors in the datasets are likely to cloud the identification of their actual effects. With few other similar studies conducted in Chad, and often unknown data collection procedures, the precision of the data is however difficult to evaluate and correct for. This becomes increasingly relevant with added analytical detail, e.g. for the analysis of interannual variabilities and its reliance on points specific values, while the analysis of long term trends is less dependent on point specific data precision. While anomalies are easily detected, there is no methodological remedy for non-anomaly errors, and the relevant relationships that are lost due to them. The largest drawback with the data usage in this thesis is however neither the limited number of observations, nor the expected lack of precision, but rather the complete omission of relevant variables. Fig. 7 and its associated sections provided an overview of the multitude of relevant and omitted factors for agricultural change in Chad. Added to this, even for the factors were data was acquired, they have not been covered exhaustively. Both the demographic and aid data coverage are case examples of this, which both hold numerous additional levels of complexity that were not covered by the acquired datasets. By using simplified estimates of each independent variable in the regression analyses, only the most apparent and consistent relationships can be identified. While this does not challenge the usefulness of evaluating the datasets at hand, it does put effective limits to the explanatory potential of the results.

On the other end of the statistical discussion, a core focus for the reliability of the results is how to distinguish actual effects from statistical chance effects. This can partly be addressed by setting up constraint ranges for the effect estimate of each relationship, e.g. under dry growing conditions it can be safely assumed that an increase from very low to low levels of soil water availability should have a positive effect on the growth potential of crops. Similarly, the regression estimates can also be constrained by certain types of relationships, such as linear, logarithmic, and

quadratic. Any statistical effects detected beyond such preconceived assumptions should thus be discarded. Another complication in accurate effect estimates concern the isolation of variable effects in multivariate regressions, which was applied in different parts of this thesis. As regression estimates essentially evaluate the patterns of variability between the independent and dependent variables, any covariation between the independent variables will confound their respective effects on the dependent variable. While this does not affect a multivariate model's combined explanatory capacity, it needs to be addressed to get reliable variable effect estimates and subsequent interpretations. This is most effectively addressed by evaluating the covariation structure, and possibly excluding or combining independent variables accordingly.

The reliability of variable effects can further be enhanced by selection of the regression estimator, or p-function as defined in Eq. 1. By default, the Ordinary Least Square (OLS) regression estimator was applied, which minimizes the sum of the squared residuals. In regression conditions where the presence of outliers might disturb an effect estimate, various forms of robust regressions can however be useful (Huber & Ronchetti, 2009). Due to the volatility in the crop statistics, and to reduce the influence of outliers on the trend estimate, the robust Huber regression estimator was applied for the trend analysis (Kelly, 1992; Lambert-Lacroix & Zwald, 2011; Stuart, 2011), with the following p-function:

$$p(r_i) = \begin{cases} \frac{{r_i}^2}{2}, |r_i| < a \\ a|r_i| - \frac{a^2}{2}, |r_i| \geq a \end{cases}$$

$$r_i = residual,\ a = tune\ \cdot s \cdot \sqrt{1 - h_i},\ tune = tuning\ constant,$$

$$s = estimate\ of\ the\ standard\ devaition\ of\ the\ error\ terms = \frac{MAD}{0.6745},$$

$$MAD = median\ absolute\ deviation\ of\ the\ residuals\ from\ their\ median,$$

$$h_i = levarage\ of\ observation$$

A default value of the tuning constant of 1.345 for Huber's M-estimator results in estimates that are approximately 95% as efficient as the OLS estimates under conditions of no outliers (Mathworks, 2016), and was used throughout the analysis.

5.2.1 Significance tests

The statistical significance level is foundational to all regression results, which gives an estimate of the likelihood of finding the current relationship purely as an artefact

of the random patterns in the data, and not due to actual effects. Significance levels can further be estimated under various types of assumptions, with the student t- and f-test statistics being the most accessible. Based on the number of observations and degrees of freedom for a regression, and under assumptions of identical and independent normal residual distributions around the mean residual, these test statistics provide a quick estimate of the significance levels. These underlying assumptions are however easily broken in many statistical applications, commonly by the presence of unaccounted for serial correlations and heteroscedasticity (Huber & Ronchetti, 2009). To not depend on any such assumptions while working with diverse and volatile datasets, a bootstrap methodology was applied to determine the statistical significance of the regression analyses. Instead of assuming a residual structure, it replicates the original residual structure in a large number of simulations (Davidson & Mackinnon, 2006). For each regression, 1000 simulated groups of residuals were generated, on which the chosen test statistic was run, commonly the t- or f-test statistics. The rate of exceedance of the original test statistics, T_{org}, to the simulated ones, T_{sim}, was calculated and taken as the test's significance level, p, i.e.:

$$p = \frac{\sum(T_{org} > T_{sim})}{n_{sim}}$$

Key to this significance method is how to identify the residual structure with sufficient precision. The sieve bootstrap was used to replicate patterns of serial correlation (Gonçalves & Kilian, 2007; Lee, 2011), which is based on approximating the serial correlation in the original residuals, r, by fitting an autoregressive model, Θ, to the data, and then using that model to generate the simulated data (Lee, 2011), defined as:

$$r(i) = \Theta_1 r_{i-1} + \Theta_2 r_{i-2} + \cdots + \Theta_L r_{i-L} + \epsilon_{res}$$

$$L = number\ of\ lags, \qquad \epsilon_{res} = estimated\ variance\ of\ the\ residuals$$

The number of lags were estimated by minimizing the Akaike Information Criterion (Lee, 2011) 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 are replicated by keeping the regressors in the model fixed and simulating residuals by multiplying each original residual with a random variable of expectation zero and variance one, from a six-point distribution, as proposed by Webb (2014):

$$v(r_i) = -\sqrt{\frac{3}{2}}, -\sqrt{\frac{2}{2}}, -\sqrt{\frac{1}{2}}, \sqrt{\frac{1}{2}}, \sqrt{\frac{2}{2}}, \sqrt{\frac{3}{2}}\ ,\ all\ with\ probability\ \frac{1}{6}$$

Which gives the simulated residual variance:

$$\epsilon_{res,sim\ i} = r_i \cdot v(r_i)$$

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

$$r_{sim}(i) = \Theta_1 r_{sim\ i-1} + \Theta_2 r_{sim\ i-2} + \cdots + \Theta_L r_{rim\ i-L} + r_i \cdot v(r_i)$$

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, Θ. 100+L points were simulated from these models, and the last L points were entered as the first L points in the bootstrap simulation.

5.3 Identifying patterns of change in crop statistics

An initial evaluation of the set of 52 region specific crops for 1983-2016 displayed a diversity of patterns, and often with non-linear progressions and apparent breakpoints, which had also been observed in crop statistics from neighbouring countries (Akinyoade et al., 2013; Elagib, 2014; Ojiako, Ifeanyi et al., 2007; Sanusi, 2014). Breakpoints are defined as points in the data series where the underlying statistical pattern changes, for instance by changes to a gradual progression, or an abrupt and lasting change to the mean value. By identifying breakpoints, subsamples can be created accordingly with more homogenous patterns. The trends in these subsamples can then be analysed more accurately. Potential breakpoints were identified by using the Wald test, based on linear regressions (see e.g. Andrews, 1993) and defined as:

$$W(t) = n(\beta_1 - \beta_2)'(V_1 \frac{n}{t} + V_2 \frac{n}{n-t})^{-1} (\beta_1 - \beta_2)$$

$$t = evaluated\ break\ point, \qquad n = sample\ size,$$

$$\beta_s = estimated\ coefficients\ for\ each\ sub\ sample\ s,$$

$$V = asymptotic\ variance\ estimator\ of\ \beta\ = X^{-1}\Omega\ X^{-1},$$

$$X = subsample\ design\ matrix,$$

$$\Omega = subsample\ variance - covariance\ matrix$$

By applying the robust Huber regression estimator, the variance-covariance matrices were calculated as (Huber & Ronchetti, 2009):

$$\Omega_{rob} = MSE_{rob} \cdot (X'X)^{-1},$$

$$MSE_{rob} = \text{robust mean squared error} = K^2 \frac{\frac{\sum \psi(r_i)^2}{n-k}}{\left(\frac{\sum \psi'(r_i)}{n}\right)^2}$$

$$\psi = p', \qquad k = number\ of\ parameters\ estimated\ in\ the\ model,$$

$$K = correction\ factor = 1 + \frac{k}{n}\frac{\sum(\psi'(r_i)-m)^2}{\sum \psi'(r_i)},$$

$$m = relative\ frequency\ of\ residuals\ satisfying - a < r_i < a$$

Wald tests based on all combinations of linear and constant regressions were calculated for each potential breakpoint. The Wald test with the lowest p-value, if ≤ 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. For the summary of the patterns of change, robust 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 significant at $p \leq 0.05$ were included in the regressions, otherwise slopes were set to zero.

5.3.1 Variance analysis

The variance of the crop statistics describes patterns in the interannual variability, and was thus evaluated for patterns of change. Analysing trends and break points in the variance of the data is preferably done on detrended data, so that the differences in trends in the levels are not mistaken for patterns in the variance. In this case, as the trends and break points of the levels already were established with the Wald test and the robust linear regressions, these were used to detrend the data and isolate the variance, $V(y)$. If the levels are transformed to the absolute first-differences of the detrended data, $V'(y)$, the same break point and trend and analysis based on linear regressions used can be applied to the analysis of variance, according to:

$$V_i'(y) = |V_i(y) - V_{i-1}(y)|,$$

$$where: V(y) = r = y - x\beta,$$

By taking the absolute first-differences, this same methodology allows for an effective identification of breakpoint positions in the variance. After the positions of the breakpoints were identified, their corresponding variances were estimated by calculating the standard deviation of the 5 nearest data points in the original data, 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.

5.3.2 Supplementary rules

When using robust fitting on volatile datasets, where residual weights will depend on their distance to the regression estimate, supplementary rules are often needed to accurately identify the breakpoints and their trend values. Two supplementary rules were applied to address this. First, breakpoints, t, were evaluated to ensure that the distance to its identified trend value, Y_t, was smaller than to the preceding trend value, Y_{t-1}, according to:

$$\text{while } |Y_t - y_t| > |Y_{t-1} - y_t| \rightarrow \ t = t + 1, t \in [t, n - 4]$$

$$Y_t = \beta_{s,a} x_t + \beta_{s,b}$$

The second supplementary rule concerned regressions that identified abrupt changes to the trend values at a breakpoint, but where there were a range of values, $[t - r_1 \ \ t + r_2]$, 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 where applied, i.e.:

$$(Y_t - Y_{t-1}) \times 0.25 < y_{t-r_1:t+r_2} - Y_{t-1} < (Y_t - Y_{t-1}) \times 0.75, \quad \text{when } Y_t > Y_{t-1}$$

$$(Y_{t-1} - Y_t) \times 0.25 < y_{t-r_1:t+r_2} - Y_t < (Y_{t-1} - Y_t) \times 0.75\ , \quad \text{when } Y_t < Y_{t-1}$$

$$if\ 1 \leq r_1 + r_2 \leq 2 \ \rightarrow fit\ transition\ trend\ on\ values\ y_{t-r_1:t+r_2}$$

The transition trend 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 criteria was based on evaluations of trend fitting results on random variables from the dataset, which together with the first supplementary rule showed satisfactory results.

5.3.3 Visualizing patterns of change

With a large number of crop variables analysed separately, the results needed to be summarized and visualized in concise and informative ways. The use of breakpoint analysis and linear regressions enabled the distinction between abrupt and gradual, i.e. linear, changes to the trends in the data. As these two change categories were likely to represent distinct causes in Chad's agricultural sector, they were separated for the visualization of the results. An abrupt change was defined as a breakpoint, t, where the trend difference to its preceding value, $Y_t - Y_{t-1}$, was larger than the slope coefficient in its subsample, $\beta_{t,a}$, resulting in the following breakpoint categorization:

$$|Y_t - Y_{t-1}| > |\beta_{t,a}| \rightarrow Breakpoint\ is\ an\ abrupt\ change\ in\ the\ trend$$

$$|Y_t - Y_{t-1}| \leq |\beta_{t,a}| \rightarrow Breakpoint\ is\ part\ of\ a\ gradual\ change\ in\ the\ trend$$

These two change categories were then summarized in so called trend graphs for the Sahelian and Soudanian zones. In the trend graphs, gradual trends for 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 two years were classified as gradual changes.

As the yield was the quotient of the production and the harvested area, the effect of changes in one yield variable for a specific year, $\Delta Yield_{var,i}$, on the average yield for its summary group, $\Delta Yield_{group,i}$, needed to be weighted based on the rate of that yield variable's harvested area, $Area_{var,i}$, to the whole group's harvested area, $Area_{group,i}$, at the time of the occurring yield change, i.e.:

$$\Delta Yield_{group,i} = \Delta Yield_{var,i} \times \frac{Area_{var,i}}{Area_{group,i}}$$

It should be noted that changes to the average yield of a group of variables can also be due to changes in the harvested areas of the included variables, even if the yield

of those variables remain constant. As the harvested area was analysed separately, and the yield trend analysis concerned dynamics in the yield of each crop, such group yield effects due to dynamics solely in the harvested area were neglected.

For each summary group, the improvement by using breakpoint analysis and robust linear regression compared to a full sample OLS linear regression was estimated by comparing the total Sum of Squared Error (SSE) and the Mean Squared Error (MSE), which takes into account the number of coefficients used in each regression. A drawback of 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.

5.4 Drivers of interannual variability

5.4.1 Detrending for variability analysis

To isolate the patterns of interannual variability in the crop statistics, they were detrended in both the levels and variability. As detrending risks removing the influence of the drivers one wishes to evaluate, the potential drivers were also detrended, which further focused the analysis on the correlated patterns of variability between the drivers and response variables. Due to the uncertainty involved in detrending under conditions of multifaceted and dynamic drivers, and given the prevalence of breakpoints and non-linear patterns in the crop statistics, two different detrending methods were evaluated. One solely used moving averages of five years as the basis of the detrending, while the other combined this with the aforementioned breakpoint analysis, where moving averages were applied within the subsamples between the breakpoints. With two trend dimensions per variable, i.e. levels and variability, this resulted in four different detrended data series per crop variable: Moving Average (MA), Moving Average with variability (MA + var.), Breakpoint (BP), and Breakpoint with variability (BP + var.). A data error filter was further applied to remove deviating values, which were defined as values exceeding two standard deviations within moving windows of five data points, in the detrended datasets.

5.4.2 Estimating effects of soil water availability

Due to uncertainties in the environmental data and few validation options, three commonly applied methods were used to estimate the seasonal crop water availability in the root zone (Fig. 10).

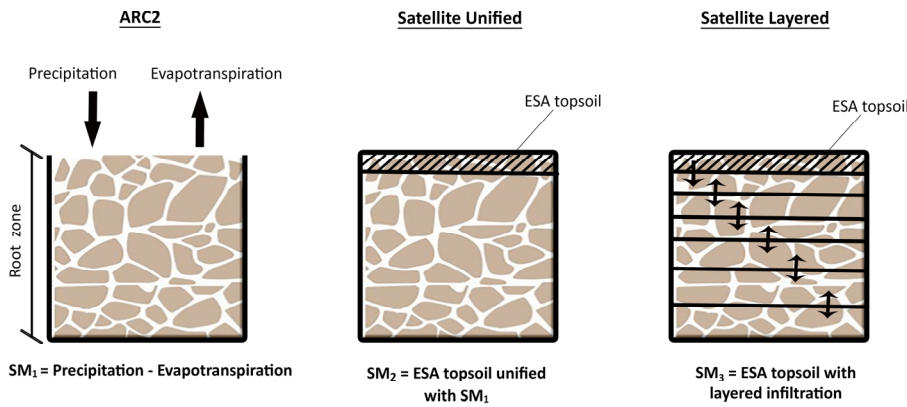

Fig. 10 *– Three different soil moisture (SM) models*

First, the daily water availability was estimated with a one-size soil bucket model with ARC2 precipitation as input, evapotranspiration demand estimated from FAO's crop soil-water model (Allen et al., 1998; Steduto et al., 2012), and gridded root zone soil water holding capacity from the Global Soil Hydraulic Properties dataset (Hengl et al., 2014; Montzka et al., 2017; Schaap et al., 2001). Secondly, a combination of the ESA estimated topsoil water content and the ARC2 model was used, where the daily root zone water variability was taken from the variability of the ESA data and unified to the seasonal mean and standard deviation of the ARC2 model. The assumptions underlying this was that the variability in the ESA data might reflect the variability in the full root zone, while actual levels and amplitudes of the root zone availability were more accurately described by the ARC2 model. Thirdly, a layered bucket model with water transfer between the layers was developed by using the ESA estimated topsoil water content combined with layered soil parameters from the Global Soil Hydraulic dataset. Water transfers at each time step was calculated according the layers' water content, conductivity, and pressure differences, where the topsoil water content was set to the ESA estimate. As sequences of missing data was common for several of the remote sensing data, daily sequences of missing data in grid cells in the ARC2 and ESA data of up to five days were replaced with linearly interpolated values, while grid cells with missing sequences larger than this were discarded from the analysis.

The start of the growing seasons for each crop and region were estimated based on livelihood calendars in FEWS NET's livelihood profiles for 2005 and 2011 (FEWS NET, 2005, 2011b). To include effects of varying atmospheric growing conditions over the studied period, an average precipitation threshold was identified based on the given crop calendars at the time of the livelihood profiles, which were used to define the start of the growing seasons. The effect of crop water deficits in specific growth stages on the yield were estimated by yield response factors and yield response relationships (Doorenbos & Kassam, 1979). The estimates of these factors as given by Doorenbos & Kassam (1979) are based on experimental results with high producing crop varieties, and are set to be valid for daily evapotranspiration deficits of up to 50 %. Yield response factors and relationships are furthermore known to vary widely between crop varieties and growing conditions, and several studies have argued for applying site specific relationships (Greaves & Wang, 2017). Due to lack of more precise information on the specific yield responses in the studied regions, both the additive and multiplicative yield reduction equations were applied (Doorenbos & Kassam, 1979; Garg & Dadhich, 2014; Jensen, 1968).

$$Additive\ Yield\ Reduction\ = \sum_{i=1}^{n} k_{y_i}\left(1 - \frac{ET_a}{ET_m}\right)$$

$$Multiplicative\ Yield\ Reduction\ = 1 - \prod_{i=1}^{n}\left[1 - k_{y_i}\left(1 - \frac{ET_a}{ET_m}\right)\right]$$

$$i = \ crop\ growing\ stage,\ k_y\ = yield\ response\ factor$$

$$ET_a = actual\ evapotranspiration,\ ET_m = maximum\ evapotranspiration$$

To address uncertainties in the yield response factors under conditions of evapotranspiration deficits above the set limit of 50%, a new set of adjusted yield response factors for each region and crop were calculated based on constrained regressions to the respective crop variable within a range of ± 50 % of the original yield response factors. A risk with this approach is that the resulting adjusted yield response factors are overfitted to the specific crop variables, while using the original yield response factors might not be applicable to the specific growing conditions. Due to the uncertainties involved in the yield reduction estimates, total seasonal precipitation and total seasonal evapotranspiration were included as less detailed, but possibly more reliable, water availability determinants. In total, this resulted in 16 water availability determinants (Table 7).

Table 7 - Seasonal water availability determinants

Water Determinants	Soil moisture models			Coverage
	ARC2	Satellite Unified	Satellite Layered	
Seasonal Precipitation	X	-	-	1983-2016
Seasonal Crop Evapotranspiration	X	X	X	1983-2016
Yield Reduction Additive	X	X	X	1983-2016
Yield Reduction Additive Adjusted	X	X	X	1983-2016
Yield Reduction Multiplicative	X	X	X	1983-2016
Yield Reduction Multiplicative Adjusted	X	X	X	1983-2016

The precipitation, relative humidity and temperature datasets were verified against monthly observations stations in Chad from the Direction des Recherches en Eau et de la Météorologie (DREM) for the period 1998-2013 (DREM, 2014), with 8 stations for precipitation and 3 stations for temperature and relative humidity. The average Spearman correlation coefficient to the nearest four grid cells of each observation station was 0.88 for the ARC2 data, 0.89 for ERA Interim Temperature, and 0.95 for ERA Interim Relative Humidity, which were acceptable validations of the remote sensing atmospheric data. Due to data limitations, additional soil characteristics such as soil salinity, soil nutrients, and fertilizer applications were not included in the analysis. Data on irrigation was also lacking from the analysis, and while it is known to be rare in the Sahelian parts of Chad, it is applied extensively in some parts of the Soudanian zone (FEWS NET, 2011b). The irrigation application in the Soudanian zones are however usually confined to certain crops, mainly rice, and might thus be of limited importance for analysis of interannual variability to the rainfed crops considered in this study.

5.4.3 Livelihood effect

To evaluate the relationships between the livelihood data in the food security reports for 2000-2016 and interannual variability in the crop production, three strands of approaches were developed. First, livelihood categories that were originally quantified in the food security reports (food security classifications and market prices) and categories that were consistently reported on were set as “Livelihood Inclusion Determinants” (Table 8). Pests, floods, and conflicts were quantified for each growing season by ascribing intensity scores from 1 to 5 according to their qualitative descriptions. All information in these data categories preceding the estimated harvest date of up to 9 months for each region and crop were averaged

and assigned to each growing season. Quantifying a large set of qualitative data with relative scores has the advantage of being applicable to statistical analysis, while a noteworthy drawback is the uncertainty in the estimated scores, especially as the descriptions and detail may vary considerably across the time series. To reduce the uncertainty in these estimates, categorical values (present/not present) were also assigned to these categories. Monthly market prices for the included crops were collected from reports and online databases from FAO, FEWS NET, and INSEED for the time period 1990-2016, and deflated with the World Bank Consumer Price Index (FAO, 2016b; FEWS NET, 1997, 2001, 2002, INSEED, 1994, 1999; World Bank, 2018c). Market prices from these sources were available for eight main cereal markets: Abéchè, Bol, Mao, Mongo, Moundou, Moussoro, N'Djamena, and Sarh. Trade routes and market connections for each region were taken from FEWS NET's livelihood profiles (FEWS 2011), which were used to connect each region to its primary market from this list. Average market prices at the primary market over 6 months preceding the estimated planting dates were included as a determinant in the statistical analysis. A general assumption underlying this approach is that market prices preceding the planting date of each season influence farmers' agricultural strategies, by focusing on certain crops, altering the planted area, investing in farm inputs, or diversifying into other livelihoods. Market prices can however also be connected to altered access to food and farm goods, which further complicates the potential relationships between market prices and crop output.

Table 8 *- Livelihood Inclusion Determinants*

Determinant	**Coverage**
Conflicts (x 2*)	2000-2016
Floods (x 2*)	2000-2016
Food security classifications	2000-2016
Market prices	1990-2016
Pests (x 2*)	2000-2016

* *Categorical and Intensity scores*

Secondly, certain events and interventions can have substantial and unique effects on the crop output, such as development projects and conflicts, which poses issues for statistical evaluation. If such effects are apparent and consistent over at least a small number of years, they could partly be detected and evaluated through a trend and breakpoint analysis, or through inclusion as categorical variables. If any such effect on other hand is transient and inconsistent, it would not be captured by either of these methods, and left unaddressed it could distort a regression analysis for the whole sample. Another strand of analysis based on the food security reports was thus added to evaluate the effect of excluding years with potentially distortive events, by evaluating the explanatory capacity to the remaining years. The groups

of events listed in Table 9, if preceding the estimated harvest date with less than 9 months, where included as "Livelihood Exclusion Determinants" for this end. A drawback with this approach is that any established explanatory capacity with excluded years will only be valid for a subgroup of the whole sample, but this could still be a considerable improvement over a lower explanatory capacity for the full sample.

Table 9 *- Livelihood Exclusion Determinants*

Determinant	Coverage
Agricultural support	2000-2016
Conflicts	2000-2016
Crop and livelihood switches	2000-2016
Floods	2000-2016
Market and trade disruptions	2000-2016
Pests	2000-2016

Thirdly, the created database with categorized and sorted qualitative data from the food security reports was used to complement the statistical analysis by providing qualitative descriptions of the livelihood conditions for selected regions and years. As the information concerning each region and growing season was taken from food security reports spanning up to two years, simply categorizing and sorting all this information into a searchable database provided valuable analytical advantages compared to the original report structure.

5.4.4 Regression analysis of variability

The statistical analysis was based on regression analyses and sought to evaluate the explanatory capacity of combinations of the water and the livelihood determinants (Table 7, 8 & 9) to the interannual variability in the crop production (i.e. response variables). It aimed to identify the combination of determinants and detrending method that provided the highest explanatory capacity to the variability in the full rainfed crop production dataset, consisting of 37 crop production variables. The explanatory capacities of the determinants to the harvested area and yield were evaluated as an alternative to the production, where the respective explanatory capacities were weighted and combined according to their relative correlation to the production. For regions and crops where the determinants had low explanatory capacity to the production, this combined analysis of the harvested and the yield could add an additional, if yet fragmented, understanding of the dynamics in the production. From the set of determinants, regression models were created and fitted to the response variables through constrained multivariate least square error linear regressions. The water determinants formed the basis of the regression models, and

were evaluated both separately and jointly with all combinations of the livelihood determinants. As the effects of the evaluated livelihood factors were expected to differ considerably between the regions and crops, contrary to the effect of water availability which should be more constant, the methodology focused on finding the water determinant that in combination with a group of livelihood determinants provided the highest overall explanatory capacity to the crop production dataset. As the livelihood data only was available from 2000, only water determinants were evaluated for the 1983-2016 period, to compare their performance over different time periods. With a large set of combinations of determinants explored for each response variable, low degrees of freedom, and uncertainties in the data, the statistical analysis needed to be conducted with constraints, and performative evaluations adapted to these conditions. Positive or negative constraint limits for the regression coefficients were thus set to comply with the expected relationships for the water and Livelihood Inclusion determinants to the response variables (Table 10).

Table 10 *- Constraint ranges for linear regression coefficients*

Determinant	**Constraint range**	**Justification**
Conflicts	Negative	Reduces productive capacities
Crop evapotranspiration	Positive	Increases crop water uptake
Floods	Negative	Reduces productive capacities
Food security classifications	Negative	Scale is negatively defined (i.e. 5 is lowest food security), and high food insecurity is presumed to reduce productive capacities.
Market prices	No constraints	Depending on the level of income and market dependence of farm households, increasing market prices can lead to both production incentives and reduced access to goods
Pests	Negative	Reduces productive capacities
Precipitation	Positive	Increases crop water uptake
Yield reduction	Negative	Inversely related to crop water uptake

To further ensure the reliability of the regressions under conditions of low degrees of freedom, a minimum of eight degrees of freedom was set, and regression performances were evaluated by leave-one out cross validated root mean squared errors (RMSE) (see e.g. Taylor, Picard, & Cook, 1984). Significance levels were estimated based on coefficients of determination (R^2) from 1000 pair-wise randomized bootstrap iterations (see e.g. Fox, 2016). Only regression models

significant at the 0.05 level were selected for the results summary. Due to the low sample size and expected uncertainties in the data sets, only linear relationships were evaluated, and no interaction terms were included in the regression models.

5.5 Drivers of long term change

5.5.1 Trend analysis of agricultural change

To evaluate the drivers of trends in the crop statistics, the same trend levels as applied to identify the interannual variabilities were used. The variance also displayed long term trends in the regional crop statistics over this time period, but their drivers were not explored due to lack of further data. To enable a comparison between regions with large differences in population and agricultural production, the growth rates over the periods of interests were used. As each region produces various type of cereals crop (FEWS NET, 2011b), regional aggregates were created for total harvested area, average yield, and total production for each year. All crops within a region were thus treated equally in their importance for the local livelihoods in the regional comparisons, which discards crop specific strategies within regions. Trends in the average yields were estimated as the effect from yield changes within each crop and region, and thus excluded changes to the regional average yield due to variations in the harvested areas of crops with different yields.

5.5.2 Gradual changes

5.5.2.1 Soil water availability effect of trends

The effect of changes in soil water availability to changes in the agricultural output ($\Delta Agr_{soil\ water}$) at a time point, t, was estimated according to the rate of difference to the soil water conditions over a group of initial values, according to Eq. 2:

$$\Delta Agr_{soil\ water} = Agr_{start} \times \left(\frac{SW_t - SW_{start}}{SW_{start}}\right) \qquad (\boldsymbol{Eq.2})$$

$$Agr = agricultural\ output$$

$$SW_t = effect\ of\ soil\ water\ availability\ at\ time\ point\ t,$$

$$Start = mean\ of\ initial\ values\ t = 1{:}3$$

The effect of soil water availability on the agricultural output for specific time points were estimated based on the analysis of driver of interannual variability. As these soil water estimates only were calculated for the rainy seasons, they do not include the hydrological dynamics relevant for the off-season flood recession farming, which was only assessed based on their mentions in the food security reports.

5.5.2.2 Demographic effect

The effects of demographic changes and on agricultural growth were evaluated by regression analyses. As the demographic data only was available for selected years, comparisons were made between the respective demographic variables to the growth in the agricultural trend levels over the time period of the demographic data. The effect of altered soil water availability on the agricultural growth over the evaluated periods were removed according to Eq. 2. Differences in the dynamics of the agricultural sectors between the Sahelian and Soudanian zones were expected to be pronounced, and the regional comparisons were thus split between these two groups of regions. As this results in small observation sets (8 regions in the Sahelian zone, 5 regions in the Soudanian zone), only generic relationships based on bivariate linear regressions were evaluated, and statistical relationship should only be seen as indicative.

5.5.2.3 Aid effect

With a large share of the population in each of the regions engaged in agriculture, the effect of aid on agricultural is likely to come through a broad range of sectors and development projects. To be able to evaluate the effect of aid received on the agricultural sector in each region, a set of four aid groups covering different DAC categories were created, and are presented in Table 11. The aid groups were created to have a decreasing direct focus on the agricultural sector, which is reflected in the increasing number of DAC categories included. Breaking up the analysis over these groups also enabled a specification of which DAC categories have the strongest and most consistent effect on the agricultural variables.

Table 11 *– Aid groups to be evaluated against the agricultural changes*

Aid Group	DAC categories
Aid Group 1	Agriculture, forestry, fishing
Aid Group 2	Aid Group 1; Emergency response; Water supply & sanitation
Aid Group 3	Aid Group 2; General environmental protection; Transport & storage; Transport & storage; Education; Health; Other social infrastructure & services
Aid Group 4	All DAC categories. In total 14 DAC categories were active in Chad during 1960-2018.

As the data on the amount of aid and agricultural growth rates were available for each year, regression analyses were run both on an annual level within each region, as well as over varying period lengths between the regions in each ecological zone. Identifying consistent relationships in the effect of aid on a particular component of an economic sector, in this case agricultural growth, is notoriously difficult. This is mainly because the conditions of aid effectiveness on the target sector, as well as the objectives of aid projects, are expected to vary considerably in time and between projects. With no further data on the determinants of these variations in aid effectiveness, there is a limited potential to detect and accurately estimate any reliable relationship through a statistical analysis. Despite these concerns, the novel data sets on the amount of aid received and regional agricultural trend levels created for this paper were deemed to be of sufficient detail to at least evaluate the consistency of these relationships. Previous studies have established that the effect of aid on GDP growth generally is decreasingly positive (Ali & Isse, 2005), which has also been seen specifically for statistical models on the GDP in Chad (Juselius, Møller, & Tarp, 2014). An evaluation of the effect of aid on the macroeconomy in Chad further found that no significant long term effects could be seen from changes to the amount of aid received, and that the amount of aid rather was driven by variations in the macroeconomic variables than the other way around (Juselius et al., 2014). Building on these studies, the annually based analysis was done with a lagged multivariate regressions analysis, by using the lagged logarithm of the amount of aid over 0-5 years on the agricultural growth each year, with significance level estimated based on the previously described bootstrap methodology. With additional detail in the data for the selected level of analysis, different versions of Vector Autoregressive Models are often applied for problems like this (Juselius et al., 2014), but a simpler analysis was opted for here due to limited data availability.

To address the issues of unknown and varying time components in the aid effect, the annually based analysis within regions was complemented with a coarser analysis between regions at varying evaluation periods, to evaluate if differences in the amount of aid received between regions have any statistically detectable effect on the agricultural growth rates. While the annually based analysis is more detailed and has the potential to provide more policy relevant results, this latter inter-regional comparison is able to account for variations in the temporal effect of aid by varying the length of the evaluation periods. Notable drawbacks are that the number of observations per period is limited by the number of regions, and that any statistically established relationships assumes that the aid effect per budget unit is equal between the evaluated regions. By evaluating the regional differences for all 1-27 year periods in 1990-2016 a large number of samples of aid received and agricultural growth were created, with observations in each sample consisting of the regions in either the Sahelian or Soudanian zone. Depending on the number and consistency of the significant relationships detected between the agricultural growth and the

logarithm of aid in these periods, estimates with varying degrees of certainty can be given for a relationship between aid and agricultural growth on an annual and regional level. As such an estimate will be based on the significant relationships between the regions in each zone, alignment or deviations to it on a regional level can indicate variations in relative aid effectiveness on agricultural for specific periods and regions.

5.5.3 Abrupt changes

Although factors of long term changes can be established based on the statistical methods described for the demographic and aid data, it does not answer how these effects on the agricultural growth are realized in practice. To answer such questions, and thereby establishing more precise and reliable causal factors behind drivers of agricultural growth, continuous and detailed qualitative data are needed, similar to the what is provided in the previously described food security reports by FEWSNET. By combining the seasonal livelihood data provided in these reports with the events of abrupt changes in the crop statistics, qualitative descriptions can be connected to abrupt changes in statistical patterns. Although arguably being the best suited database for such an analysis in Chad, the information in the FEWSNET reports generally lack the detail and consistency to establish causal factors to specific events with a high degree of certainty. Taking the qualitative and uncertain nature of this dataset into account, a link scoring system was created to provide a consistent evaluation framework, which is presented in Table 12. Only scores of 5 are considered to be explanations for abrupt and lasting changes, while scores of 3 and 4 simply are providing explanations to why the year of the occurring abrupt and lasting change might have deviated in the identified direction from its previous years. Scores of 1 or 2 are equivalent to no relevant information being found for the evaluated pattern in the evaluated sources, indicating either a wrongly identified abrupt change, or a complete lack of relevant livelihood information.

A prominent risk with this method is that of false positives, i.e. with enough diversity in the qualitative information source one can always find some description that corresponds to the evaluated statistical pattern of change. The explanations provided through this analysis should thereby not be taken as exhaustive and definite, but rather as the best possible explanations given the employed data sources. Another issues when using the FEWSNET reports to infer on changes in crop statistics is that generally no crop specific information is provided in FEWSNET reports, which instead primarily distinguishes between rainfed or off-season farming, and cotton. Some distinctions in potential causes of patterns in the crop statistics can still be found through differences in market prices and crop specific output, but generally the same production conditions were assumed to apply equally for all crops in each region. Due to the uncertain and speculative nature of

this methodology, it was crucial to see if any general patterns arose in the identified causes of the abrupt changes, from which more reliable conclusions could be drawn.

Table 12 *– Link scoring system for causes of abrupt changes*

Link score	Description	Examples	
		Positive	**Negative**
1	Breakpoint characteristic in the wrong direction	-	-
2	No link in the right direction	-	-
3	Weak link in the right direction	• Increased market prices* • Increased production and food security from previous year*	• Decreased market prices* • Decreased production and food security from previous year*
4	Strong link in the right direction without breakpoint character	• Increased rainfall • Humanitarian aid, e.g. subsidized seeds or food aid	• Conflicts • Pests • Drought
5	Strong link in the right direction with breakpoint character	• Farm specific training • Farm machinery • Expanded market coverage • Livelihood switches to a specific crop	• Livelihood switches from a specific crop • Production shocks leading to poverty traps, e.g. due to conflicts or pests. Given the high poverty levels, positive production shocks are not expected to leave lasting positive effects.

** The expected effects on regional crop production from variations to market prices and productive capacity from previous years are uncertain, as the household responses will vary according to their market dependencies*

5.5.4 Combined evaluation

With a diverse set of datasets used to explain long term changes in the agricultural sector, the key purpose was to evaluate to what extent they could be combined, and

how exhaustive the explanations provided by such a framework would be. To illustrate this, the various relationships established from the data specific analyses were joined for specific regions. By using the long term estimates on the agricultural growth from the continuous aid data, expected levels of agricultural output can be estimated for specific points in time. Building on this, both patterns of abrupt changes in the crop statistics and pronounced deviations from the estimated output levels can be attributed based on the seasonal livelihood data from the FEWSNET reports. Finally, deviations from expected output levels within shorter periods can be evaluated based on the variations in the yield reduction factors. When combined, these datasets and the presented analytical methods presents an overview of the current explanatory capacity of long term changes in the agricultural sector in Chad on a regional level of analysis, and forms a reliable foundation from which to identify shortcomings and recommendations for further improvements.

6 Results

6.1 Patterns of agricultural change

The harvested area and the yield for the Sahelian and Soudanian zones are presented in Fig. 11, to provide an overview of what the patterns of change look like on this level of analysis.

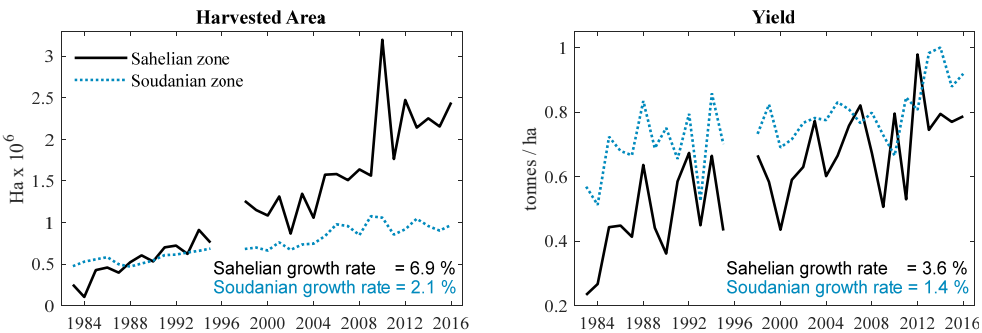

Fig. 11 *– Aggregated harvested area and yield for cereal crops in the Sahelian and Soudanian zones. Growth rate = annual average growth rate*

In accordance with several others studies from the nearby countries, both the harvested areas and the yields show considerable and linear increases on this level of analysis, which can also be seen in the national level data (see e.g. FAO, 2017; MA, 2005; World Bank, 2015). The linear progressions are stronger for the harvested areas than for the yields, and the harvested area for the Sahelian zone has a noticeably 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, 2018c), resulting in an overall increase in cereal per capita availability. Despite considerable 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, 2010, 2011a). The gaps for 1996 and 1997 are due to missing data, which is seen in all of the result figures.

Fig. 11 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 Fig. 12. The variance of the harvested areas display 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 in the variance for the Sahelian zone and decreasing trends for the Soudanian zone.

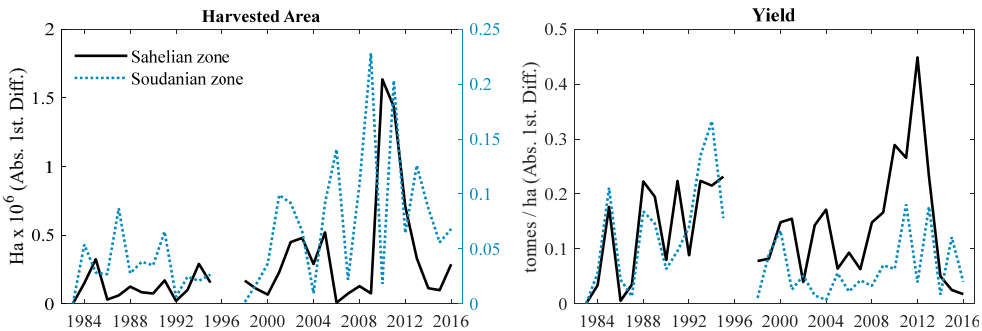

Fig. 12 *– Standardized absolute first differences of the harvested area and the yield for the Sahelian and Soudanian zones. Note that the harvested area is plotted on two axes*

6.1.1 Harvested area

However, the linear progressions in the aggregated data in Fig. 11 are constituted by more complex patterns which are only visible on more detailed levels, as seen in the trend graphs for the harvested area of the crops in the respective zone in Fig. 13 and Fig. 14. 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 trend analysis methods. Abrupt changes are separated by white lines, while all gradual changes for each year are joined together.

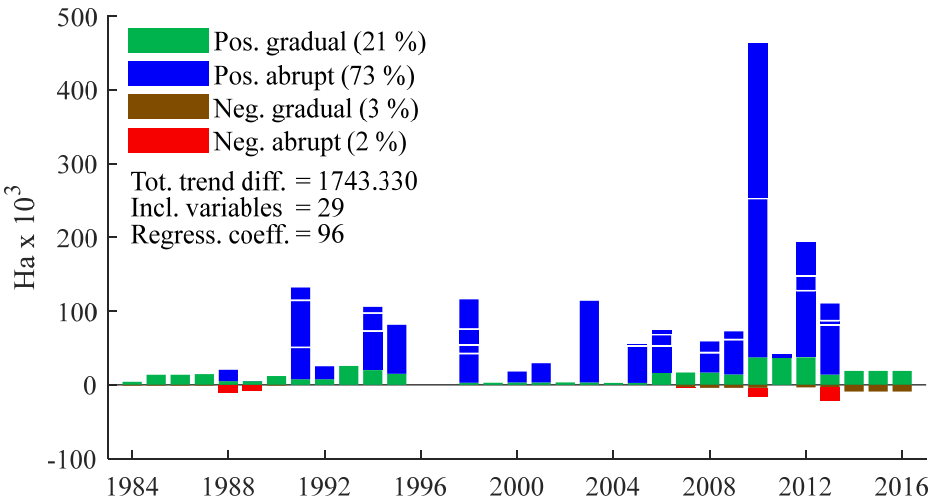

Fig. 13 *– Trend graph for the harvested area in the Sahelian zone*

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 Fig. 11) 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 the aggregated data in Fig. 11, 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 1,750,000 Ha. This can be compared with the change in mean values between the end sections of the aggregated data in Fig. 11, which is around 1,900,000 Ha, a difference of 8 %. Some differences are to be expected between the two estimates, as the trend estimates behind Fig. 13 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 MSE for the Sahelian zone by 48 %, and the SSE by 52 %. Positive abrupt trend evens dominate in the trend graph for the harvested area in the Soudanian zone as well (Fig. 14), with similar rates of MSE and SSE reductions at 41 and 44 %, but displays a stronger presence of negative trends in its constituting crops than in the Sahelian zone.

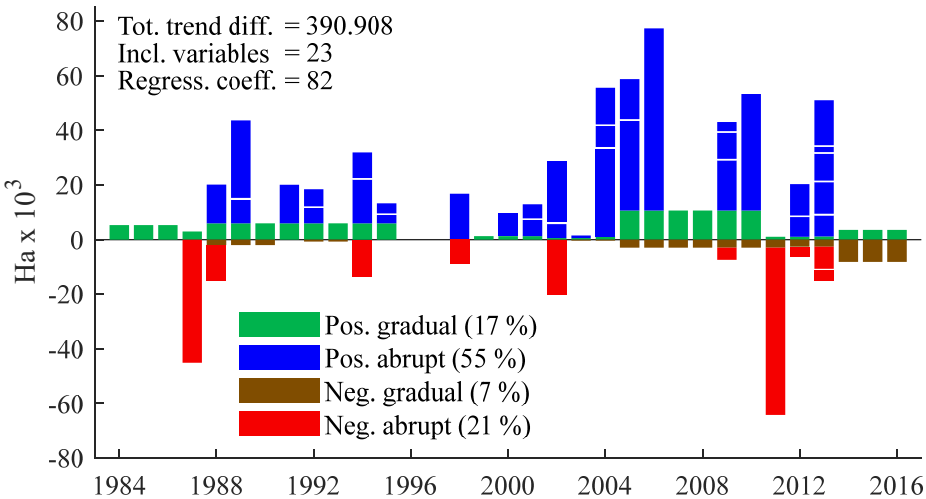

Fig. 14 *– Trend graph for the harvested area in the Soudanian zone*

6.1.1.1 Variance

The trend graphs for the variances of the harvested area are presented in Fig. 15 and Fig. 16, where the bars represent the estimated trend changes to the zone's standard deviation (SD.) for each year. Although almost three times higher in the Sahelian zone, the two trend graphs display similar patterns of trend changes, being foremost driven by positive abrupt changes (62 & 45 %), followed by positive gradual and negative abrupt changes in adjacent periods, indicating variance reducing interventions or events on a national scale. The increasing trend changes can be noticed earlier in these figures than in Fig. 12, which only displays increases after year 2000. Besides the more detailed trend analysis employed, this is mostly explained by how the aggregated data in Fig. 12 attenuates crop specific differences. The MSE and SSE reductions for this trend estimate compared to the full sample OLS linear regression are 32 and 33 % for the Sahelian zone, and 28 % and 31 % for the Soudanian zone.

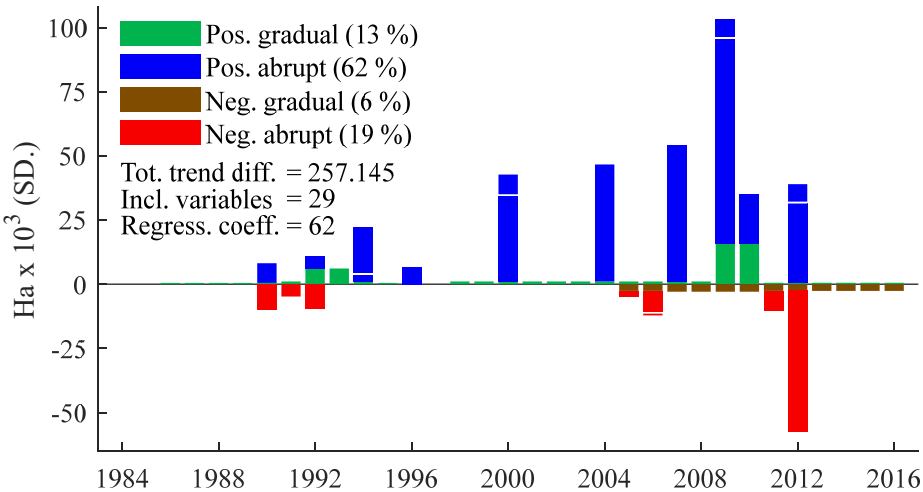

Fig. 15 *– Trend graph for the variance of the harvested area in the Sahelian zone*

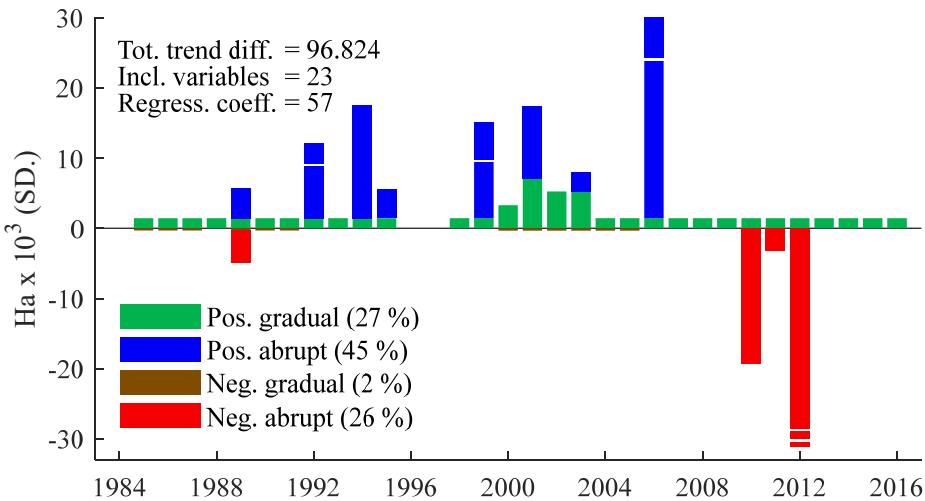

Fig. 16 *– Trend graph for the variance of the harvested area in the Soudanian zone*

6.1.2 Yield

The trend graphs for the yield variables are presented in Fig. 17 and Fig. 18. Ongoing increases in the data are visible in these figures as well, with a similar total increases and relative contribution from positive abrupt changes (80 & 72 %). Compared to the trends in the harvested area, the positive gradual processes are less present. The SSE reduction compared with a full sample OLS linear regression is 24 %, and 22 % for the MSE for the Sahelian zone, and 36 and 35 % for the

Soudanian zone. The yield changes over the whole period as estimated from this methodology is an increase of around 0.16 ton/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 Fig. 11 (0.43 ton/ha) and the crop specific yield changes, to 0.27 ton/ha. For the Soudanian zone these estimates are 0.29 ton/ha for the total yield changes, 0.16 for the crop specific yield changes, and thus 0.13 ton/ha for the area driven yield changes. This indicates that increases to the total yield is due to both expansions of relatively high-yielding crops, and yield improvements within specific areas and crops, with stronger area expansive yield component in the Sahelian zone.

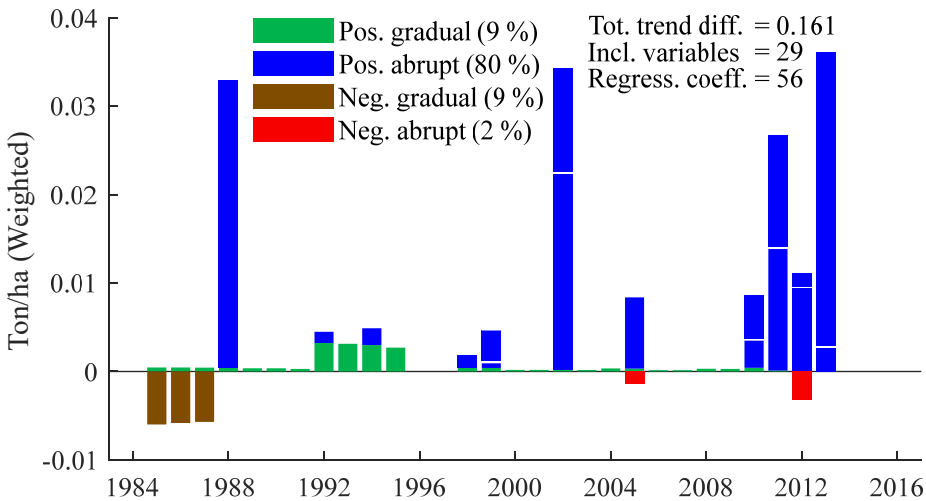

Fig. 17 *– Trend graph for the yield in the Sahelian zone*

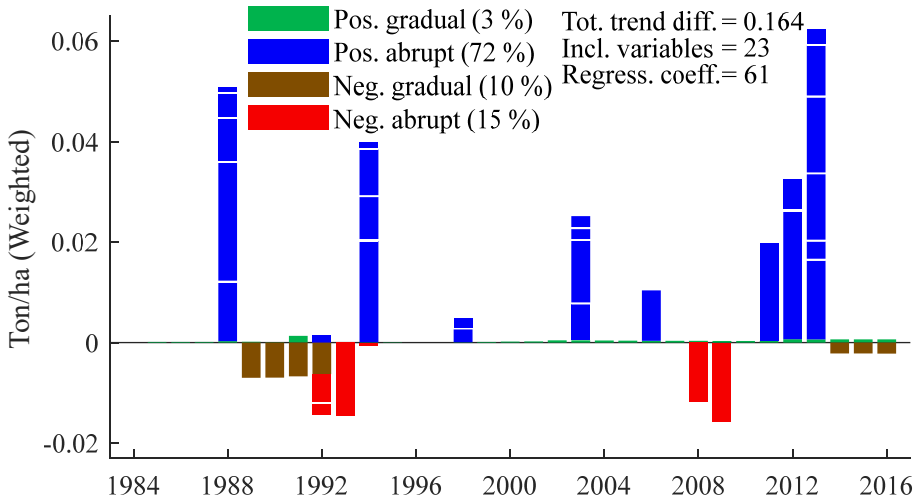

Fig. 18 *– Trend graph for the yield in the Soudanian zone*

6.1.2.1 Variance

In Fig. 19, the variance is seen to increase slightly in the Sahelian zone, while it decreases slightly in the Soudanian zone (Fig. 20), which can be concluded from Fig. 12 as well. Again, the trend changes are mainly driven by abrupt changes, with variance decreasing abrupt events being mostly pronounced in the middle ranges of this time period, while several abrupt increases are occurring towards the end. The MSE and SSE reductions compared to the full sample OLS linear regressions are 43 and 42 % for the Sahelian zone, and 35 % and 36 % for the Soudanian zone.

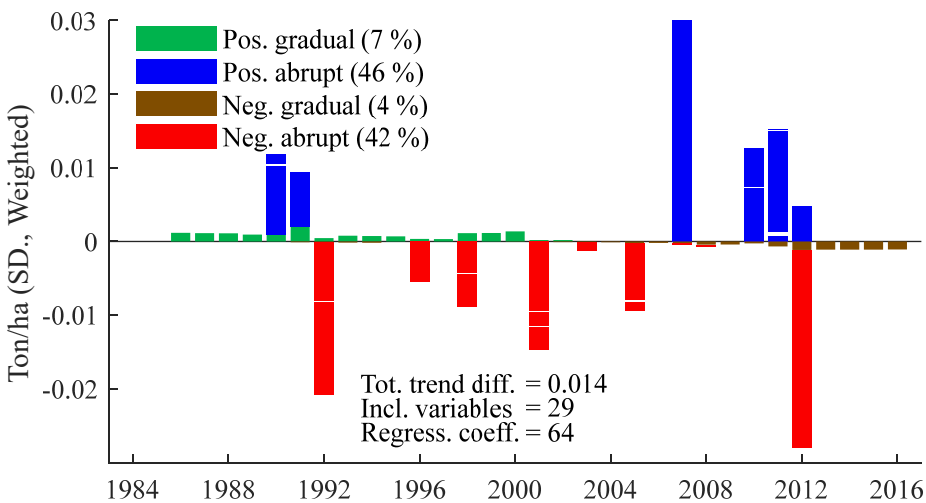

Fig. 19 *– Trend graph for the variance of the yield in the Sahelian zone*

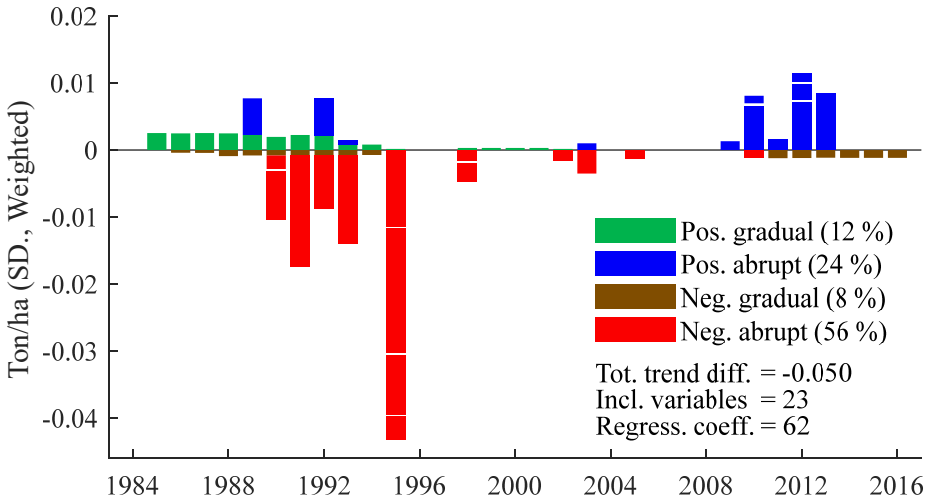

Fig. 20 *- Trend graph for the variance of the yield in the Soudanian zone*

6.2 Drivers of regional interannual variability

The breakpoints in the trends as identified in the previous sections for the various crop variables were used to detrend the data, and isolate the patterns of interannual variability (see section 5.4.1). The following sections present the evaluation of the combined predictive capacity of the potential drivers of interannual variability under the current data availability.

6.2.1 Summarized determinant combination performances

The summed significant cross validated R^2 to all of the 37 rainfed crop production variables is presented for each detrending method and determinant category in Fig. 21. For the determinant categories with livelihood data (yellow, purple, and green lines), the livelihood determinants that in combination with each water determinant give the highest cross validated R^2 are selected. Contributions from the analysis of the harvested area and the yield are included, as described in section 5.4.4. As the rate of significant variables are low for all of the determinant combinations, the R^2s presented here are low, and should only be interpreted in relation to each other. The improved explanatory capacity with addition of the livelihood data in the determinant categories (moving to the right in the legend) is clear from Fig. 21, with a mean relative improvement in summed cross validated R^2 of 286 % between only using water determinants (red lines) and combined water with both Livelihood Inclusion and Exclusion determinants (green lines). Addition of the Livelihood

Inclusion determinants (yellow lines) generally outperforms additions of Livelihood Exclusion determinants (purple lines). By combining both of them, the explanatory capacity improves considerably, and foremost for the "BP + var." detrending method. As the regression models evaluate a large set of determinants for each of the livelihood determinant categories, improvements in the cross validated R^2s are expected on purely statistical grounds. With a larger number of determinant combinations, this can also explain why the Livelihood Inclusion determinants generally outperforms the Exclusion determinants, and that their joint improvements over only using water determinants are larger than their summed respective improvement. For a reliable evaluation of the explanatory capacity between the livelihood determinants and the crop production variability, livelihood determinants with high selection rates in the determinant combinations must be identified, which is done in the upcoming section 6.2.3. By only including determinants from the livelihood determinants categories (not presented in Fig. 21), i.e. excluding water determinants altogether, the results are similar as for the water determinants for 2000-2016, with an average relative increase of 12 % in mean summed cross validated R^2. The low and comparable separate performances of these determinant categories, and their noteworthy combined improvements, show that they all are correlated to the crop production, and that their joint effects need to be acknowledged. The two periods of water determinants, 1983-2016 and 2000-2016, show similar results with only minor improvements seen for the later period, which indicates that there is no pronounced difference in data quality over the two time periods.

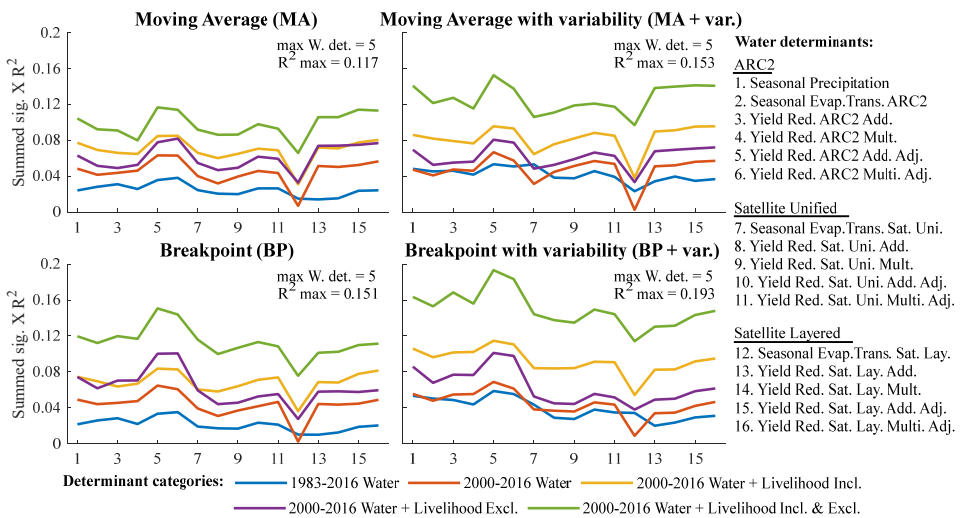

Fig. 21 *– Summed significant cross validated R^2 for the production variables per detrending method, determinant categories, and water determinant (for explanations of the determinants see section 0 & 5.4.3)*

The four detrending methods show similar results for all but the joint Livelihood Inclusion and Exclusion determinant category, where on average the two variability based detrending methods have the highest performances. Here, the "BP + var." detrending method increases the mean summed cross validated R^2 by 18, 33, and 54 % relative to the three other detrending methods. These differences are in line with the increased analytical detail involved in adding a detrending of the variability, and applying a breakpoint methodology to a dataset known to have structural breaks. It further shows that there are trends in the variability of the crops, and breakpoints in both the mean and the variability. That only slight differences are seen between the detrending methods for the rest of the determinant categories can be explained by their overall low performance, as additional detrending detail is not adding any considerable improvements in the summed cross validated R^2s. The differences in detrending performances are on the other hand most apparent for the highest performing determinant and determinant category, identified as the ARC2 driven Yield Reduction Additive Adjusted determinant with the Livelihood Inclusion and Exclusion determinant category. Compared to the basic "MA" detrending method, both the "MA + var." and the "BP" have relative improvements of 30 % for this determinant and determinant category, while the "BP + var." clearly outperforms the others with a relative improvement of 65 %.

6.2.2 Selected determinant combination performance

The ARC2 driven Yield Reduction Additive Adjusted determinant, with the "BP + var." detrending and the joint livelihood determinant category, has a total significant cross validated R^2 of 0.193 to the full rainfed crop production dataset of 37 variables. Its performance is more clearly understood when reviewing its summed significant cross validated R^2 to all the crop categories in the Sahelian and Soudanian zone (Table 13). The highest explanatory capacity is generally found in the Sahelian zone, and primarily for the production variables. Noteworthy results are especially the pronounced difference between the harvested area and the production variables in the Sahelian zone, as well as the lack of any significant variables found for the yield variables in the Soudanian zone. As the production and harvested area is what is assessed from the fields, and the yield being derived from the two, the higher performance of the production variables points to uncertainties and possible inconsistencies in the data on harvested area and subsequently the yield.

Table 13 *- Significant cross validated R2 per subgroup for the ARC2 driven Yield Reduction Additive determinant, with the Livelihood Inclusion and Exclusion determinant category. Results are presented both for all of the variables in each subgroup, as well as only for the variables with significant regression models.*

	Area		**Yield**		**Production**	
	All	Sig.	All	Sig.	All	Sig.
Sahel (R^2)	0.07	0.29	0.15	0.30	0.20	0.50
Variables (no.)	22	5	22	11	22	9
Soudan (R^2)	0.09	0.34	0	0	0.12	0.44
Variables (no.)	15	4	15	0	15	4

The rates of significant variables in Table 13 show that only a minority of the included crop variables have significant regression models established, with an average of 35 % for the production variables, which explains the low values for the summed cross validated R^2s as seen against the whole production dataset (0.20 & 0.12). However, the mean cross validated R^2s are much higher within each subgroup's set of significant variables, which is in line with the few other studies conducted on environmentally driven regressions models against crop output in Chad (McNally et al., 2015; E. Nilsson et al., 2016). This further affirms that the best performance is within the production variables, with an average cross validated R^2 of 0.50 for 9 production variables in the Sahelian zone, and 0.44 for 4 production variables in the Soudanian zone. The spatial distribution of the explanatory capacity to the production, including contributions from the harvested area and the yield where no significant regression models were established for the production, is presented in Fig. 22. The significant regression models for maize are generally found in the Soudanian zone, while for millet and sorghum they are generally found in the Sahelian zone. These spatial differences are best understood in terms of accuracy of the crop statistics, and regional variations in rainfed farming, as the Sahelian zone is rainfed to a higher degree than the Soudanian zone, which in turn has more extensive irrigation practices (FEWS NET, 2011b). Moreover, for the maize variables in Guéra and Moyen-Chari, both with cross validated $R^2 \geq 0.50$, the regression models excluded the water determinant altogether and only included livelihood determinants, which further points to the decoupling of these crops' variability from the atmospheric water conditions. The higher proportion of millet production found in the Sahelian zone (DPSA, 2017; FEWS NET, 2011b) could also explain these patterns, as measures for data collection and the responses to varying water conditions both might be more consistent than for the other crops.

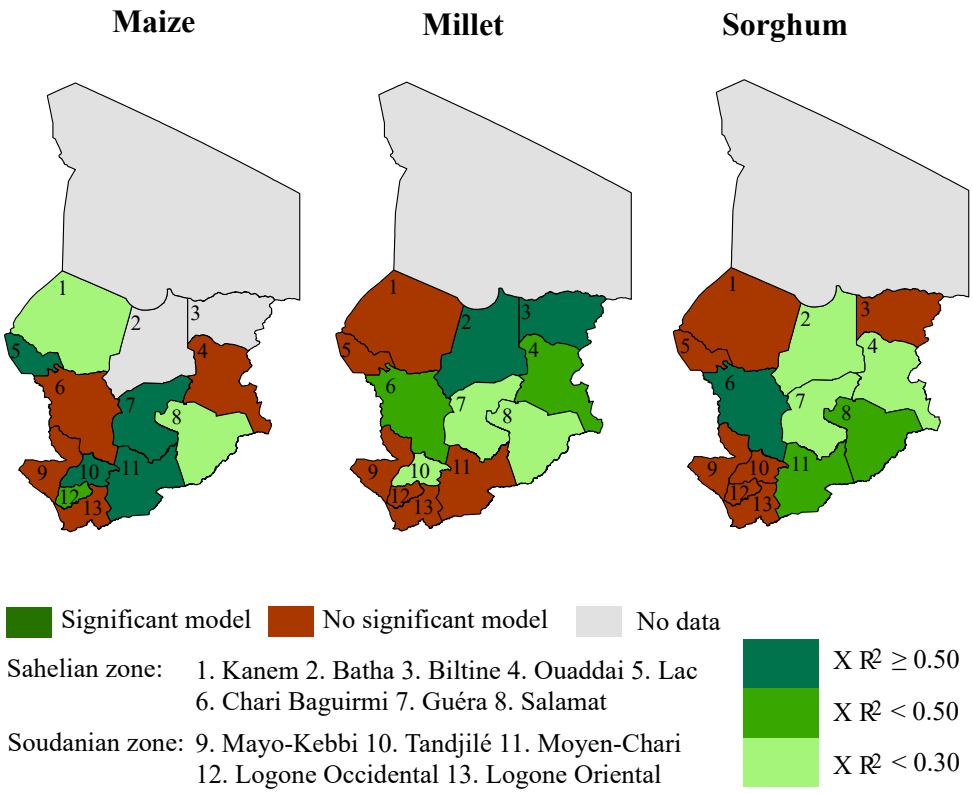

Fig. 22 *– Spatial distribution of the explanatory capacity for the production variables*

6.2.3 Evaluation of livelihood determinants

To get a reliable evaluation of the explanatory capacity of the livelihood determinants, their selection rates in the highest performing regression models are presented in Table 14. As this table only shows which livelihood determinants improved the explanatory capacity of the regression models the most, it does not exclude the possibility that other livelihood determinants had significant correlations, but should serve as an indication of which livelihood determinants are most potent for this end. Seen for the 21 production variables with significant regression models in both zones, the Livelihood Inclusions determinants are selected in 57 % of the cases, while the corresponding rates for Exclusion determinants are 71 %. The most frequently selected Inclusion determinants are Market Prices and Food Security Classifications and, for the Exclusion determinants, Conflicts and Agricultural Support. Market Prices and Food Security Classifications were the only Inclusion determinants that were quantitative in their

original form, while the rest of the Inclusion determinants where quantified based on the qualitative information in the food security reports. Their high selection frequencies point to their relevance, and to the uncertainties involved in quantifying the livelihood data. Moreover, for the group of quantified livelihood determinants, only categorical determinants were selected, and no intensity determinants, which further confirms the uncertainties in the quantification processes.

Table 14 *- Selection rates (%) of the Livelihood Inclusion and Exclusion determinants for the highest performing regression models. Note that the significant variables are given in absolute numbers*

Livelihood Inclusion determinants	**Sahel**	**Soudan**
Market Prices, Food Security Classifications, Conflicts[1], Pests[1], Floods[1]	0	20
Market Prices, Food Security Classifications, Pests[1], Floods[1]	0	20
Market Prices, Food Security Classifications	13	0
Floods[1]	0	20
Food Security Classifications	6	0
Market Prices	25	20
Pests[1]	6	0
Not selected	50	20
Significant variables (no.)	16	5

Livelihood Exclusion determinants		
Agricultural Support, Crop Switches, Market Disruptions	0	20
Agricultural Support, Crop Switches	0	20
Agricultural Support, Market Disruptions	13	0
Agricultural Support	13	0
Conflicts	31	40
Crop Switches	0	20
Market Disruptions	6	0
Not selected	38	0
Significant variables (no.)	16	5

1. Categorical

6.2.4 Combined analysis of variables with high explanatory capacity

Even though the explanatory capacity is considerably improved when involving livelihood determinants, it is still low as seen for the whole dataset (Table 13). For the selected water determinant and determinant category, 16 of the 37 production variables have no significant regression models established, and the mean cross

validated R^2 for all the significant production variables is 0.36. For specific production variables, as seen in Fig. 22, the cross validated R^2s are however much higher, which can serve as examples of the usefulness of this methodology. With an increasing rate of explained variability for a crop variable, there is also an increasing potential to attribute the unexplained variability to qualitative descriptions of the livelihood conditions for specific years, which can provide a more comprehensive understanding of the drivers of production variability in these systems. Table 15 lists all the production variables with cross validated R^2s above 0.5 together with the selected livelihood determinants, indicating where the evaluated methods perform best.

Table 15 *- Production variables with cross validated $R^2 \geq 0.50$*

Region	Crop	X R^2	Livelihood Inclusion	Livelihood Exclusion
Batha	Millet	0.61	-	-
Biltine	Millet	0.78	-	Agricultural Support
Chari Baguirmi	Sorghum	0.64	Market Prices^N	Conflicts
Guéra*	Maize	0.57	Market Prices^p, Food Security Classification	-
Lac	Maize	0.52	Market Prices^p	Conflicts
Moyen Chari*	Maize	0.61	Market Prices^p	Agricultural Support, Crop Switches, Market Disruptions
Tandjilé	Maize	0.51	Market Prices^N, Food Security Classifications, Pests, Floods	Conflicts

** No water determinant included, only livelihood determinants. ^{P} Positive regression coefficient. ^{N} Negative regression coefficient. Variables without superscripts have regression coefficients according to their constraint range (Table 5).*

The utility of this kind of combined analysis can be exemplified with two of highest performing variables, millet production in Batha (Fig. 23) and Biltine (Fig. 24). Here, high prediction deviations, set to 0.8 standard deviations, are given potential explanations based on the information in FEWS NET's food security reports for the respective growing season.

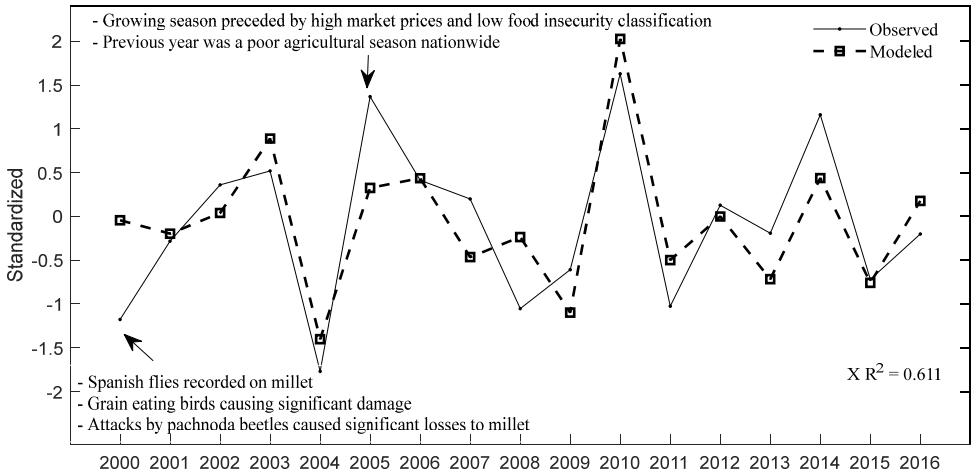

Fig. 23 *– Detrended millet production in Batha and prediction from the ARC2 driven Yield Reduction Additive Adjusted determinant. Prediction deviations above 0.8 standard deviations are given potential explanations from FEWS NET's food security reports for the respective growing season*

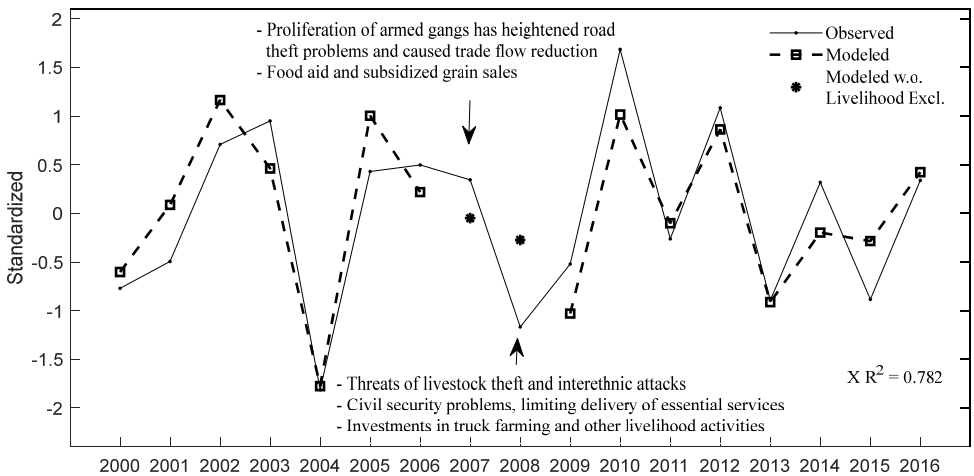

Fig. 24 *– Detrended millet production in Biltine, and prediction from the ARC2 driven Yield Reduction Additive Adjusted determinant and the Agricultural Support Livelihood Exclusion determinant. Deviations in the excluded years are given potential explanations from FEWS NET's reports for the respective growing season*

The effect of excluding agricultural support years in Biltine (Fig. 24), for 2007 and 2008, although correctly identifying deviating prediction performances, also shows the uncertainty involved in this methodology, as the resulting deviation goes in different directions for the two years. The effects of agricultural support on the crop

production on regional scales will depend on a range of factors which cannot be assessed further without additional sample cases and more detailed data. On this level of analysis, as agricultural support is usually triggered by low food security and conflicts, growing seasons with agricultural support recorded could as well be linked to underperformance of the water availability conditions. For operational purposes, the main usage of identifying categorical variables that correlate with prediction deviations, like agricultural support in this case, is first and foremost to give an early indication of deviations from normal production patterns, and secondly to determine their effects. For the additional production variables with high performing regression models established (Table 15), the years with high prediction deviations are given potential explanations in Table 16. The qualitative attributions in this analysis show that negative deviations are generally more robustly established than positive ones (Fig. 23, Fig. 24, and Table 16), which stems from the negative bias in the food security reports, which are more focused on monitoring and averting crises than optimizing the production systems. Several of the explanations given here were also evaluated but not selected as Inclusion or Exclusion determinants for the respective variables in the statistical analyses, such as Agricultural Support, Floods, and Pests. The uncertainty involved in the effects of these factors, stemming from their broad descriptions in the food security reports as well as their interaction with other factors, limits their potential to establish any statistically reliable causalities. Using them as potential explanations in qualitative terms holds less explanatory and predictive applicability, but is still able to point to potential relationships with more precision than previous studies.

Table 16 *- Explanations of prediction deviations in production variables with X* $R^2 \geq 0.50$

Region	Crop	Year	Std. deviations from predictions	Potential explanations
Chari Baguirmi	Sorghum	2002	+ 0.85	- Country-wide investments due to upcoming elections, contributing to inflation - Increased market demand due to oil projects in southern parts of the country - Harvested area of millet is reduced with similar extent as harvested area of sorghum area increased, pointing to potential crop switches
		2012	- 0.82	- Disruptions in imports from Nigeria and Libya - Floods

Region	Crop	Year	Std. deviations from predictions	Potential explanations
Guéra	Maize	2009	- 0.80	- Poor seed availability, limiting planted area - High market prices, limiting food access for low and average income households - Threats from grain eating birds - Effects of last year's price caps are discouraging wholesalers - Lost income due to prohibition on charcoal making
		2016	+ 0.90	- Subsidized food sales and farm support from NGOs - Stable cereal prices, sustained by the presence of manufactured food from Libya and Sudan - Early first rains, prompting early crop planting
Lac	Maize	2003	+ 1.25	- *No links established*
		2010	- 0.90	- Food aid and assistance programs due to low food security - Effects of last year's price caps are discouraging wholesalers - Subsidized sales have had limited effect in curtailing price increases - Heightened levels of pests
Moyen-Chari	Maize	2016	+ 1.69	- Low food insecurity levels - Early planting and major expansions in crop growing areas, resulting in loss of rangelands. No further information on what drove these expansions.
Tandjilé	Maize	2006	+ 1.08	- *No links established*
		2007	- 1.07	- Poor households were hard hit by flooding - Grasshopper attacks
		2010	- 0.99	- Eroded productive capacity due to flooding and poor harvests over three previous growing seasons
		2012	- 1.31	- Deteriorating food security expected without food aid - Severe flooding, causing below average harvests - Locusts and grain eating birds, with damages estimated to 10-15 % of crops

6.3 Drivers of regional long term changes

The same breakpoint and trend analysis that was used to identify the patterns of change (section 6.1) and to isolate the interannual variability (section 6.2), formed the basis of the evaluation of drivers of long term changes in cereal crop production. The acquired datasets on demographics, livelihoods, soil water availability, and international aid for 1990-2016 are evaluated against these trend levels in the following sections.

6.3.1 Overview of datasets

6.3.1.1 Regional agricultural output

The relative change in agricultural output and total population per region for 1990-2016 are presented in Fig. 25, joint with the agricultural and total population for 1993, 2009, and 2014 in Fig. 25B. Fig. 25A shows that the majority of the changes seen in the agricultural sector are driven by increases in the harvested area, while yield improvements generally represent smaller ratios. Despite having one of world's highest population growth rates, agricultural production is outgrowing population with considerable margins in almost all regions, which emphasises the importance of factors beyond population driven demand and labour availability. A linear regression between the production growth rates and their start levels in 1990 gives an R^2 of 0.05, demonstrating that the agricultural growth rates in this period are independent from their initial conditions. Fig. 25B shows that the relative size of the agricultural population in relation to the total population is declining in all regions over the studied time period, and that the absolute size of the agricultural population has even declined in four of the 13 regions. Caution is however warranted over the validity of the estimates from the 2014 survey, which only covered a sample rate of 9% of the household, contrary to 100% sample rates in 1993 and 2009. Moreover, the variations in population changes in Fig. 25B illustrate that the demographic dynamics differ between the regions. The causes behind these demographic changes are however beyond the scope of this thesis, as the focus here rather is to evaluate demographic variables as potential predictors of agricultural change.

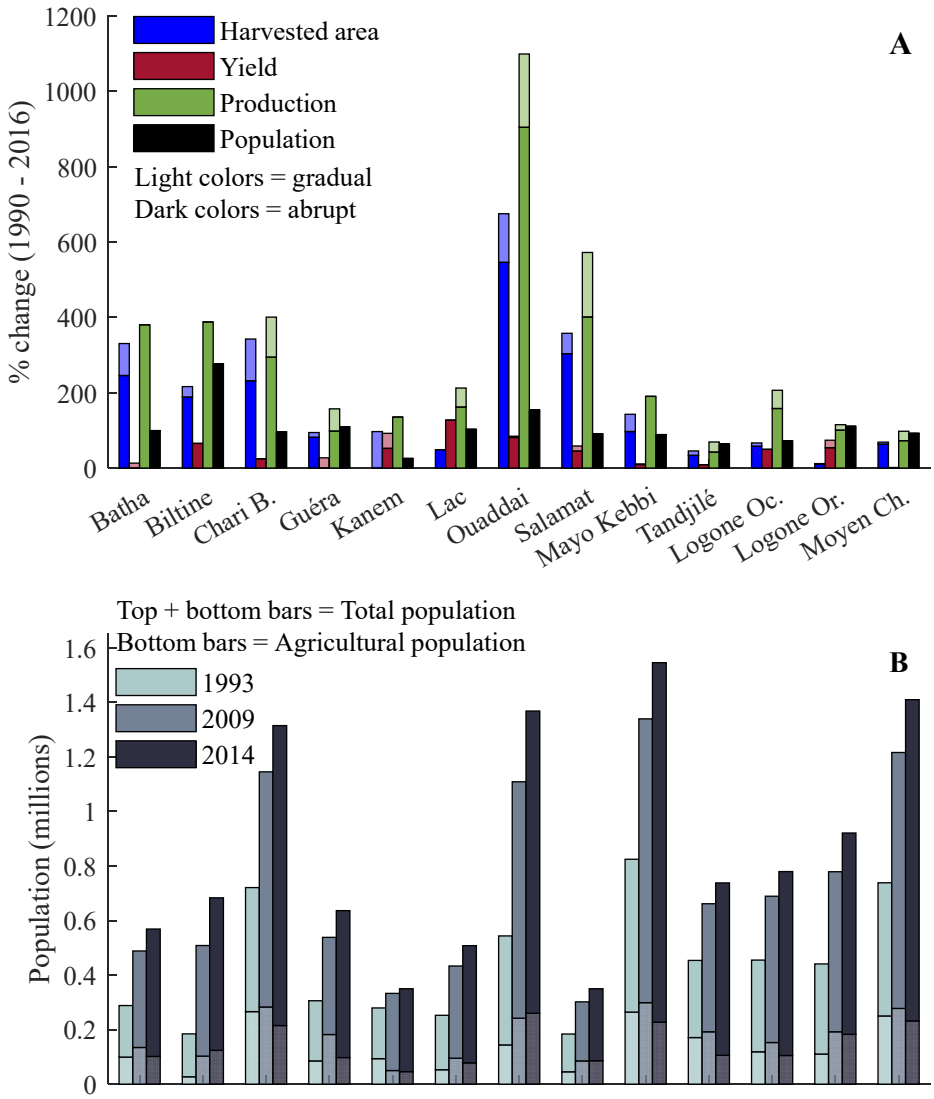

Fig. 25 *– **(A)** Agricultural % change for 1990-2016 for harvested area, yield, and production per region; and **(B)** Total and agricultural population*

6.3.1.2 Soil water

To evaluate any potential shifts or trends in the soil water availability, Fig. 26 shows how the yield reduction factor, which was selected as the best predictor of rainfed crop variability, has evolved for the Sahelian and Soudanian zones for 1990-2016, and indicates consistently water stressed growing conditions. It should also be noted that a shift from e.g. 50% to 60% in estimated yield reductions is equivalent to a

decrease in the agricultural output of 20%, according to Eq. 2. Besides the strong interannual variabilities, some distinct differences in can be seen between selected periods, which justifies including differences in yield reduction factors as potential predictors of long term agricultural change.

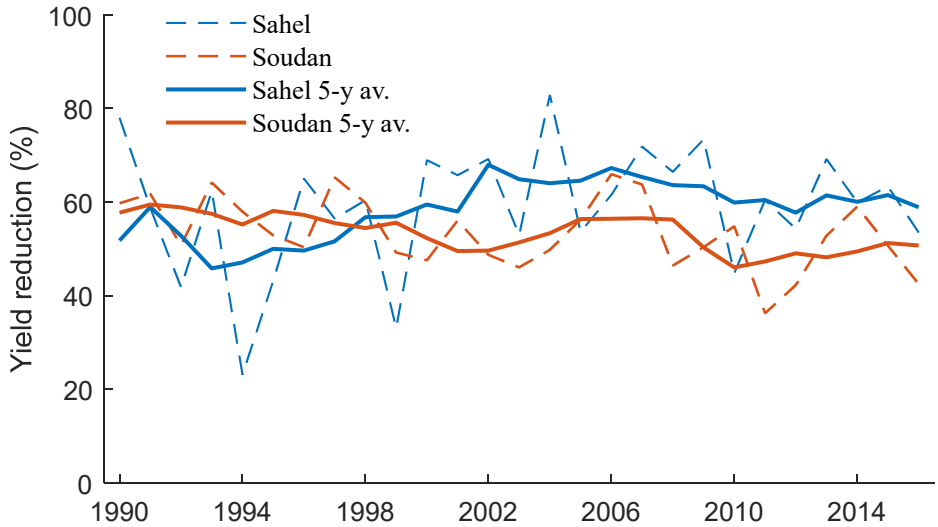

Fig. 26 *– Estimated yield reduction factor due to water limitations for the Sahelian and Soudanian zones*

6.3.1.3 Aid

The total amount of gross ODA received in Chad for 1960-2017, covering 4451 project entries from the IATI database and donor specific project data bases, is summarized in Fig. 27, together with the regional attribution and aid group division (see section 5.5.2.3).

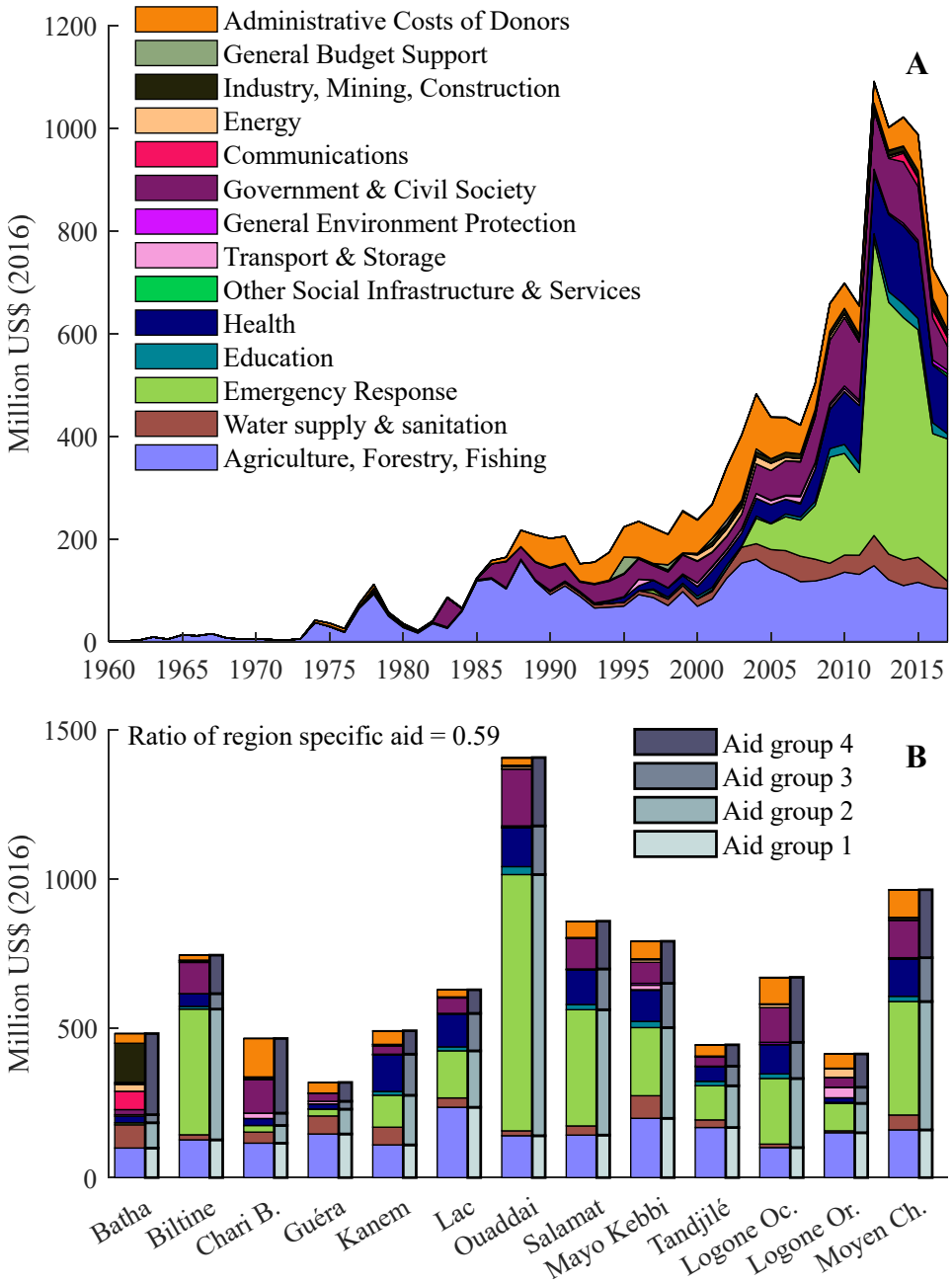

Fig. 27 *– **(A)** Gross ODA to Chad in 1960-2017 per DAC category; and **(B)** region. Note that the aid groups in this figure are represented cumulatively (i.e. Aid group 2 is the first 2 aid bars)*

A comparison with the net ODA as presented in the World Bank database and Fig. 5 shows a strong agreement for 2000-2010, but almost doubled amounts in the World Bank estimates for 1980-1995, and 30-40 % lower amounts for 2010-2016. While the difference between net and gross estimates partially can explain the latter discrepancy, it is likely due to an exclusion of some of the Emergency Response aid in the World Bank data in this period. While the earlier discrepancy was not explored further, an increase in aid reporting to the IATI database and in the organization specific project databases is likely to explain part of the general increase in Fig. 27A. The peak after 2010 can however not be explained by any such differences in aid reporting, and is best understood as a response to the heightened humanitarian crises in Chad and its neighbouring countries during this time, due to: Boko Haram related conflicts in Nigeria, the civil war in the Central African Republic, and ongoing conflicts in Sudan. This is illustrated by the high ratio of Emergency Response received over this period, but these effects can also be seen in the differences in aid received in the regions in Chad (Fig. 28B). The regions with the highest ratios of Emergency Response (Biltine, Ouaddai, Salamat, and Moyen Chari) are all located along the south eastern and eastern borders in Chad, and are thus directly affected by conflicts and refugees from the Central African Republic and Sudan. Besides Emergency Response, the other top categories in gross ODA are, in descending order: "Agriculture, Forestry, and Fishing", "Health", "Government and Civil Society", "Administrative Costs of Donors", and "Water Supply and Sanitation". With a ratio of region specific aid at 59%, the location attribution methodology is considered to be successful enough to be able to compare the effects of aid between the regions. The remaining 41% of the aid with no specific location established, is likely to be a mixture of aid given to national ministries and project entries that have only have generic project descriptions, or lack descriptions completely.

6.3.1.4 Livelihood data

An overview of the differences in reporting in FEWSNET's food security reports for the respective regions is provided in Fig. 28, together with their average food security classifications (for category definitions see Section 4.4). A comparison between Fig. 28A and Fig. 28B show that there is some agreement in general food insecurity and number of mentions in the food security reports, a reflection of FEWSNET focus on issues of food insecurity. This results in the Sahelian zone (Batha to Salamat) receiving more attention than the Soudanian zone. The three regions receiving the highest amount of Emergency Response aid (Ouaddai, Biltine, and Salamat), as identified in Fig. 27B, are also the regions with the highest number of Conflict related mentions in Fig. 28A. This summary further illustrates how both pastoral conditions and market dynamics are receiving more attention in the Sahel, a reflection of their importance for livelihoods in the central and northern parts of the country.

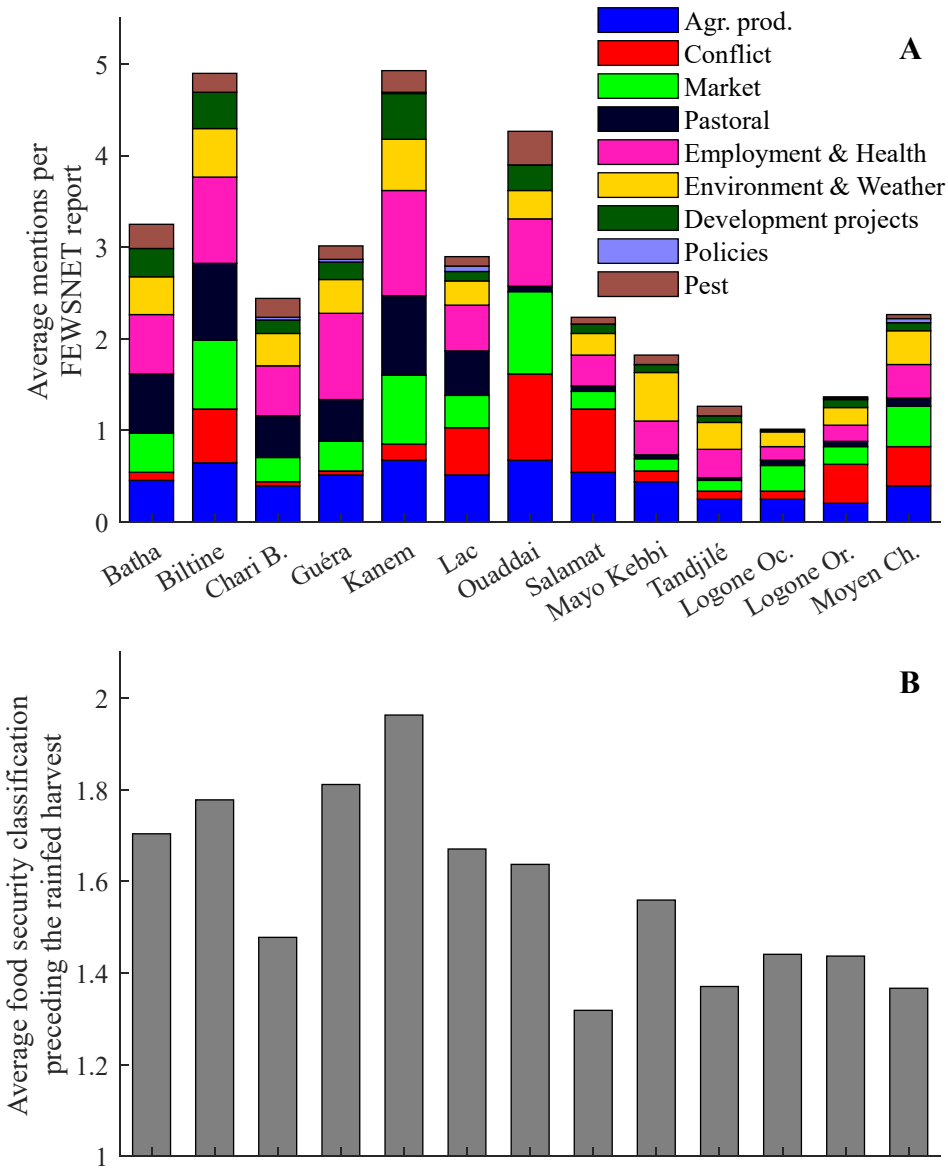

Fig. 28 *– **(A)** Average number of entries in food security reports per category and region for 2000-2016; and **(B)** average food security classification in the 3 months preceding the rainfed harvest per region for 2008-2016. Note that food security classification 1 indicates full food security, while any number above that indicate food insecurity (see Section 4.6 for definitions)*

6.3.2 Gradual changes

6.3.2.1 Relationships between key demographic variables and agricultural change

The associations between demographic and agricultural changes between the regions in the Sahel and the Soudan are presented in Table 17. All crop categories are generally increasing for these time periods, which implies that a negative correlation to a demographic variable means that the agricultural growth decreases when the demographic variable grows, and not that the resulting agricultural growth is negative. Although the small sample sizes (Sahel = 8, Soudan = 5) limits the possibilities for statistical significance, there are a number of interesting associations between demographic and agricultural variables to interpret.

Table 17 *– Coefficients of determination (R^2) from linear regressions between % change to key demographic and agricultural variables*

	Harvested area		**Yield**		**Production**	
	Sahel	Soudan	Sahel	Soudan	Sahel	Soudan
Total population (1993-2009)	0.43**	0.01	0.63**	0.02	0.2**	0.03
Agricultural population						
(1993-2009)	0.39**	0.41	0.44**	0.68*	0.20**	0.04
(1993-2014)	0.16*	0.07	0.54**	0.45*	0.35**	0.13
(2009-2014)	0.1	0.21	0.17	0.09	0.16	0.03
Poor population (%, 2003-2013)	0.6	0.44**	0.04	0.08	0.77*	0
Literate population (%, 1993-2009)	0.07	0.01	0.45**	0.08	0.04	0.11
Mean income (%, 2003-2011)	0	0.08	0.01	0.23	0.06	0
Income inequality (%, 2003-2011)	0.05	0.31*	0.1	0.59	0	0.57

** ≤ 0.05 significance level. ** ≤ 0.01. Regressions with negative slope coefficients are underlined*

Table 17 identifies a range of distinct associations between the Sahel and the Soudan. The effects from changes to the total and agricultural population, which are linearly correlated (Pearson correlation coefficient in Sahel = 0.92, in Soudan = 67), are likely due to combinations of increased local demand for agricultural products and an increasing rural population engaging in agriculture following common cultural practices, either by expanding the agricultural areas or increasing the

amount of labour and inputs per area. The lack of associations to the total population in Soudan demonstrates that its agricultural systems respond to demands beyond the respective regions to a larger degree than in Sahel, either through sales to national or cross-border markets. While the agricultural population is associated to both the harvested area and the yield in Sahel, in Soudan it is only linked to the yield. These differences reflect the more extensive farming practices in the Sahel, and more intensive farming practices in the Soudan (FEWS NET, 2011b; Republic of Chad, 2009). Moreover, the R^2s to the agricultural population are generally decreasing over the data available time periods, which either implies a shift from these relationships with growing population density, or inaccurate estimates from the partial demographic census in 2014. Regions in Soudan with higher growth rates in poor population are negatively correlated with growths in the harvested area, indicating that the growth in harvested area in Soudan partly are driven by economically potent groups, presumably through investment heavier practices than in Sahel. This can also been inferred from the negative correlations seen for the growths of both the total and agricultural population to the harvested area in Soudan. Additionally, the negative association between harvested area and income equality in the Soudan is probably due to a similar dynamic, namely that increasing income inequality reflects economic accumulation within top income cohorts, a process which in turn push agricultural intensification over extensification. This can also be hinted at through the high, but non-significant, positive association between income inequality and yield in Soudan. Contrary to Soudan, a positive association is identified between growth in the poor population to the production in Sahel. Although not significant, this is likely realized through the expansions of agricultural areas connected to growth in the rural poor population. Lastly, the growth in the amount of literate population is strongly associated to growth in the yield in the Sahel, which emphasises the role of educational improvements in small-scaled farm management and intensified practices. Growth in the literate population is further strongly linearly correlated to the total population (Pearson correlation coefficient = 0.77) and the poor population (0.74). The pronounced difference in association between the growth in literate and poor population to the yield thus indicates that it is the processes of increased literacy that is not due to the growth in poor population that drivers the increasing yields in Sahel, such as additional educational investment. The lack of association between literacy and yield in Soudan is probably explained by the considerably higher literacy rates in these regions, which in 2009 on average was 29 % compared to the Sahelian average of 8 %.

6.3.2.2 Relationships between international aid and agricultural change

From an annually based lagged multivariate regression between the logarithm of aid and agricultural growth of the four aid groups (see section 5.5.2.3), only one region, Kanem in Sahel, had any significant correlations established, which discards the

validity of this method for these datasets. Turning instead to the intraregional regression analysis over extended evaluation periods, interesting results emerge (Table 18). The effect of altered soil moisture conditions over the time period is included by removing the trend differences in estimated yield reduction factors (see section 5.5.2.1). The variations in aid reporting over the studied time period is expected to affect the regions equally, and should therefore not affect the reliability of this analysis. It is interesting to note that Aid group 1, which only focuses on agriculture (and forestry and fishing which are less common in Chad), has the weakest associations with every agricultural variable for both zones in all aid groups. Moreover, it is only for Aid group 4, including all types of aid, that statistically significant associations with harvested area and production appear, and then only in Sahel (Table 18). For the yield, Aid group 2-4 produce significant associations in Sahel, with the strongest association between the yield and Aid group 3, which in addition to Aid group 2 includes *General Environmental Protection*, *Transport & Storage*, *Education*, *Health*, and *Other Social Infrastructure & Services*. That both education related aid and the amount of literate population (Table 17) are positively associated to the yield in the Sahel, and not in the Soudan, is noteworthy. This relationship is further supported by that the amount of education related aid received in the regions in Sahel has a detectable positive association to the growth in literate population (linear regression $R^2 = 0.29$, p-value = 0.07), while no significant association is detected in Soudan.

Table 18 *– Coefficients of determination (R^2) from linear regressions between the logarithm of total aid per aid group and % growth in agricultural variables for 1990-2016*

	Harvested area (%)		**Yield** (%)		**Production** (%)	
	Sahel	Soudan	Sahel	Soudan	Sahel	Soudan
Aid group 1	0	0.22	0.21	<u>0.05</u>	0.06	0
Aid group 2	0.34	0.47	0.30*	<u>0.24</u>	0.59	0.13
Aid group 3	0.28	0.52	0.38**	<u>0.23</u>	0.52	0.19
Aid group 4	0.6**	0.37	0.25*	<u>0.12</u>	0.78**	0.22

** ≤ 0.05 significance level. ** ≤ 0.01. Negative correlations are underlined.*

To be able to give an estimate of the association between the amount of aid received and agricultural variables over time, a more detailed review is conducted by looking at the variations in these associations over a large number of sub-periods for each of the aid groups. The rates of significant associations ($p \leq 0.05$) between the logarithm of aid and agricultural variables for the 351 possible periods (all periods at length 2-27 years for 1990-2016) per aid group were thus calculated to identify which aid group is the best predictor of agricultural variables (Table 19). Aid group 4 is again seemingly the best predictor of change in the agricultural variables, which stresses the importance of understanding the agricultural sector as being intertwined

with and affected by developments in society in general. The remarkably low rates of significant associations for the yield and production in Soudan points to the general decoupling of its agricultural variables from the amount of aid received, contrary to Sahel.

Table 19 *- Rate of periods* with significant associations*

	Harvested area		**Yield**		**Production**	
	Sahel	Soudan	Sahel	Soudan	Sahel	Soudan
Aid group 1	0.11	0.12	0.1	0.01	0.07	0.05
Aid group 2	0.14	0.29	0.21	0	0.23	0.05
Aid group 3	0.13	0.29	0.22	0	0.21	0.05
Aid group 4	0.25	0.26	0.12	0	0.32	0.08

** Number of periods = 351*

As the logarithmic relationship between aid and agricultural growth varies over the evaluated periods and the significant regressions behind the results in Table 19, the best estimate of a consistent such relationship was taken as the mean of all the significant relationships together with its 95% confidence interval. Fig. 29 and Fig**. 30** present this estimated effect of the amount of aid received per year on the annual agricultural growth rate, for the regions in Sahel and Soudan. As the only factors involved in these regression based estimates are the amount of aid and changes to soil water, they are bound to overestimate to effect of aid. The degree of overestimation will depend on the relative importance of the amount of aid compared to non-included factors, which have not been evaluated due to data limitations. And as the estimated equations for Sahel and the Soudan are taken as the best estimate from the full set of significant regressions, these results should mainly be read as indications of the relative effectiveness and influence of aid on agricultural production between the regions and periods. Despite the pronounced differences between the regions in production and aid levels, the region specific graphs in Fig. 29 and Fig. 30 show that these estimates generally align with the agricultural changes over this period. The ranges of the confidence intervals further show that these relationships are fairly over the full set of periods with significant regressions (Table 19). Overestimations are seen for Chari Baguirmi, Kanem, Lac, and Moyen Chari, which point to a general decoupling in agricultural growth from the amount of aid received in these periods. As these estimates are based on the amount of aid in all DAC categories (Aid group 4), this could be interpreted as that aid in periods of overestimation are directed towards non-agriculture related sectors, or simply that the aid has been less effective than in the other regions and periods. The equation estimates for the two zones are notably similar, with equation intercepts at -7.7 for Sahel and -12.1 for Soudan, and logarithmic slope coefficients at 4.9 and 5.6 respectively. According to these estimates, positive annual agricultural growth effects from aid are only detected after approximately $5 million

per year and region in Sahel, and $9 million per year and region in Soudan. Additionally, Fig. 29 and Fig. 30 show that while the amplitudes of the variability in the soil water estimates based on the aid level are in the same range as the variability in the agricultural production, the year-to-year agreement is visibly low. Moreover, it shows that the estimated effects of long term changes in soil water availability are minor in comparison to the aid estimates, and that they have had a negative development in the Sahel and positive in the Soudan. The largest and most consistent deviation from the soil water estimate is displayed in Batha and Biltine, both in northern Sahel.

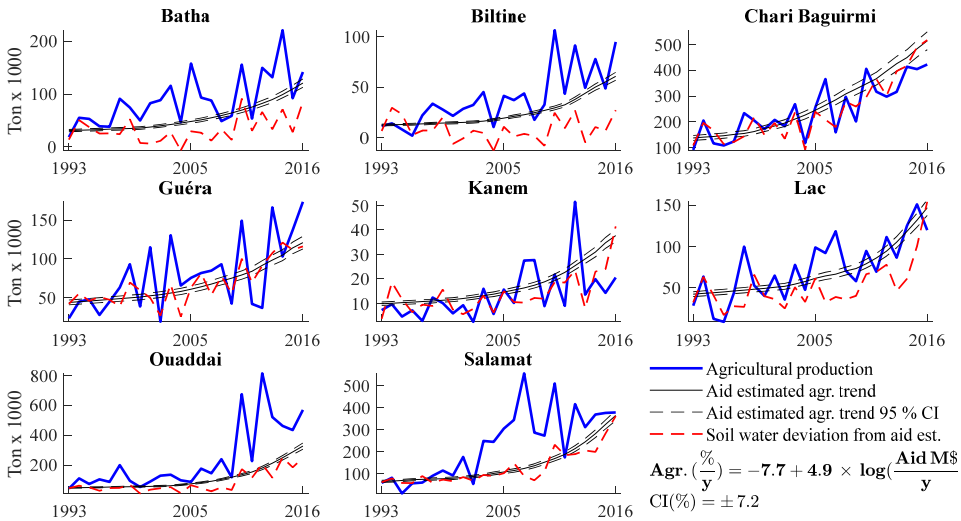

Fig. 29 *– Agricultural production and aid estimated agricultural trend levels with estimated soil water deviation for the regions in Sahel (1993-2016)*

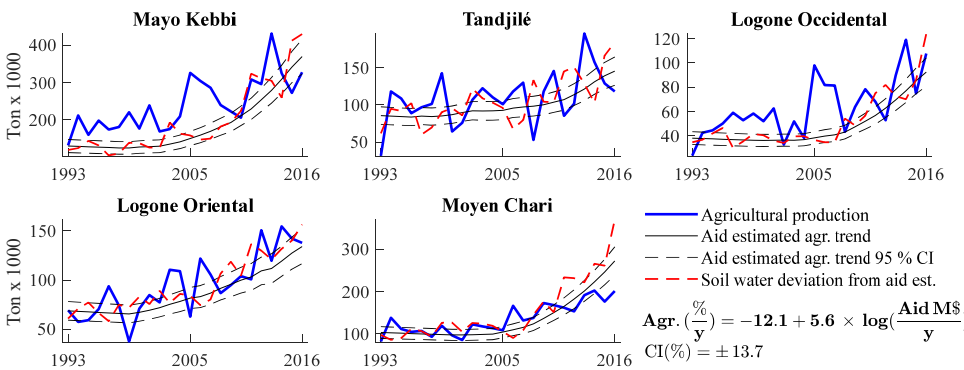

Fig. 30 *– Agricultural production and aid estimated agricultural trend levels with estimated soil water deviation for the regions in Soudan (1993-2016)*

6.3.3 Abrupt changes

While the aid estimates in Fig. 29 and Fig**.** 30 align well with the long term production changes, marked deviations are noticed in several periods. To address this, potential causes for the full set of 45 abrupt changes in the harvested area, as identified by the previous breakpoint and FEWSNET's food security reports for the respective growing seasons, are presented in the Appendix in **Paper 4.** The summary of link scores and attributed factors for these changes, based on the full tables in this Appendix, is presented in Table 20. All information is from the FEWSNET and SODELAC reports, while the interpretations and combined connections to the abrupt changes are made by the author. According to the applied scoring system, 60% of the abrupt changes to the harvested area have been successfully linked to potential causes (link score 5), 18% were only linked to conducive productive capacities for the occurring year (link score 4), while the remaining 23% (link score 1-3) represents abrupt changes with no causal indications established. Given the large proportion of change to the harvested area constituted by abrupt changes (Sahel 81%, Soudan 80%), the set of factors listed under link score 5 can be seen as a key drivers of changes to the harvested area in Chad. At the same time, the lack of detail in these factors point to the limits of these datasets and methods, which need further specification to be applicable in quantitative evaluations. The various types of farm support are the most prevalent factors linked to the positive breakpoints, which was reported in 17 out of the 45 breakpoint events. The summary of link scores and attributed factors for the abrupt changes to the yield is presented in Table 21, while the full range of 24 abrupt changes to the yield are given attributions in the Appendix. Slightly lower than for the harvested area, the rate of link score 5 is at 46%, and again with a high prevalence of farm support.

Table 20 *– Summary of link scores and attribution factors behind the abrupt changes to harvested area. Factors with breakpoint characteristics are in bold, and factor occurrences in parentheses*

Score	Occurrence	Positive factors	Negative factors
1	0 (0 %)	-	-
2	3 (7 %)	-	-
3	7 (16 %)	• High market prices (6) • Refugee communities increasing the amount of harvested area (2) • Humanitarian assistance programs (2) • Unverified crop switch from cotton (2) • Delayed start of rainy season could have led farmer to focus on recession farming	-
4	8 (18 %)	• High market prices (4) • Good rains (4) • Flooding increased area for recession farming (3) • Government assistance (2) • Humanitarian assistance programs • Increased demand due to oil project • Government investments during election year • Potential cereal crop switch • Farm seeds	-
5	27 (60 %)	• High market prices (16) • **Farm inputs (9)** • **Crop switch from cotton (7)** • **Farm trucks/tractors (7)** • **Community assistance for refugees (5)** • Good rains (5) • **Cereal crop switch (4)** • Farm seeds (3) • **Farm training (4)** • Floods (2) • **Lifting of trade embargo with Sudan (2)** • **Livelihood switch from charcoal production** • **Livelihood switch from pastoralism** • Humanitarian aid • **Increased demand from Sahel due to closed border with Libya**	• **Large number of refugees** (1) • **Cereal deficits** (1) • **Delayed rains** (1) • **Floods** (1)

Table 21 – Summary of link scores and attribution factors behind the abrupt changes to the yield. Factors with breakpoint characteristics are in bold

Score	Occurrence	Positive factors	Negative factors
1	0 (0 %)	-	-
2	3 (13 %)	-	-
3	1 (4 %)	• Government investments during election year • Floods	-
4	9 (38 %)	• Food aid (5) • Good rain (4) • High market prices (4) • Potential cereal crop switch (2) • Reduced harvested area • Farmer mobilization	-
5	11 (46 %)	• **Farm inputs (9)** • **Farm trucks/tractors (4)** • Humanitarian aid (4) • High market prices (2) • Good rains (3) • **Farm training** • **Increased market opportunities with Sudan** • **Increased market opportunities with CAR** • **Government awarding lands to settlers**	-

6.3.4 Combined evaluation

From the estimated aid and soil water availability relationships in Fig. 29 and Fig**. 30**, three evaluation groups ("Aid alignment", "Aid overestimation", "Mid-period aid deviation") were created with one region from each zone, to identify potential explanations for their patterns of change. Fig. 31-Fig**. 33** present these groups together with livelihood relevant data for points of pronounced deviations and abrupt changes. As the breakpoints in

Table 20 and Table **21** were identified and linked on the crop level within each region, the aggregated data displayed in these figures often cloud the distinct patterns of change for individual crops. In the "Aid alignment" group (Fig. 31), 3 out of the 6 livelihood links are related to some kind of farm support, which are further likely to be reflected by the amounts aid attributed to the respective regions. The large increases in the last five years in both Guéra and Logone Oriental are well matched by an increasing amount of aid, and partly linked to specific support interventions in 2012 and 2013, as well as favourable growing conditions. The only noteworthy deviation from the aid estimation is the increased production in Logone Oriental in 2003 to 2007, a general increase which in 2003 is attributed to a resumption of trade with the Central African Republic, assistance provided to refugees, and favourable growing conditions. The estimated effect of soil water availability fluctuates but with a stable patterns, and only occasionally match variabilities in the agricultural data, indicating that omitted drivers with high variability are influential. In the "Aid overestimation" group (Fig. 32), the estimated aid effects diverge from the agricultural trends after drops in the production in 2012 for both Chari Baguirmi and Moyen Chari, despite the fact that their levels of aid and agricultural production differ considerably. Taken together, these relationships indicate that both aid to the rural sector could have turned towards non-cereal crops in this period, and that the events around 2012 resulted in a decrease in the agricultural growth rate in the following years. In the "Mid-period deviation" group (Fig. 33), agricultural production display marked increases without being matched by an increasing amount of aid, occurring around 2003-2006 in both Salamat and Logone Occidental. The pronounced jump in Salamat in 2003 have been linked to an exceptional flooding event, which both expanded the amount of area available for flood recession sorghum that year and presumably sustained that production level for the coming years, as farmer oriented their livelihoods towards this cropping system. And while no strong link was found for this deviation in Logone Occidental, favourable market conditions for cereals over cotton might have pushed farmers to focus on the former.

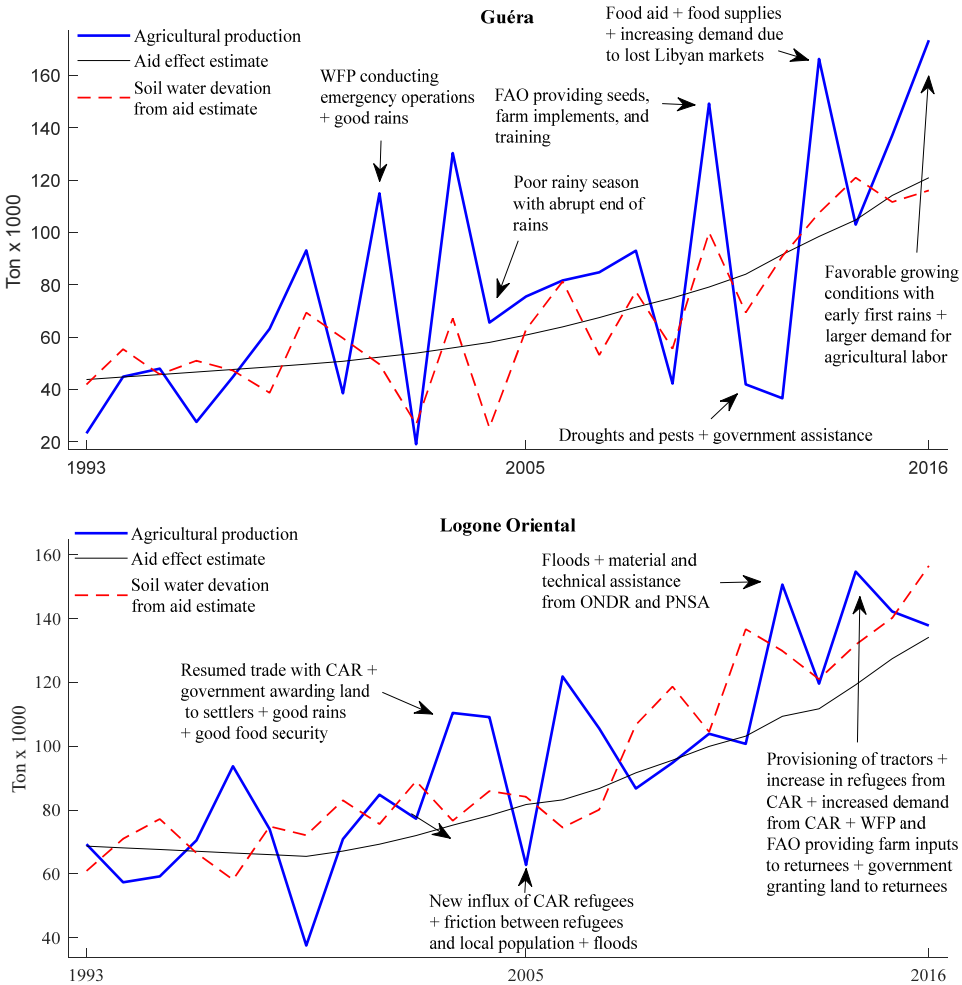

Fig. 31 *– "Aid alignment"*

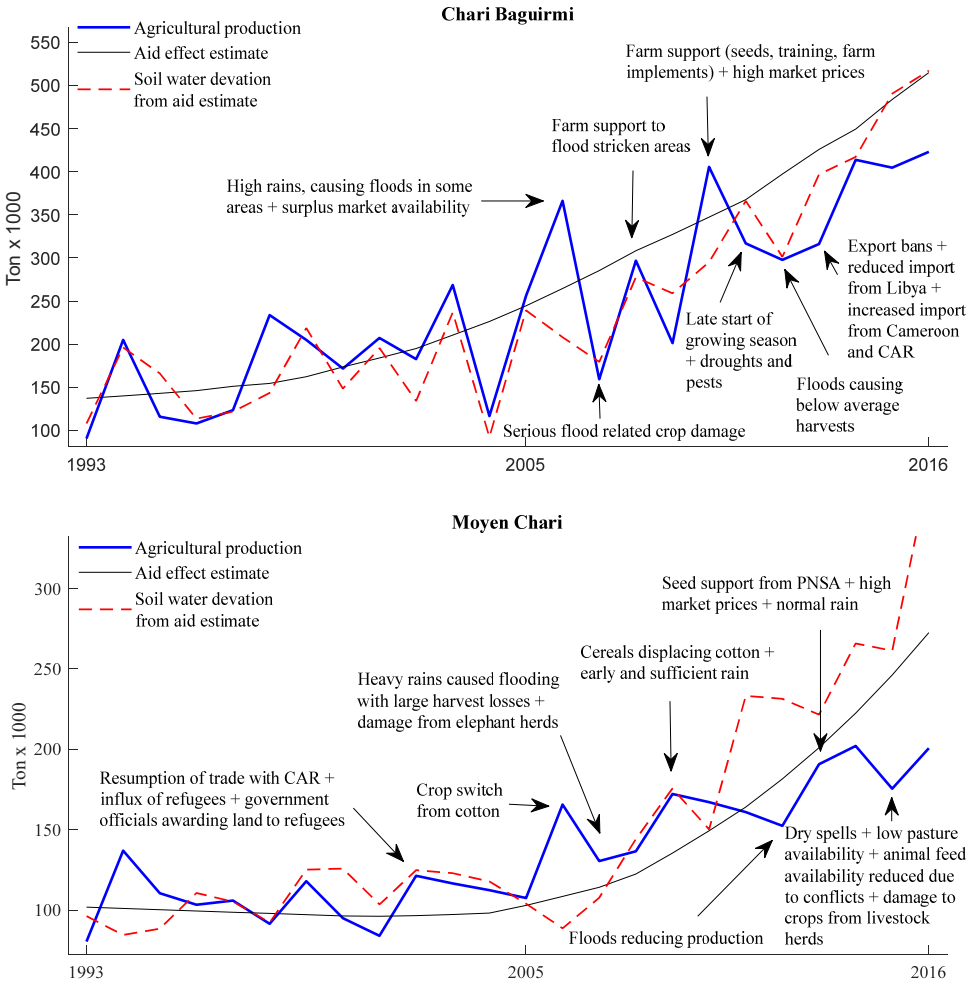

Fig. 32 *– "Aid overestimation"*

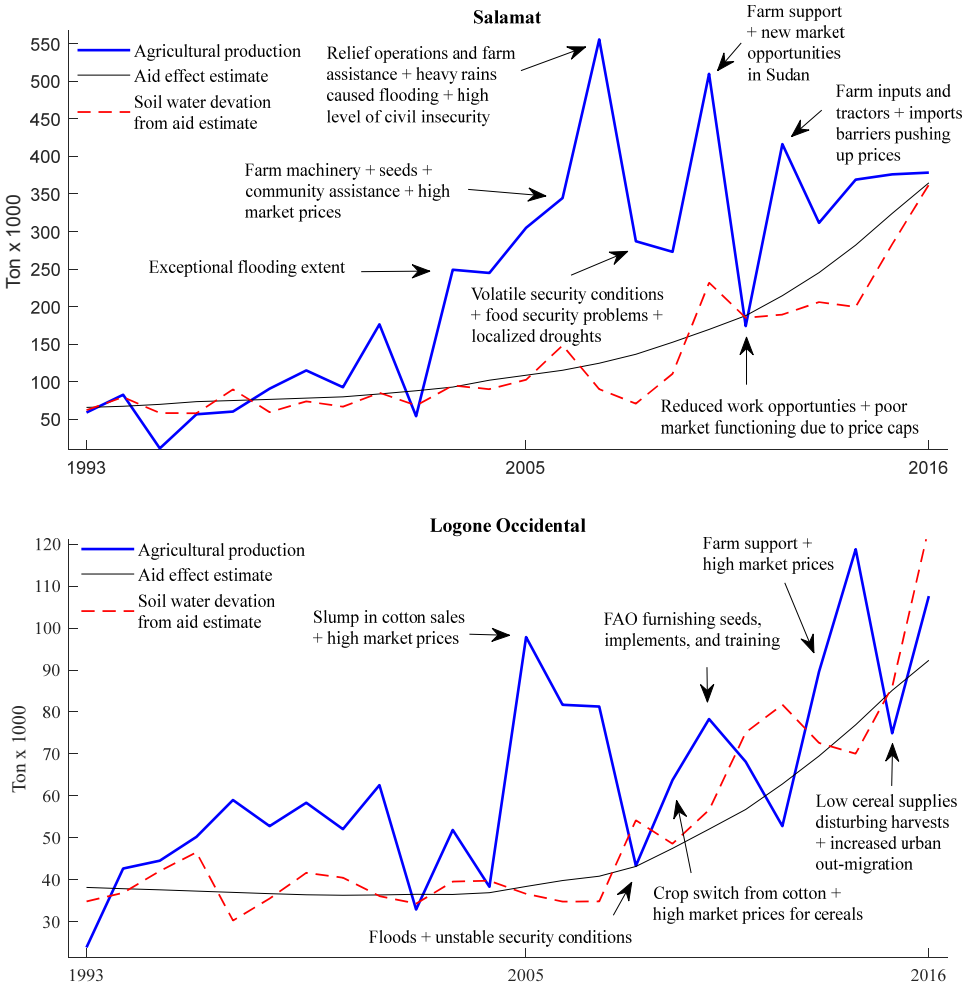

Fig. 33 – *"Mid-period deviation"*

7 Discussion

7.1 Patterns of change

The developed trend graphs in this thesis were specifically adapted to visualize non-linear patterns in datasets consisting of numerous and diverse variables. Based on a breakpoint and robust regression analysis, they were 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). A breakpoint analysis on the sub-regional crop statistics in the Lac region **(Paper 1)** was also able to estimate the effect of a dam construction in the Lake Chad region in 1998 to an increase of 18,000 ha. Simply by clarifying the importance of such specific events, it advanced the understanding of patterns of change in the agricultural sector in Chad. And while the underlying methods and data collection to arrive at these trend graphs is time consuming, their visual presentation is able to communicate complex patterns of change in a concise and intuitively comprehensive manner, thus making them suitable for scientific communication beyond academia. However, while using the region specific crops as the unit of analysis provides more information than regional and multi-regional aggregates, it does not analyse joint crop dynamics, e.g. as farmers might switch between crops. Additional information on farmers' decision making and crop strategies would be able to improve this. Moreover, by identifying periods of gradual and abrupt changes, these trend graphs and their underlying analysis advanced the potential of identifying drivers with more precise scopes than what would be possible if just relying on the nationally aggregated data, which formed the basis of **Paper 3** and **Paper 4.** Additionally, by showing the prevalence of nonlinearities in the case of Chad, an emphasis was 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 reviews conducted for this thesis have from several angles indicated that this methodology could improve current analytical practices of trend and driver analyses in agricultural systems across Sahel and 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.

A prominent drawback with this method and its relevance for practical applications is the detail and quality of the data on which it is built. While the data collection efforts in this thesis have showed that the data availability for the agricultural sector in Chad far exceeds its use in reports and studies accessible online, issues of data quality and added detail still remain. The data quality for application like these 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 and Sahelian 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. With ongoing improvements to institutional capacities, data collection, and data availability, the need for analytical methods to incorporate the full complexity and potential this brings is increasingly necessary. The analysis and visualization of patterns of agricultural change as developed in this thesis presents a proposal of how this can done, with sufficient flexibility to be able to adapt to diverse and changing data environments.

Added to the uncertainties in the data quality are the uncertainties in the statistical results. Reducing volatile time series into smooth trends is essentially a process of simplification, and can lead to a range of equally accurate outcomes depending on the choice of method. In the application to the crop statistics in this thesis, a robust regression estimator was selected to reduce the influence on the trend estimates of outliers. Crucial to all statistical analysis is further the reliability estimates, commonly exerted through significance tests. The significance tests based on the bootstrapped residuals throughout the statistical analyses in this thesis hold some clear advantages over normality based student tests. However, the generally small number of observations used limit the potential of identifying the relevant relationships, and increases the probability of establishing erroneous ones.

Concerning the applicability of the developed pattern identifying method for other users, the time effort and analytical complexity implies that it is not likely that it will be picked up broadly by actors involved in agricultural development. A more realistic application might instead be to create a generalized platform where the relevant data, e.g. sub-national crop statistics, is uploaded and analysed by a specialized organization. While requiring some statistical and data management training, the skills required are certainly covered by most professional development organizations on both national and international levels of operation.

7.2 Interannual variability in agricultural production

In the evaluation of drivers of interannual crop variability in **Paper 3** (Section 6.2)**,** a diverse set of environmental and socio-economic variables were included. **Paper 1** was also based on an analysis of interannual variability, but was mainly conducted based on hydrological variables, and served more as an initial evaluation and familiarization of the research methods than applicable results. The livelihood variables with the highest selection rates in the regression models (Market Prices and Food Security Classifications), were both quantitative variables originally, while quantifying the qualitative information in the food security reports was of less use. Given the broad descriptions used in these reports and the complexity involved in regional agricultural systems, this comes as no surprise, and goes to show that this information foremost lends itself to updates on the food security conditions, rather than for predictive crop variability purposes. The relatively high performance of the breakpoint based trend analysis confirms the findings from **Paper 2** (Section 6.1) that the progressions in these datasets have non-linear elements with abrupt and structural breaks, which needs to be accounted for in studies of both long term trends as well as drivers of variability. And as exemplified by the examples of high-performing production variables, it has shown how a more comprehensive understanding can be achieved in studies of crop variability on regional scales by including qualitative livelihood information. But despite applying a broad range of datasets and analytical combinations, the majority of the regional crop production variability is left unexplained, with only 21 of the 37 production variables having significant regression models established for the best performing determinant combination. The role of water availability has arguably been explored more exhaustively than the livelihood factors, and builds on established methodologies from a long tradition of crop-water studies. The detailed adjustments of such methodologies for the specific conditions in Chad have however not been established, as the water variables were only crudely validated, and as all of the crop specific factors behind the yield reduction estimates were set according to generic assumptions about crop type and agro-ecological conditions. The set of evaluated water determinants in this study has addressed some of these issues, and found that the precipitation driven Yield Reduction Additive Adjusted determinant had the best overall performance, which outperformed determinants driven by a satellite measured topsoil moisture dataset, the ESA CCI SM v03.2.

Evaluating the relative performance of atmospherically driven soil water estimates and remote sensed soil water products in the different regions has not been explored, which could be of interest to future studies, as increasing rates of irrigation might improve the performance of satellite measured soil moisture products over precipitation as predictors of crop water uptake. Further selecting and adjusting water availability estimates and crop specific factors can be advanced by

categorizing information from governmental institutions and development organizations on various spatial scales, and increasing its accessibility for research projects. Increased validation and calibration potential of such datasets could come through agricultural field trials, but with added costs.

The lack of higher explanatory capacities to the interannual variability to crop production can further be explained by data quality issues in the crop statistics, with potentially inconsistent data collection methods and coverage. Although the explanatory capacity was similar for the time periods 1983-2016 and 2000-2016, indicating that there are no consistent changes to data quality in any direction, year-to-year changes in data collection could limit the potential of the regression models to capture the crop variability. Besides the already ongoing initiatives to improve data quality and coverage in Chad (see e.g. World Bank, 2017a), accessing and evaluating the sub-regional crop data that constitute the regional data used here could improve the identification of erroneous data points. With improved crop statistics and soil water estimates, together with increased detail in the food security reports and similar assessments, new valuable research opportunities would open up. This could also address the neglected joint crop dynamics within regions, as crops within each region only were analysed separately. Benefits of research enabled by this kind of data would come in terms of improved food security assessments, evaluations of rural development projects, and identifications of investment opportunities in the agricultural sector. As information channels are already established for these ends by governmental institutions and development organizations, increasing the quality and quantitative applicability of the collected data, and its accessibility, might be a cost-efficient strategy for food security and rural development purposes.

7.3 Long term changes in agricultural production

The trend analysis from **Paper 2** also came to play a fundamental role in the evaluation of drivers of long term agricultural change in **Paper 4.** The estimated trend levels of the crop statistics for the respective crops served as the basis for the regressions against aid and demographic variables, as well as the identification of abrupt changes to be evaluated against the seasonal livelihood information. Although the relevance of aid for the rural sector in Chad has been known and studied previously, this was the first time the amounts of aid have been disaggregated on a sub-national level and evaluated against the changes to the agricultural production. Except for the extensive time required to collect and establish the agricultural and aid data, this is promising for similar applications in other Sahelian countries. But despite the general agreements seen over the full periods of estimated aid effect and the agricultural growth, periods of marked

deviations in some of the regions point to additional complexities. Application of the livelihood information were able address some of these deviations, and overall provided reliable explanations for 50% of the abrupt changes in the cereal production series, albeit in broad terms. While still requiring additional coverage and detail, it points to the potential of combining a statistical pattern analysis with continuous qualitative descriptions. The combined analysis of demographics, aid, soil water, and livelihood information also point to several shortcomings. Due to the small sample sizes, mainly in the demographic data and the interregional aid analysis, several key relationships are bound to have been missed, while the established relationships lack precision and certainty. Both the demographic and aid data were thus analysed in bivariate regressions, implying that they are behind the full range of change in the agricultural data. As such, their estimated effects are on their own overestimated, and are best interpreted relative to the other regions. Added to the uncertainties in these estimates, both joint crop dynamics within regions as well as long term changes to the patterns of variance were excluded from this analysis, which both require additional dataset to be evaluated.

While the institutional and statistical capacities of Chad have been identified as one of the lowest in the Sahel, and the presence of sub-national socio-economic statistics in published reports and articles is sparse, the collaborations, reviews, and results of this thesis have showed that detailed and relevant socio-economic datasets are available. The current data availability is thus likely to exceed the established knowledge on sub-national levels of analyses in a range of Sahelian contexts, which calls for additional research efforts. A couple of data related recommendations can be drawn from this. As the time required to collect and compile the data used for this kind of research might not be motivated under most funding schemes, especially the time spent on quality checking and categorization of the livelihood and aid datasets, the research environment could undoubtedly benefit from increased accessibility to already collected datasets. Specific examples includes: location specific and quality verified aid data, location specific and categorized livelihood data, sub-regional crop statistics, and soil water products adapted to local growing conditions. For instance, the food security reports and general monitoring conducted continuously by FEWSNET, WFP, FAO, and various NGOs, as well as the evaluation reports for development projects, provide a wealth of livelihood related data. Improving the detail and accessibility in these reports, together with additional collaborative and coordinating efforts, could be a cost-efficient alternative of enhancing a data-driven research environment in Chad and other countries in the Sahel. Beyond coordinating the current data availability, the next step in data improvements require additional data collection, primarily in demographics and sub-regional agricultural output, to be complemented with data on agricultural practices. While comprehensive demographic and agricultural surveys are

expensive and complicated, several monitoring functions are already in place in Chad and other Sahelian countries to address these issues.

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, government 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 socio-economic changes generally are poorly understood.

7.4 Generalized evaluation framework of agricultural changes

Based on the evaluated methods and results as presented in the case of Chad, the following methodological framework for analysis of changes to crop production is proposed.

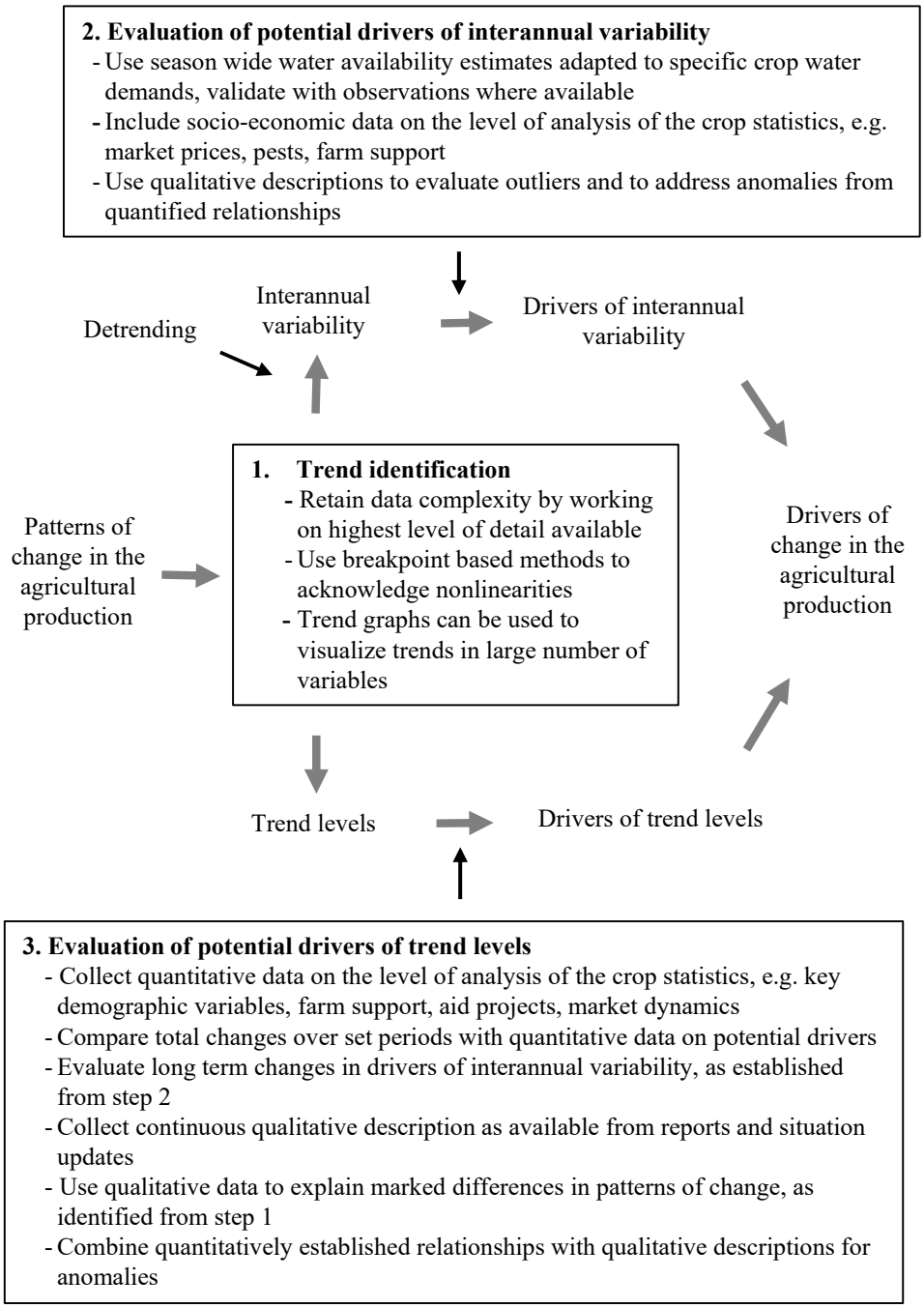

Fig. 34 *– Proposed evaluative framework for changes to crop production*

8 Conclusions

By combining diverse and extensive datasets with adapted research methods, a range of key advancements have been achieved in the study of patterns and drivers of change in the agricultural sector, primarily relevant for Chad but with considerable applicability to the wider Sahel. As a foundation to most of the analyses lies an improved understanding of the patterns of change, which in the case of Chad have been analysed with unprecedented detail. This in turn enabled a more precise evaluation of drivers of change to both the interannual variability and long term changes. By creating and compiling an extensive sets of data types, these drivers were evaluated to an extent and detail which had not been done in Chad prior to this thesis.

The results stress the importance of having detailed data on agricultural dynamics to capture sub-national diversities, but also the added analytical requirements that come with large and diverse datasets. The data collection process further showed that sub-national data relevant for the agricultural sector is collected in various forms, although often dispersed between sources and topics, and thus not readily accessible for research purposes. The agricultural and demographic statistics collected by the Chadian government and its partners, food security reports and situation updates by development organizations, as well as aid budgets and project evaluation documents, together give a broad coverage of changes to rural societies in Chad. As large parts of this information has not been compiled and addressed in combined evaluations, it is likely to hold substantial analytical potential as relevant for food security and rural development in general. This thesis has developed methods that can be applied to such ends, and pointed out the specific conclusions it enables. However, it has also showed the limits of the currently available datasets and research methods. The majority of the interannual variabilities in the crop production is left unexplained, and the drivers connected to long term changes are mostly presented in broad terms. Here, additional data efforts are needed to provide more detail. While awaiting this, continuing to compile already available and continuously updated datasets, increasing their accessibility, and improving the combined analytical methods required to capitalize on their full potential, is poised to provide notable improvements in the knowledge of agricultural dynamics, in Chad and elsewhere.

Finally, the main specific conclusions from this thesis are listed as follows:

- Crop production in the Lake Chad region **(Paper 1)**
    - Extensive crop records have been collected on a sub-regional level in the Lake Chad region by SODELAC, and are available in their annual reports from 1988. These crop records are now available online through the published version of **Paper 1.**
    - The crop statistics showed that on average the harvested area of maize increased by 18,000 ha after a dam construction in 1998.
    - Observed hydrological data on rainfall and lake level showed high and significant correlations to the interannual variability of maize and millet.
- Patterns of change in regional agricultural production **(Paper 2)**
    - Processes of agricultural extensification and intensification are prevalent in both the Sahelian and Soudanian zones of Chad.
    - The extensification and intensification rates are higher in the Sahelian than in the Soudanian zone.
    - A majority of the long term changes to both harvested area and yield in the region specific crops are attributed to abrupt, rather than gradual, processes of change. These patterns of change are largely clouded on larger scales of aggregation.
    - Extensification is progressing faster than the intensification in both zones, which fits general descriptions of the dynamics in the agricultural sector by earlier work.
    - 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.
- Drivers of interannual variability in regional agricultural production **(Paper 3)**
    - Addition of livelihood data to the commonly assessed water availability considerably improved the explanatory capacity to crop variability.

- The livelihood variables with the highest selection rates in the regression models were Market Prices and Food Security Classifications, which were already quantitative variables in the food security reports.
- The majority of the quantified livelihood variables from the food security reports did not hold any predictive capacity to the crop variability.
- Added detail in the detrending methods was able to further improve the explanatory capacities, where a breakpoint based detrending of both the mean and the variability showed large improvements over the more basic detrending methods.
- Despite applying a broad range of datasets and analytical combinations, the majority of the regional crop production variability is left unexplained, with only 21 of the 37 production variables having significant regression models established for the best performing determinant combination.
- The precipitation driven Yield Reduction Additive Adjusted determinant, based on FAO's crop water use methods, had the best overall performance, which outperformed determinants driven by a satellite measured topsoil moisture dataset, the ESA CCI SM v03.2.
- The explanatory capacity was similar for the time periods 1983-2016 and 2000-2016, indicating that there are no consistent changes to data quality in any direction
- For the couple of crop variables with high-performing regression results, qualitative livelihood information can act as a useful complement to evaluate causes of deviating production patterns.

- Drivers of long term change in regional agricultural production **(Paper 4)**
  - Increases in the agricultural population are connected to increases in the agricultural production.
  - Changes to soil water availability is largely decoupled from the long term trajectories in agricultural production.
  - The relationships established between aid and agricultural growth for the Sahelian and Soudanian zones show considerable agreement within each region, as well as similarities between the zones
  - Amount of total aid is a better predictor of agricultural growth than aid focused solely on the agricultural sector.

- Periods of marked deviations from the estimated aid effects were seen in some of the regions.
- Education oriented aid is associated with increased literacy in the Sahelian zone, which in turn is associated with improved yields. These associations are not seen in the Soudanian zone.
- Application of the livelihood information provided reliable explanations for 50% of the abrupt changes in the production series, albeit in broad terms.

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