Rainfall Variability and Agricultural Vulnerability in the Amhara Region, Ethiopia

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Abstract

Ethiopian agriculture is mostly rain fed, whereas inter-annual and seasonal rainfall variability is high and droughts are frequent in many parts of the country. Rainfall variability has historically been a major cause of food insecurity and famines in the country. Surprisingly, however, the relationships between rainfall variability and fluctuations in agricultural production at regional and sub-regional scales have not been studied in detail. The objective of this study is to analyze rainfall variability and trends, and examine vulnerability of food grain production to rainfall variability in the Amhara Region of Ethiopia. The data used for the study were historical rainfall records from 12 stations (for the 1975-2003 period) and available time series data on area coverage, production and yield of cereals during the meher season- main growing season (for the 1994-2003 period). The results reveal that there are significant intra-regional differences in rainfall amount, variability and trend; and the variability increases as rainfall amount decreases. Rainfall amount is higher and its variability lower in the western part of the region than in the eastern. Four drought years have occurred over the period 1975-2003, of which two were extreme in severity. Examination of trends in annual and seasonal rainfall generally shows absence of any systematic patterns of change across the region. Significant correlations were observed between the seasonal rainfall and crop production. Inter-annual and seasonal rainfall variability is therefore an important influence on food security of farming households; it also suggests that predicted climatic change will have significant impacts. Hence, water resources development including household level rainwater harvesting needs to be widely undertaken as it has a potential to serve as an adaptation strategy to current rainfall variability as well as to future changes in the climate.

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Introduction

Agriculture is the source of livelihood to the overwhelming majority of Ethiopia's population. It employs over 80% of the labour force and contributes ~45% to the national GDP, on average. The Ethiopian agriculture is characterized by extreme dependence on rainfall, low use of modern agricultural inputs and low output levels. For instance, the use of chemical fertilizers in 1999/2000 was only ~35 kg ha^{-1} on average (Tadesse 2002), irrigated land accounts for < 2% of the total cultivated land of the country and crop yields oscillate around 1.2 t ha^{-1} (Befekadu and Berhanu 2000). The amount and temporal distribution of rainfall is generally the single most important determinant of interannual fluctuations in national crop production levels (Mulat et al., 2004). According to von Braun (1991), for instance, a 10% decrease in seasonal rainfall from the long-term average generally translates into a 4.4% decrease in the country's food production. Adugna (2005) has shown that rainfall variability has significant impacts on crop yield (of *tef*, maize, wheat, barley and sorghum) in his study that covered the former provinces of Gojjam, Gondar, Harar and Jimma. Rainfall in much of the country is, on the other hand, often erratic and unreliable; and rainfall variability and associated droughts have historically been major causes of food shortages and famines (Wood, 1977; Pankhurst and Johnson, 1988). In addition to high inter-annual variability, some researchers report that rainfall has recently exhibited a downward trend in parts of the country (Yilma and Demarée,.1995; Mahdi and Sauerborn, 2002; FEWS, 2003), whereas others reported absence of any long-term trend in other parts (Conway, 2000; Conway et al.., 2004; Meze-Hausken, 2004; Yilma and Zanke, 2004; Yilma and Camberlin, 2006). Conflicting results about the existence of change in the Ethiopian rainfall suggest, among others, that local scale temporal and spatial variability of rainfall in Ethiopia is so far largely unknown and remains to be investigated (Woldeamlak and Conway, 2007). Given that the Ethiopian agriculture is almost entirely rain-fed, any trend in rainfall, possibly influenced by climate change, will have significant implications for food security.

Even though rainfall variability and drought are not new phenomena in Ethiopia, their frequency of occurrence has reportedly increased during the past a few decades (Ketema,1999). Yet, very few studies have considered in detail the relationships between crop yields and rainfall characteristics in the country. At the national scale the link between drought and crop production has been documented (e.g. von Braun, 1991), but the details of specific events at regional and sub-regional scales, however, remain contested with debate about the interactions and importance of confounding factors such as civil war, land tenure, poverty and long-term environmental change (Desalegn, 1991; de Waal, 1994). Indeed, statistical associations between rainfall and crop production at regional and sub-regional scales have not been studied in any detail.

The impact of rainfall on crop production can be related to its total seasonal amount or its intra-seasonal distribution. In the extreme case of droughts, with very low total seasonal amounts, crop production suffers the most. But more subtle intra-seasonal variations in rainfall distribution during crop growing periods, without a change in total seasonal amount, can also cause substantial reductions in yields. This means that the number of rainy days during the growing period is as important, if not more, as that of the seasonal total. Jackson (1989) notes that even in wet locations rainfall variability at the daily time scale is critical to plant growth, particularly in the early part of the rainy season before soil moisture reserves have been built up. Generally, the effect of rainfall variability on crop production varies with types of crops cultivated, types and properties of soils and climatic conditions of a given area.

The aim of this study is to analyze rainfall variability at annual and seasonal time scales and examine vulnerability of food grain production to rainfall variability in the Amhara Region of Ethiopia. The specific objectives are to: i) examine local scale rainfall variability and trend by using data from a relatively dense network of stations, and ii) assess the magnitude of relationships between rainfall and crop production in the region. The following section presents a brief description of the study area and the data sources and methods of analysis. This is followed by the results and discussions, and conclusions sections, respectively.

Materials and Methods

The Amhara National Regional State (ANRS): A Brief Description of Study Area

The ANRS is located in the north-western and north-central parts of Ethiopia (fig. 1). It has a total area of ~170,000 km^2, which is divided into 11 administrative zones (provinces) and 105 *Woredas* (districts). Rugged mountains, plateaux, valleys and gorges characterize its physical landscape. Elevations range from 700m in the eastern part to over 4,600m in the northwest. About 69% of the total area of the ANRS is highland (≥1,500m asl) and the remaining 31% is lowland (<1,500m asl). Around 50% of the total area of the region is considered to be arable land. Currently, 60% of the total area is used for cultivation and grazing (30% each), 17% is under forests, woodlands and shrub lands, 4% is covered by water bodies, 3% is occupied by settlements and 16% is wasteland (Lakew et al., 2000). Subsistence agriculture is the principal economic activity in the ANRS; it is characterised by a mixed farming system where crop production and livestock rearing are practised concurrently by farming households.

Crop production accounts for the lion's share of households incomes. Owing to the variegated agro ecological conditions prevailing in the region, different types of crops are produced: cereals, pulses, oil seeds, and horticultural crops. Cereals occupy the largest area under crops. CSA (2001) estimated that 81% of the total cultivated land, which is estimated at 4.2 to 4.3 million ha (BoRD, 2003), was under cereals in the 2000/01 cropping year. During the same year, the shares of pulses and oil seeds were 12.5% and 6.5% of the total area under crops, respectively. *Tef* and sorghum are predominant among the cereals, whilst faba bean, chickpea and field pea are the pulses extensively grown. There are two cropping seasons in the region- the *meher* season (by using the *kiremt* rains) and the *belg* season (by using the *belg* rains). The *meher* season is the main cropping season and it accounts for the overwhelming proportion of the total area cultivated and annual crop production. For instance, 91% of the total cultivated area was cropped during the *meher* season in 2000/01 cropping year (CSA 2001).

Land degradation and drought are the major physical challenges to agriculture in the ANRS. The rugged topography, expansion of cultivation into steep lands owing to increasing population pressure, intense grazing pressure, and torrential rains are the immediate causes of land degradation, the major process of which is soil erosion by water. According to Lakew et al. (2000), 10% of the total area of the ANRS suffers from annual soil loss rates of >200 t/ha, and 29% of the total area experiences soil loss of 51-200 t/ha per year. In the remaining area, annual soil loss rates are 16-50 t/ha (in 31% of total area) and <16 t/ha (in 30% of total area). Agricultural drought is the other major problem in the region. Out of the 105 *woredas*, 48 are drought-prone and food-deficit; crop production in these *woredas* on average meets only 62% of the requirements for food assuming a daily food requirement of 2,100 Kcal per capita (~225 kg of cereals per person per annum) (BoRD, 2003). The eastern parts of the region are particularly affected by recurrent droughts. According to USAID (2000:3), "there has been no single year since 1950 where there was no drought in this part of the region". This statement is however not based on analysis of climatological records; it probably refers to the persistent problem of food insecurity in the area. Droughts often translate into food shortages and famines in the- region because of the heavy dependence of agricultural production on natural rainfall. Irrigated agriculture is negligible in the ANRS, although 500,000 ha of land is considered to be suitable for irrigation (IWMI, 2004).

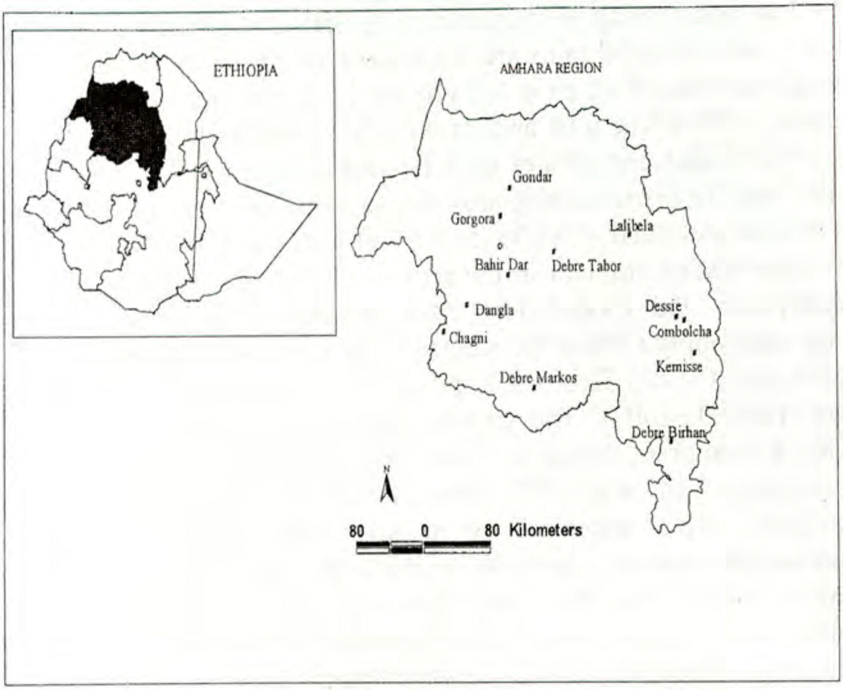


Figure 1. The ANRS and location of the 12 stations used in the study

Data Sources and Methods of Analysis

The data used for the study were historical rainfall records and time series data on area coverage, production and yield of cereals during the *meher* season. The rainfall data were collected from the Ethiopian National Meteorological Services Agency. Relatively long rainfall records were obtained for 12 stations, with a reasonably good geographic distribution to cover the region (fig. 1). Station records span from 1975 to 2003. The agricultural statistics, aggregated at the level of Administrative Zones, were collected from the Central Statistical Authority for the 1994-2003 decade. The study considered only the *meher* season because well over 90% of the total cultivated land of the region is cropped during this season.

Various methods of data analysis were employed in the study. Analysis of the rainfall data involved characterizing long-term mean values, and calculation of indices of variability and trends at monthly, seasonal and annual time steps. The coefficient of variation and the Precipitation Concentration Index (PCI) were used as statistical descriptors of rainfall variability. The PCI values were calculated as given by Oliver (1980):

$$\mathrm{PCI} = 100*[\Sigma P_i^2 / (\Sigma P_i)^2]$$

Where P_i is the rainfall amount of the i$^{\text{th}}$ month; and Σ = summation over the 12 months.

According to Oliver (1980), PCI values of less than 10 indicate uniform monthly distribution of rainfall, values between 11 and 20 indicate high concentration, and values of 21 and above indicate very high concentration.

The least squares regression technique was used to quantify trend in annual and seasonal rainfall and the Spearman's *rho* test was used to test statistical significance of trend. Standardized anomalies of rainfall were calculated and used to assess frequency and severity of droughts, as in Agnew and Chappel (1999):

$$S = [P_t - P_m] / \sigma$$

Where S = standardized rainfall anomaly,

P_t = annual rainfall in year t,

P_m = long-term mean annual rainfall over a given period of observation, and

σ = standard deviation of rainfall over the period of observation.

The drought severity classes are extreme drought ($S < -1.65$), severe drought ($-1.28 > S > -1.65$), moderate drought ($-0.84 > S > -1.28$), and no drought ($S > -0.84$). The class intervals correspond with the 95, 90, and 80 percentiles assuming that annual rainfall data are normally distributed.

The monthly rainfall series of all the stations were used to calculate an areal average rainfall for the region as follows (Nicholson, 1985):

$$R_j = I_j^{-1} \Sigma X_{ij}$$

Where R_j is areally integrated rainfall for year j; X_{ij} is rainfall at station i for year j and I_j is the number of stations available for year j. Variability and trend in the areal rainfall were also examined using the same methods.

Correlation and regression methods were used to examine relationships between monthly and seasonal rainfall and crop production. The patterns of inter-annual rainfall variability and fluctuations in cereal production are also presented graphically to gain a better insight into rainfall-crop production relationships in the region. Intra-regional variations in terms of types of cereals dominantly cultivated and yields were examined, and the relationships between zone-level cereal production and rainfalls at individual stations located within or nearby a given zone were assessed by using the correlation method. It is important to note here that consideration of production of cereals was considered to be more appropriate than yield in investigating the influence of rainfall variability, because the latter can miss out impacts of extreme climatic conditions involving severe droughts that might lead to abandonment of planted areas prior to harvest. In other words, total production aggregates, impacts of climate on both production and yields and harvested areas had greater economic relevance than yield. Further, amount and temporal distribution of rainfall also has influence on area cultivated in a given year.

Results and Discussion

Rainfall Variability and Trends

Seasonal Patterns of Rainfall

The annual total rainfall in the highlands of the ANRS varies from slightly over 770 mm in Lalibela to more than 1,660 mm in Chagni (Table 1). Only three stations (Debre-Birhan, Gorgora and Lalibela) experience annual rainfall amounts of less than 1,000 mm. Three stations (Chagni, Dangla and Debre Tabor) receive more than 1,500 mm of rainfall per year. Rainfall is unimodal in most of the region; and bimodal in the Wello highlands. Much of the rainfall is concentrated in the four months of the *kiremt* season. The rainfall shows moderate interannual variability as shown by the coefficients of variations (Table 1). Generally the *belg* (small rainy season, March-May) and the *bega* (dry season, October-February) rainfalls are much more variable than the *kiremt* (main rainy season, June-September) rainfall. A similar conclusion - that *belg* and *bega* rainfalls are more variable than *kiremt* rainfall- was arrived at by Engida (1999) in his study that analyzed rainfall data from 419 stations throughout the country. Engida (1999) also reported that rainfall variability is higher in areas of low annual rainfall.

Table 1. Annual and seasonal rainfall (mm), coefficient of variation the Precipitation Concentration Index (PCI), 1975-2003

Station	Annual		*Kiremt*		*Belg*		*Bega*		PCI (%)
	mean	CV	mean	CV	mean	CV	mean	CV	
Bahir Dar	1445	0.17	1214	0.18	115	0.68	121	0.55	22
Chagni	1665	0.12	1252	0.11	174	0.50	252	0.34	17
Combolcha	1045	0.17	669	0.23	230	0.40	143	0.53	18
Dangla	1542	0.14	1165	0.14	183	0.50	178	0.46	17

Debre Birhan	893	0.13	691	0.17	139	0.35	60	0.61	24
Dessie	1193	0.16	787	0.23	251	0.44	163	0.50	18
Debre Markos	1349	0.12	978	0.12	208	0.41	162	0.55	17
Debre Tabor	1580	0.18	1253	0.19	156	0.54	160	0.67	20
Gondar	1110	0.17	876	0.22	140	0.48	109	0.49	20
Gorgora	959	0.21	815	0.25	93	0.60	68	1.47	22
Kemissie	1063	0.23	675	0.27	219	0.56	150	0.63	20
Lalibela	772	0.22	594	0.29	136	0.58	53	0.97	27

The contribution of *kiremt* rainfall to the annual total ranges from 64% in Combolcha (in the eastern part of the ANRS) to nearly 85% in Gorgora (in the north-western part). *Belg* rainfall makes a considerable contribution to the annual total in the more easterly stations of Combolcha, Dessie, Kemissie and Lalibela. The extreme concentration of rainfall can also be seen from the contribution of the single largest monthly total to annual total rainfall at each of the stations. The highest monthly totals generally account for a very high proportion of the annual totals and range from 23% in Chagni to nearly 40% in Lalibela. The calculated PCI shows that rainfall in the ANRS is generally characterized by high to very high monthly concentration (PCI values ranged from 17% in Chagni, Dangla and Debre Markos to 27% in Lalibela).

Annual and Seasonal Rainfall Trend and Variability

For the period 1975-2003, annual rainfall shows negative trend in four out of the 12 stations and positive trend in eight of the stations (Table 2). The positive trends at Dessie (128 mm/decade) and at Lalibela (101 mm/decade) are statistically significant at less than 0.01 and 0.05 levels, respectively.

The positive trends in annual rainfall at Bahir Dar, Combolcha, Debre Birhan, Debre Markos and Kemissie are also high, though not statistically significant due to large inter-annual fluctuations. For the *kiremt* rainfall, increasing trends at Dessie and Lalibela are statistically significant. The other significant trends are the decreasing *kiremt* rainfall at Debre Tabor and the decreasing *belg* rainfall at Dangla (both to < 0.1 significance level).

Table 2. Annual and seasonal rainfall trend during 1975-2003

Station	Annual		*Kiremt*		*Belg*	
	Trend (mm/10yrs)	Spearman's *rho*	Trend (mm/10yrs)	Spearman's *rho*	Trend (mm/10yrs)	Spearman's *rho*
Bahir Dar	45	0.17	42	0.16	8	0.09
Chagni	-24	-0.17	-12	-0.12	-4	-0.12
Combolcha	51	0.26	60	0.27	-15	-0.16
Dangla	-22	-0.03	12	0.36	-19	-0.56*
Debre Birhan	62	0.20	73	0.23	-23	-0.16
Dessie	128	0.62***	107	0.48***	2	-0.04
Debre Markos	55	0.26	33	0.26	6	0.04
Debre Tabor	-103	-0.28	-101	-0.40*	25	0.23
Gondar	-36	-0.02	-29	-0.04	-19	-0.28

Gorgora	29	0.12	11	0.13	-10	-0.01
Kemissie	34	0.21	30	0.11	5	0.04
Lalibela	101	0.47**	104	0.45**	-19	0.09

*Significant at 0.1 level; **Significant at 0.05 level; ***Significant at 0.01 level

Areal Rainfall Indices for the Region

The annual average areal rainfall in the Amhara Region is 1194 mm, with a standard deviation of 124 mm and coefficient of variability of 10.4%. The anomalies in the annual and seasonal areal rainfalls are shown in Figure 2. The rainfall in the region is characterized by alternation of wet years and dry years in a periodic pattern. Of the 29 years of observation, 17 years (59%) recorded below the long-term average annual rainfall amount while 12 years recorded above average. Most of the negative anomalies have occurred during the 1980s (8 of 17). Between 1978 and 1992 the annual rainfall has been below the long-term mean, excepting the years of 1980 and 1988 when rainfall was slightly above the mean, and 1991 for which no records were available at many of the stations because of the political instability in the country in that year. The 1984 rainfall amount emerges as the lowest on record in the region, showing the worst drought year in the country's modern history. It was a culmination of droughts that started in 1978. Rainfall has shown some recovery since the 1990s, from the low values of the 1980s, but drier conditions have been experienced in 2002 and 2003. According to drought assessment method by Agnew and Chappel (1999), there have been four drought years during 1975-2003 in the Amhara Region, with varying severity. There were two extreme (1984 and 1987), one severe (1990) and one moderate (1992) drought years, which together represent 14% of the total number of observations. Once again, the year 1984 stands out as the worst year, with a standardized rainfall anomaly of -2.75. In contrast, 1996 was the wettest year in the region over the period of record followed by the year 2000.

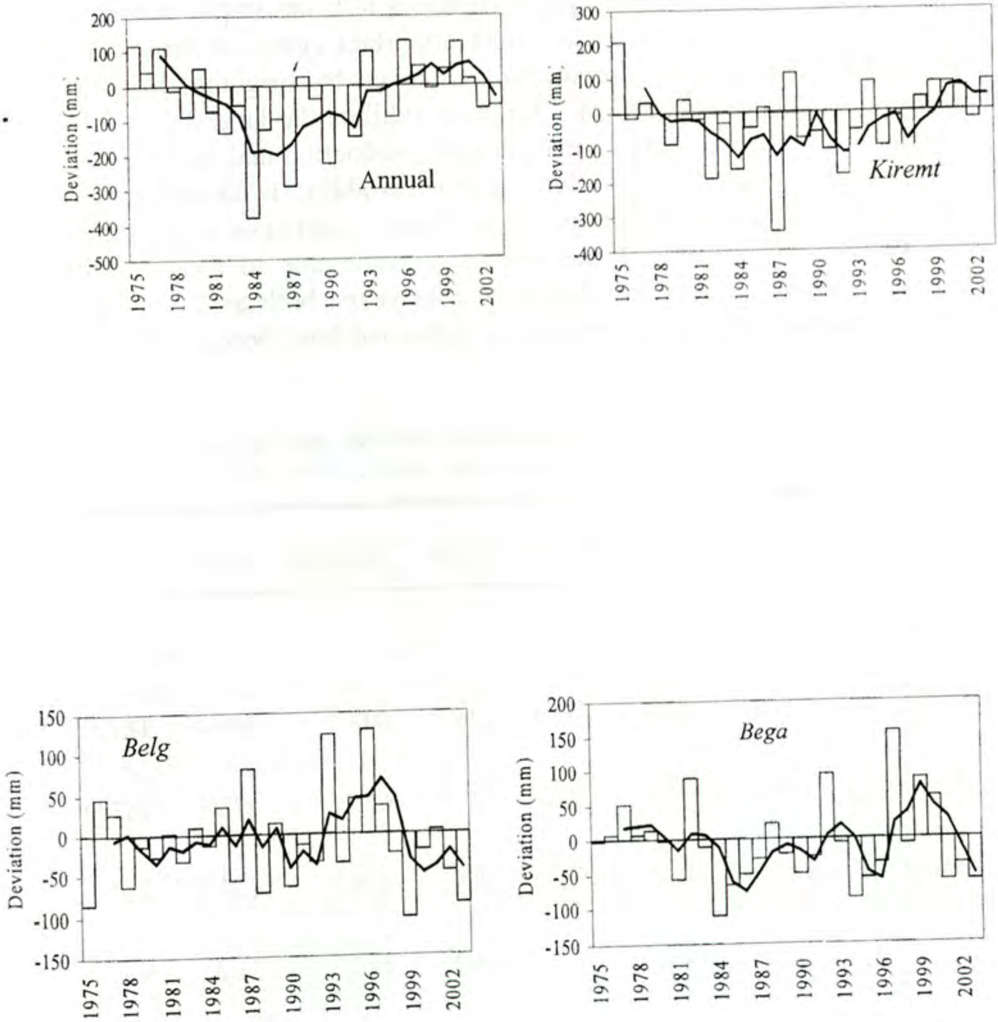


Figure 2. Deviations of annual and seasonal rainfalls from long-term averages (bold line- 3-yrs moving average)

Rainfall-Crop Production Relationships

Table 3 presents summary statistics on cereal production in the ANRS during the period 1994-2003. *Tef* (*Eragrostis tef*), the staple food crop in many parts of the region, is the most important cereal in terms of area cultivated as well as total production, followed by sorghum. In terms of yield, maize has the largest one. Sorghum exhibits the largest year-to-year variability in terms of area cultivated, total production and yield compared to the other cereals. This high inter-annual variability is caused mainly by inter-annual variability in rainfall. As sorghum is cultivated in semiarid and arid parts of the region, it is particularly vulnerable to the vagaries of weather. During agro-meteorologically drier years, both area planted (and thus production) and yield per unit of cultivated land become lower than average.

Table 3. Summary statistics on area cultivated (000 ha), production ('000 Qt) and yield (Qt ha^{-1}) of cereals in the ANRS, 1994-2003

	Tef	Barley	Wheat	Maize	Sorghum	Millet	Total
Area							
Minimum	744.4	220.7	185.8	226.5	303.4	136.4	1899.7
Maximum	949.3	357.2	332.6	377.8	626.2	273.8	2632.0
Mean	852.2	285.0	268.0	285.5	428.2	177.5	2296.4
CV (%)	7.5	14.2	17.7	16.2	22.2	21.8	9.3
Production							
Minimum	5190.0	1997.5	2071.9	3148.8	2533.0	898.6	18180.7
Maximum	7685.4	3671.1	4145.7	6488.8	8021.2	2180.2	27385.1

Mean	6795.3	2583.7	2896.3	4945.1	4946.1	1626.9	23793.4
CV (%)	12.9	21.2	23.7	23.4	31.7	20.4	15.4
Yield							
Minimum	6.9	7.4	8.9	13.9	6.9	6.6	-
Maximum	9.0	11.4	13.4	21.5	13.2	10.8	-
Mean	8.0	9.0	10.8	17.2	11.4	9.2	-
CV (%)	9.2	13.5	14.2	12.8	16.9	14.5	-

Results of correlation analysis between monthly, seasonal and annual areal average rainfalls and cereal production are shown in Table 4. *Tef*, barley and wheat production show considerably high correlations with the *kiremt* rainfall, while sorghum production shows a stronger correlation with the *belg* rains. Except for sorghum, correlations between cereal production and *belg* rainfall are low and some negative; mainly because of the significant inverse relationship between the *belg* and *kiremt* rainfalls ($r = -0.661$, $p = 0.038$). Annual rainfall is weakly correlated with production of cereals, and hence it is a poor predictor of yields as well as total outputs. The correlation between wheat production and *kiremt* rainfall is statistically significant (< 0.01 level of significance). At the monthly time scale, correlations between areal rainfalls during May to September and cereal production are all positive. May to September covers the period from preparation of fields and sowing to maturity stage of crops. The production of *tef* shows high correlations with August and September rainfalls. Barley and sorghum productions show stronger correlations with May and June rainfalls than with the others. For millet production, rainfall during May appears to be particularly important. The production of wheat shows high correlations with rainfalls in all of the five months.

Table 4. Correlations between production of cereals and areal monthly, seasonal and annual rainfalls in the ANRS

	Tef	Barley	Wheat	Maize	Sorghum	Millet
May	0.137	0.444	0.506*	0.309	0.492	0.503
June	0.189	0.421	0.414	0.188	0.503	0.176
July	0.199	0.049	0.612*	0.345	0.079	0.224
August	0.623*	0.273	0.564*	0.349	0.260	0.236
September	0.493	0.348	0.733**	0.149	0.212	0.127
Belg	-0.001	-0.24	-0.17	0.19	0.57	0.21
Kiremt	0.47	0.43	0.80***	0.23	0.10	-0.005
Annual	0.26	-0.35	-0.17	0.33	0.37	0.23

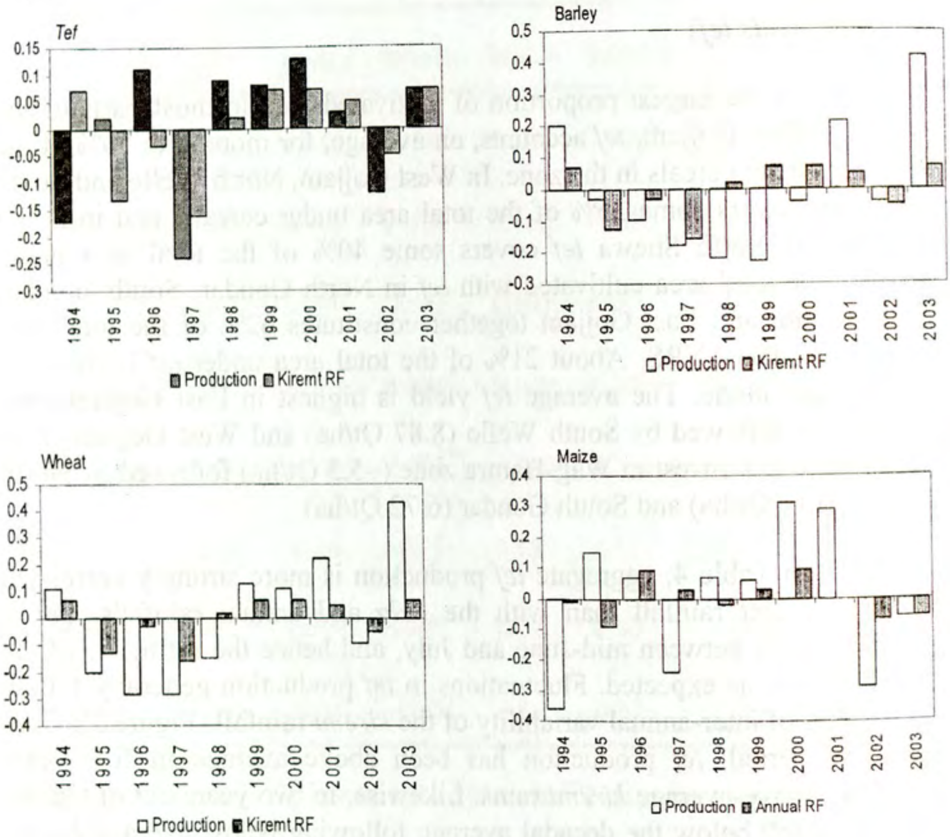
*Significant at the 0.1 level; **Significant at the 0.05 level, ***Significant at the 0.01 level

Even though correlation coefficients are positive, most are not significant in statistical terms. This is not unexpected given the short length of the production data used and the non-linear nature of relationships between crop production and rainfall amount. As noted above, temporal distribution of rainfall at sub-monthly time scales is also important in affecting yield of crops. Correlation coefficients between production and monthly and seasonal total rainfalls are, in other words, inadequate to capture the essence of impacts of rainfall variability on crop production. In recognition to this, the general patterns of inter-annual rainfall variability and fluctuations in cereal production are presented graphically (Figure 3) to gain a better insight into rainfall-production relationships in the region; and correlations between production of cereals at the Zone level and *kiremt* rainfall from stations within a given Zone or closely located are shown in Table 5. The following discussion is based on these information.

Tef (Eragrostis tef)

Tef occupies the largest proportion of cultivated area in most parts of the ANRS. In East Gojjam, *tef* accounts, on average, for more than 50% of the total area under cereals in the zone. In West Gojjam, North Wello and South Wello, *tef* covers some 35% of the total area under cereals; and in South Gondar and North Shewa *tef* covers some 40% of the total area under cereals. The total area cultivated with *tef* in North Gondar, South Gondar, West Gojjam and East Gojjam together constitutes 62% of the total area under *tef* in the ANRS. About 21% of the total area under *tef* is found in East Gojjam alone. The average *tef* yield is highest in East Gojjam zone (~10 Qt/ha) followed by South Wello (8.87 Qt/ha) and West Gojjam (8.00 Qt/ha); and it is lowest in Wag-Hamra zone (~5.5 Qt/ha) followed by North Gondar (6.11 Qt/ha) and South Gondar (6.72 Qt/ha).

As shown in Table 4, aggregate *tef* production is more strongly correlated with the *kiremt* rainfall than with the *belg* and annual rainfalls. *Tef* is generally sown between mid-June and July, and hence the influence of the *kiremt* rains is as expected. Fluctuations in *tef* production generally follow the patterns of inter-annual variability of the *kiremt* rainfall (Figure 3). Over the 10-yr period, *tef* production has been above average in five years following above-average *kiremt* rains. Likewise, in two years out of ten, *tef* production fell below the decadal average following below-average *kiremt* rains. In 1997, both *tef* production and *kiremt* rainfall were at their lowest levels for the decade 1994-2003. *Tef* production was substantially below the 10-yr mean in 1994 whilst the *kiremt* rainfall was above average. The primary reason for the very low *tef* production in 1994 was the very low yield level obtained in the same year (6.9 Qt/ ha), which is the lowest on record for the period 1994-2003. The latter is to be explained by several factors, one of which is likely to be intra-seasonal distribution of the *kiremt* rainfall during that specific year. In 1995 and 1996, *tef* production was above the 10-yr mean, while the *kiremt* rainfall was below its mean; and it is partly due to the above-average *belg* rainfall during those years which contributes to increased soil moisture availability. The highest *belg* rainfall was recorded in 1996 over the period 1994-2003.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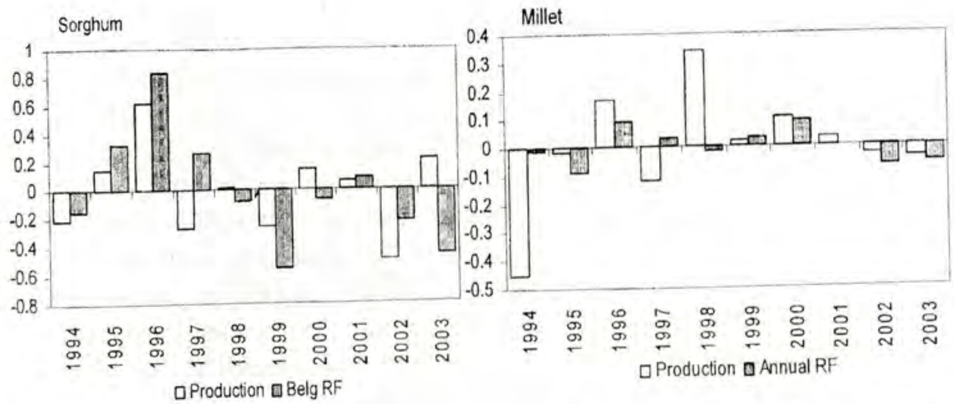

Figure 3. Standardized anomalies of production of cereals and seasonal and annual rainfall amounts in the ANRS (1994-2003)

The production of *tef* in the different zones shows considerable correlation with rainfall at some key stations that are located within a given zone or near it (Table 5). *Tef* production in South Gondar shows strong correlation with *kiremt* rainfall at Gondar, Gorgora and Bahir Dar, all of which are significant in statistical terms. In North Shewa, another major *tef* growing area, *tef* production shows strong correlations with *kiremt* rainfall at Debre Birhan and Kemissie, both of which are statistically significant at 0.01 level. Similarly, *tef* production in North Wello shows statistically significant correlations with *kiremt* rainfall at Bahir Dar and Gondar. Surprisingly, rainfall at Debre Markos is not a good indicator of moisture availability for *tef* production in the East Gojjam zone. In fact, *tef* production in East Gojjam shows a stronger correlation with *kiremt* rainfall at Debre Birhan.

Barley and Wheat

The major barley growing zones in the ANRS are Oromiya, North Wello, South Gondar and East Gojjam. Barley on average covers 62%, 19%, 18% and 13% of total areas cultivated with cereals in these zones, in order of sequence. The three zones of Oromiya, South Gondar and East Gojjam account for 48% of the total area under barley in the ANRS. Oromiya zone alone accounts for 21% of the total area under barley in the region. On average, yield of barley is highest in North Wello (~11 Qt/ha) and lowest in

Wag Hamra (7.7 Qt/ ha), where also *tef* yield is the lowest. In Oromiya zone, where a large segment of the cultivated area is devoted to barley, the average yield is 9.3 Qt/ ha. Barley production in North Wello shows statistically significant correlations with *kiremt* rainfall at Gondar and Lalibela. Correlations between barley production in South Gondar and *kiremt* rainfall at Gondar and Gorgora are also high, though non-significant statistically. Similarly, barley production in Oromiya zone shows a high, but statistically insignificant, correlation with *kiremt* rainfall at Debre Birhan. As is the case with *tef* production, barley production in East Gojjam shows a high, and statistically significant, correlation with rainfall at Debre Birhan, and no correlation with rainfall at Debre Markos.

Wheat occupies substantial parts of areas under cereals in five zones of the ANRS: North Shewa, Wag Hamra, South Wello, North Wello, East Gojjam and South Gondar. On average, area under wheat accounts for about 34% of the total area under cereals in Wag Hamra. In North Shewa and South Wello, wheat constitutes slightly over 20% of total area under cereals in the respective zones. About 18% of the total area under cereals in North Wello and East Gojjam each is cultivated with wheat. Three zones- East Gojjam, South Wello and North Shewa- contribute about 57% of the total area under wheat in the ANRS. Area under wheat in Oromiya zone is negligible. Yield of wheat ranges from a maximum of 12.7 Qt/ ha in East Gojjam to a minimum of ~8.0 Qt/ ha in Wag Hamra. It is above 11 Qt/ ha in West Gojjam, North Wello and South Wello, and slightly above 12 Qt/ ha in North Shewa.

Table 5. Correlation coefficients between *kiremt* rainfall and cereal production in the ANRS

	Tef	**Barley**	**Wheat**	**Maize**	**Sorghum**	**Millet**
N. Gondar						
Gondar	0.436	0.838***	0.432	0.609*	0.428	0.003
Gorgora	0.025	0.190	-0.202	0.122	0.048	-0.025
Bahir Dar	0.344	0.526	0.014	0.419	-0.043	-0.012
S. Gondar						
Gondar	0.693*	0.430	0.695*	0.416	-0.515	-0.165
Gorgora	0.645*	0.502	0.654*	0.841***	0.198	-0.232
Bahir Dar	0.775***	0.313	0.538	-0.047	0.720*	0.310
Debre Tabor	-0.254	0.285	0.200	0.494	0.575	-0.548
Awi						
Dangila	0.485	-0.244	0.110	0.325	NA	0.414
Bahir Dar	-0.255	-0.305	0.561	0.723**	NA	0.698**
Debre Markos	0.155	0.092	0.376	0.39	NA	0.136

W. Gojjam						
Bahir Dar	-0.159	0.365	0.733*	0.443	NA	0.593
Dangila	-0.504	-0.657**	-0.251	0.633*	NA	-0.081
Debre Tabor	0.656*	-0.089	-0.269	-0.232	NA	-0.620
E. Gojjam						
Debre Markos	-0.056	-0.085	0.009	-0.482	NA	0.434
Debre Birhan	0.572	0.676**	0.741**	0.286	NA	0.041
Debre Tabor	-0.422	-0.067	0.148	0.418	NA	-0.368
N. Wello						
Lalibela	0.165	0.752**	0.511	NA	0.313	NA
Bahir Dar	0.831**	0.314	-0.566	NA	0.519	NA
Gondar	0.644*	0.818***	-0.158	NA	0.867***	NA
Debre Tabor	-0.399	0.459	0.837***	NA	0.216	NA
S. Wello						
Dessie	0.291	-0.394	0.164	0.324	-0.191	NA
Combolcha	0.165	0.114	0.370	0.539	0.317	NA

Kemissie	0.309	-0.390	-0.074	0.671^{*}	0.223	NA
Wag-Hamra						
Lalibela	-0.140	0.605^{*}	0.699^{**}	0.353	0.281	NA
Dessie	0.377	0.557	0.447	0.414	0.469	NA
Debre Tabor	-0.461	0.456	0.642^{*}	-0.108	0.458	NA
Oromiya						
Combolcha	0.316	-0.21	NA	0.472	0.592	NA
Kemissie	0.582	-0.192	NA	0.874^{***}	0.546	NA
Debre Birhan	0.848^{**}	0.415	NA	0.674^{**}	0.512	NA
N. Shewa						
Debre Birhan	0.653^{**}	0.205	0.749^{**}	0.335	0.398	NA
Debre Markos	-0.337	0.349	0.564	-0.573	-0.259	NA
Kemissie	0.798^{**}	-0.255	0.004	0.910^{***}	0.086	NA

***Significant at 0.01 level; **Significant at 0.5 level; *Significant at 0.1 level.

NA: data were less than 7 yr long.

Note: Correlations between cereal production and *belg* rainfall are not presented because the *belg* and *kiremt* rainfalls in most stations showed statistically significant negative correlations with each other. For instance, correlation coefficient between *belg* and *kiremt* rainfalls at Bahir Dar for the period 1994-2003 was -0.85, p = 0.002.

Barley and wheat are sown in June, usually earlier than *tef*. Like that of *tef*, aggregate barely and wheat production show higher correlations with the *kiremt* rainfall. The production of barley was below the 10-yr mean in four years out of ten, as was the *kiremt* rainfall. In three of the ten years, both barley production and *kiremt* rainfall were above their respective decadal averages. Between 1998 and 2000, for three years, barley production has been below its 10-year mean while the *kiremt* rainfall has been slightly above its 10-yr mean. A partial explanation to this discrepancy can be related to the *belg* rainfall which was below its 10-yr mean during those three years. In fact, the lowest *belg* rainfall for the period 1994-2003 occurred in 1999. The production of wheat showed positive anomaly during five of the ten years, as did the *kiremt* rainfall. Similarly, negative anomalies in wheat production during four years were along with four years of negative anomalies in the *kiremt* rainfall. In 1996 and 1997, when wheat production fell by 28% from its 10-yr mean, area cultivated with wheat was also considerably below its 10-yr average. At the Zone level, in Wag Hamra, where wheat accounts for the largest area under crops, production of wheat is significantly correlated with rainfall at Lalibela and Debre Tabor (Table 5). Wheat production in North Shewa and rainfall at Debre Birhan are also significantly correlated, as are Debre Birhan rainfall and wheat production in East Gojjam. Correlation between wheat production in North Wello and rainfall at Debre Tabor is also statistically highly significant.

Maize and Sorghum

The important maize growing zones of the ANRS are West Gojjam, Awi, East Gojjam and South Gondar. In West Gojjam, maize accounts for 32% of the total area under cereals in the zone. In East Gojjam and South Gondar, maize covers about 12% of total areas under cereals in the respective zones; and in Awi 21% of total area under cereals is cultivated with maize. The two zones of West Gojjam and East Gojjam combined account for 51% of the total area under maize in the ANRS. Maize yield is highest in West Gojjam (20.7 Qt/ ha), closely followed by that of Awi (19.4 Qt/ ha), and lowest in Wag Hamra (8.7 Qt/ ha). In four zones out of ten, yield of maize is between 11 and 12 Qt/ ha. Maize production in West Gojjam and Awi zones and rainfall at Bahir Dar and Dangla show high correlations. The production of maize in South Gondar and North Gondar are significantly correlated with rainfall at Gondar and Gorogra, respectively. Correlations are weak between maize production in East Gojjam and rainfall at nearby stations.

Sorghum is mainly produced in North Gondar and the eastern part of the ANRS which includes North and South Wello, Wag Hamra, Oromiya and North Shewa. In North Gondar, roughly 36% of the total area under cereals is occupied by sorghum; and in North Shewa, sorghum accounts for slightly over 25% of the total area under cereals. In the other four zones (North Wello, South Wello, Wag Hamra and Oromiya) area under sorghum is 22 to 24% of total area under cereals in each zone. About 65% of the total area cultivated with sorghum in the ANRS is found only in three zones of North Gondar, North Shewa and South Wello. Area under sorghum is negligible in Awi and West Gojjam zones. Sorghum yield ranges from a maximum of 12.8 Qt/ha in South Wello to a minimum of 7.5 Qt/ha in South Gondar.

Maize appears to require a more even distribution of rainfall throughout the *belg* and *kiremt* seasons, as it can be seen from patterns of anomalies in maize production and the *belg* and *kiremt* rainfalls and from the high correlation between maize production and annual total rainfall. The production of maize recorded positive anomalies in six out of the ten years, four of which are accompanied by positive anomalies in the *kiremt* rainfall and two are accompanied by positive anomalies in the *belg* rainfall. Likewise, out of four negative maize production anomalies, two are accompanied by negative anomalies in the *kiremt* rainfall and two by negative anomalies in the *belg* rainfall. The production of maize was 36% and 29% below its 10-yr mean in 1994 and 2002, respectively. In 1994, both area under maize and yield of maize (13.9 Qt/ ha) were at their lowest levels on record for the period 1994-2003. The low maize production in 1994 and 2002 was apparently because of the below-average *belg* as well as *kiremt* rainfalls.

Sorghum production is particularly related to the *belg* rains. This is because of the fact that sorghum is sown in early May or even late April, which makes the *belg* rainfall critically important. Sorghum production reached its highest decadal mark in 1996; and this is the year with the highest amount of *belg* rainfall for the decade under study. In 1996, the area coverage of sorghum was at its highest and its yield the second highest. Thus, in 1996 favorable *belg* rainfall condition had allowed cropping of a larger area and improved sorghum yield per ha of cultivated land. At the zone level, correlation between sorghum production in South Gondar and rainfall at Bahir Dar is statistically significant, as is sorghum production in North Wello and rainfall at Gondar. Although most of the correlation coefficients between zonal sorghum production and rainfall are considerably high, only few are significant statistically. This is not unexpected given the fact that sorghum production is more strongly correlated with *belg* rainfall than the *kiremt* rainfall, as noted elsewhere above.

In general, for the production of both sorghum and maize, which are long-cycle crops sown early from the *kiremt* rains, the significance of *belg* rainfall is quite obvious. By the beginning of the *belg* season, which follows the long dry season of *bega* (October to February), soil moisture is virtually nil. Hence, occurrence of adequate rainfall in the early periods of the season (*belg* season) is important for maize and sorghum production. During the *kiremt* season, not only that rainfall occurrence is likely to become more common, but also that soil moisture reserves will be sufficient to support plant growth during any dry spells. Sorghum in particular has a good tolerance for water stress caused by dry spell occurrences. Similarly, sorghum tolerates end-of-season dry spells (rainfall shortage in September) than maize, so it is more sensitive to rainfall in *belg*, while maize is more sensitive to dry spells throughout its growing period beginning in *belg* and until the end of *kiremt*.

Millet

Nearly the entire production of millet in the ANRS comes only from four zones: Awi, West Gojjam, South Gondar and North Gondar. These four zones together account for 98% of the total area under millet in the region; and the first two zones alone (Awi and West Gojjam) constitute 53.2% of the total area under millet in the region. Millet accounts for 24% and 18% of total areas under cereals in Awi and West Gojjam, respectively. Average yield of millet is between 8.5 and 10 Qt/ha. Anomalies in millet production show influences from the *belg* and annual total rainfalls, with a slightly higher correlation with anomalies in annual total rainfall. Over the 10-yr period, millet production recorded positive anomalies in five cases, of which two are accompanied by positive anomalies in annual rainfall, two by positive anomalies in *belg* rainfall and one by positive anomalies in both *belg* and *annual* rainfalls. Negative anomalies in both *belg* and annual rainfalls in 2002 and 2003 contributed to negative anomalies in millet production. In 1994, millet production was 45% below the 10-yr average; and both area under millet and millet yield were at their lowest for the decade 1994-2003. During the same year, *belg* rainfall was 15% below its 10-yr mean. Millet, production in Awi and West Gojjam shows high correlations with *kiremt* rainfall at Bahir Dar.

Production of each cereal crop has shown negative anomaly in 1997 and 2002. This was due to high negative anomalies in seasonal rainfalls. The *kiremt* rainfall in 1997 was at its lowest for the period 1994-2003 (16% below the 10-yr mean). In consequence, total cereal production reached its lowest record for the decade (24% below its 10-yr mean) in the same year (1997). In 2002, both *kiremt* and *belg* rainfalls were below their respective decadal averages; and correspondingly total cereal production in the same year was 21% below its 10-yr average. In addition to these two years (1997 and 2002), the production of *tef*, maize, sorghum and millet recorded negative anomalies in 1994 as well, which contributed to the below-average total cereal production in the region (16% below the 10-yr mean). The number of relief food assisted population in the region was around 2.02 million, 3.12 million and 1.20 million in 1997-98, 2002-03 and 1994-95, respectively (Woldeamlak, 2006).

Regression analysis with production data of cereals as dependent variables and area cultivated, and *belg* and *kiremt* rainfalls as independent variables clearly reveals the significance of fluctuations in cropped areas and rainfall variability as the major determinants of food production in the ANRS. Table 6 shows regression equations derived for each cereal crop and total cereal production in the region. The multiple correlation coefficients are generally high for all crops, and the multiple coefficients of determination are 0.69 for *tef*, barley and millet, 0.78 for maize, 0.79 for wheat and 0.86 for sorghum. In other words, fluctuations in areas cropped and inter-annual variability of the *belg* and *kiremt* rainfalls explained 69% of the variance in production of *tef*, barley and millet, 78% of the variance in maize production, 79% in wheat production and 86% in sorghum production. For production of cereals altogether, variability in area cultivated and inter-annual seasonal rainfall variability explained 75% of the total variance.

Table 6. Multiple linear regression equations relating cereal production to area cultivated and seasonal rainfall amounts in the ANRS

	Equation	R	R^2
Tef	$-5518.4 + 8.8a + 3.2b + 4.6k$	0.83	0.69*
Barley	$-2634.7 + 12.1a + 3.0b + 1.4k$	0.83	0.69*
Wheat	$-1874.3 + 5.5a + 0.7b + 3.9k$	0.89	0.79*
Maize	$-1208.8 + 21.9a + 0.7b + 0.2k$	0.88	0.78*
Sorghum	$-7358.4 + 11.8a + 7.7b + 6.4k$	0.93	0.86**
Millet	$-189.8 + 6.8a + 1.6b + 0.4k$	0.83	0.69*
Cereals	$-22135.3 + 10.8a + 20.7b + 18.9k$	0.86	0.75*

Note: Y = total cereal yield; a = total area under the cereals; b = *belg* rainfall; and k = *kiremt* rainfall. Areas are in '000 ha and rainfall in mm

*Significant at 0.05 level; **Significant at 0.01 level

Conclusions

This study has presented analyses of recent rainfall behavior and relationships between rainfall variability and fluctuations in crop production in the drought-prone ANRS of Ethiopia. Historical rainfall records from 12 stations and time series data on area coverage, production and yield of cereals during the *meher* season were used as inputs. The findings of the study show that there are significant intra-regional differences in rainfall amount, variability and trend. Annual rainfall varies from about 770 mm in the eastern part (Lalibela) to more than 1660 mm in the western part (Chagni) of the region. Rainfall amount is higher and its variability lower in the western part of the region than in the eastern. Recovery of rainfall during the 1990s from the low values of the 1980s obscures decadal scale trends in annual and seasonal rainfall at some stations. Many stations show drier conditions in 2002 and 2003. Examination of trends in annual and seasonal rainfall generally shows absence of any systematic patterns of change across the region. The observed trends in some of the indices are thus mainly dependent on local scale climatic controls, rather than large scale climatic forcing.

Inter-annual and seasonal variability of rainfall is a major cause of fluctuations in production of cereals in the region. Over the 1994-2003 decade, for which crop production data are available, the patterns of inter-annual variability in productions of the six major cereals (*tef*, barley, wheat, maize, sorghum and millet) cultivated in the region show similar patterns of inter-annual variability in the seasonal or annual rainfall amounts. Productions of *tef*, barley and wheat show stronger correlations with the *kiremt* rainfall while sorghum production is more strongly correlated with *belg* rainfall. Maize appears to require a more even distribution of rainfall throughout the *belg* and *kiremt* seasons. Sorghum shows the largest year-to-year variability as it is cultivated in the semi-arid parts of the region where rainfall variability is high. Productions of the cereals also showed statistically significant correlations with each other, suggesting that rainfall is the common yield-limiting factor as use of chemical fertilizers and other agricultural inputs is limited. These findings are generally consistent with results of a recent study by Adugna (2005) that reported existence of a high correlation between rainfall and crop yield in the four former provinces of the country covered by his study. The fact that there are high correlations between cereal production and rainfall in the region suggest that farmers are vulnerable to food-insecurity related to rainfall variability. Thus there is a need for water resources development including household level rainwater harvesting for crop production. According to Woldeamlak (2006), household level rainwater harvesting, with appropriate management and utilization, has a potential to serve as an adaptation strategy to current rainfall variability and supplement rain fed crop production by enabling production of high market value crops such as vegetables and fruits, with implications for adaptation to future climate change as well.

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