The Effect of Climate and Aerosol on Crop Production: A Case Study of Central Asia

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SUMMARY

The effect of recent climate change in Central Asia poses a significant and potentially serious challenge to the region's agricultural sector. An investigation of the aerosol-climate- crop yield correlation in this region is essential for a better understanding of the effect of aerosols and climate on Central Asian agriculture. Our goal is to investigate the linkages between aerosol, climate and major crop production (cotton, maize, wheat, and rice) in specified agricultural regions in the five Central Asian countries. Our approach is to perform the Pearson's Correlation Coefficient analysis in order to observe the statistical correlation between crop yield, temperature, precipitation, and aerosol optical depth (AOD), for each indicated agricultural region in the selected countries. Besides, using NASA GIOVANNI website tools, we retrieve distribution maps and time series of temperature, precipitation and AOD to facilitate the analyses. The research shows that in some aspects, the relation between AOD, climate, and crop yield is different in Central Asia than in previous global or large scale research hypotheses. The statistical correlations vary not only across countries but also across agricultural regions. For example, in Kazakhstan, opposite correlations exist between precipitation and AOD in two different agricultural regions even though both regions are rain-fed. In the more arid countries (with lower rain rates) such as Turkmenistan and Uzbekistan, no correlation exists between crop production and temperature, precipitation, and AOD, while the less arid (with higher rain rate) countries (Kazakhstan, Kyrgyzstan, and Tajikistan) indicate a positive correlation.

INTRODUCTION

Global warming has had a greater impact in Central Asia (CAS) than in many other areas of the world, not only because of the region's constantly increasing global temperatures during the 20th and 21st centuries, but also because of its continual desertification. One of the most catastrophic results of desertification over the last century has been severe drought, and the anthropogenic impact of land-cover and land-use changes (LCLUC) on desertification in the region remains a complex issue. Recently, the understanding of the global climate change effect in CAS has been increasing. The IPCC (2007) report provides an extended discussion on expected sequences of global climate change for this vast arid region, and several more recent publications discuss these issues in more detail [*Conrad et al.*, 2011; *Gintzburger et al.*, 2005; *Lerman and Sedik*, 2009; *Tubiello and Fischer*, 2007]. Nevertheless, more research into this area is needed to address important questions that remain regarding the future impact of climate and environmental changes in CAS [*Lioubimtseva and Cole*, 2006]. Some researchers argue that the temperature trends in this region are less a consequence of global climate temperature trends, and more a consequence of intensive human-induced regional environmental changes, such as extensive irrigation, overgrazing, and desertification processes. In fact, LCLUC have increased dramatically in intensely populated areas of the region [*Gintzburger et al.*, 2005; *Lioubimtseva and Cole*, 2006].

Recently, scientists have focused on aerosol-cloud interaction and its effect on climate change [*Andreae*, 2009; *Andreae and Rosenfeld*, 2008; *Arimoto et al.*, 2006;

Darmenova et al., 2005; *Field et al.*, 2010; *Hansen et al.*, 1997; *Indoitu et al.*, 2009;z*Orlovsky et al.*, 2005; *Shao and Dong*, 2006; *Sokolik and Toon*, 1996; *Washington et al.*, 2003]. However, an understanding of the effect of aerosols on the Earth's climate system still remains an unknown quantity in the climate debates. Even in the most recent climate report [*IPCC*, 2007], the aerosol effect is the least understood cause of climate change, but clear and rapidly growing evidence now exists indicating that atmospheric aerosols may have significant impact on the thermodynamic and radiative energy balance of the Earth's atmosphere [*Andreae and Rosenfeld*, 2008].

Aerosols affect Earth's radiation balance directly or indirectly by modifying clouds. They also have a semi-direct effect that creates a warming influence in the atmosphere because low clouds have a high albedo but do not reduce outgoing long wave radiation [*Hansen et al.*, 1997].

Direct effect: Aerosols can affect incoming solar radiation through the absorbing and scattering process. By scattering the incoming radiation, aerosol has a net cooling effect on the Earth's climate system, but it also has a warming effect in an aerosol layer of atmosphere above the Earth's surface by absorbing incoming solar radiation.. Both of these processes could reduce the radiation needed for biological processes from reaching the Earth's surface.

Anthropogenic dust also requires special consideration in climate change research because human activities such as LCLUC and construction can increase the dust source in a geographic area, such as the Aral Sea region. A dust event has been defined as "when two or more stations located in a particular source region report visibility less or equal than 5 km" [*Darmenova et al.*, 2005]. The source of dust is not always a naturally occurring factor, such as deserts, but may also include anthropogenic components. Research by Sokolik and Toon (1996) estimates the anthropogenic fraction of dust to be about 30% to 50% of the total dust in the atmosphere, but the range of uncertainty regarding this component remains large [*Sokolik and Toon*, 1996].

Indirect effect: The basis of aerosol's indirect effect, known as the Twomey effect. [*Twomey*, 1974], showed that increased aerosol particle number concentration leads to increased cloud droplet number concentration, which causes an increase in cloud top albedo. The Twomey effect serves as cloud condensation nuclei (CCN) and ice nuclei (IN), which affect the lifetime, microphysics, and the formation of precipitation in clouds [*IAPSAG*, 2007]. The indirect effect of aerosols, therefore, is the potential changes in cloud properties on a global scale due to anthropogenic perturbations of the concentration and physical and chemical properties of the particles that form cloud droplets or ice crystals. Aerosol particles can act as CCN depending on their chemical composition and size distribution [*Kumar et al.*, 2011]. No single-pattern global aerosol exists; instead, different regions have unique sources and spatial and temporal patterns, and each region has specific microphysical and chemical characteristics. Particle composition and size play a key role in the radiative effects of aerosols and their effect on clouds.[*Heintzenberg et al.*, 2003].

Semi-direct effect: Another impact, called the semi-direct effect of aerosol, arises from the direct absorption of radiant energy by aerosols, which causes change in the temperature of the troposphere and the Earth's surface. This change has a cooling effect on the surface, which can alter the humidity, which in turn affects clouds and precipitation. Therefore, aerosols can affect the radiation budget of the Earth by changing precipitation and temperature, and impacting the general climate of a region.

In dry areas, especially where high aerosol concentration exists, more energy is released and therefore precipitation increases more rapidly. Further, an increase in the aerosol load, when a surplus exists, can interrupt normal cloud formation processes. In areas with high atmospheric aerosol content, therefore, the continuation or deterioration of those conditions can lead to lower than normal rainfall or even drought [*Rosenfeld et al.*, 2008]. Moreover, Field et al. (2010) suggest that important feedback occurs between aeolian dust flux and vegetation in the desert areas [*Field et al.*, 2010]. Their hypothesis points out that aeolian dust flux plays an important role in the redistribution of sediments and the loss of soil, which affects the amount and distribution of vegetation on the land. The amount and distribution of vegetation affects the degree and spatial pattern of dust on the land surface. Thus, a question arises as to "what roles does the regional dust transportation play on the climate and biochemical fields?" Field et al. (2010) rely on previous studies to approach this issue in two different ways. First, dust can have a significant effect on the atmospheric radiative balance and the concentration of condensation nuclei, which can affect climate variability by changing temperature and precipitation patterns [*Yoshioka et al.*, 2007]. Moreover, a recent study that investigated the effect of extreme heat on wheat senescence in India showed that potential wheat yield losses for warming in northern India have been underestimated, given that the heat shortens the growing season, a key mechanism for yield loss. [*Lobell et al.*, 2012]. Second, in addition to the climate effect, dust can be a substantial source of changes in nutrients. For example, the transport of Saharan dust to the Amazon basin has played a significant role in offset the existing nutrients ([*Koren et al.*, 2006]). These studies, however, are regional in nature and focus on the impact of dust radiative forcing only at Sahel precipitation and the dust transportation from Sahara to Amazon basin, respectively.

It is well known that in CAS, specifically in the vicinity of the Aral Sea, lies the best known anthropogenic mineral dust source area in the world due to extensive irrigation [*Prospero et al.*, 2002]. Temperature in CAS increased on average of about 3^{o}C during the 20th century [*Lioubimtseva and Cole*, 2006], and it will increase about 3.7 degrees by the end of the 21st century [*IPCC*, 2007]. This increase is potentially catastrophic for the 63 million people residing in this arid region.

Preliminary analysis suggests that the drought is related to large-scale variations in the climate across the Indian and Pacific Oceans, including the recent La Niña in the eastern Pacific. A study by Lotsch et al.(2005) integrated the correlation of ocean circulation and vegetation anomalies [*Lotsch et al.*, 2005]. Their research shows that below-normal precipitation in the Northern Hemisphere coincided with limited moisture availability for plant growth during the period from 1999-2002.

Spatiotemporal dynamics of normalized difference vegetation index (NDVI), precipitation, and sea surface temperature data show that synchronous patterns of ocean circulation anomalies in the Pacific, Atlantic, and Indo-Pacific have an explicit correlation with observed joint variability in NDVI and precipitation in the Northern Hemisphere during this period. To test the reduced plant growth, they examined a spatiotemporal correlation between the 1981– 2002 NDVI time series retrieved from National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR) data and global precipitation, and the link between principal modes of precipitation variability with SSTs.

Prior modeling studies showed that a prolonged phase of cold eastern Pacific sea surface temperatures SSTs (La Niña) and warming in the Indo-Pacific from 1998 – 2002 was a key mechanism that caused general Northern Hemispheric drought. In their empirical analysis, Lotsch et al. (2005) found that ocean-atmosphere dynamics outside of the tropical Pacific also contributed to observed NDVI anomalies and need to be further considered to precisely explain the drought patterns [*Lotsch et al.*, 2005]. They reported empirical evidence of joint variability in the ocean-atmosphere-biosphere system during the period of observation. Plant growth affected by precipitation deficits during 1998-2002 was associated with warmer temperatures in semi-arid ecosystems. Warmer temperatures associated with precipitation deficits have negative consequences for plant growth, especially in semi-arid ecosystems such as those affected by the 1998– 2002 drought.

Some studies suggest that aerosols have a strong effect on regional climate via the biological pathways, especially on CO_2 fluxes. Aerosols can increase CO_2 fluxes over forests and croplands and decrease over grassland; hence, C_4 vegetations show the largest sensitivity and C_3 crops show the least influence on CO_2 fluxes [*Monfreda et al.*, 2008; *Niyogi et al.*, 2004]. The greater water use efficiency of C4 plants gives them an advantage over C3 plants in hot, dry conditions [*Monfreda et al.*, 2008].

The hypothesis of Lobell et al. (2011) that linkage between yields of the four largest commodity crops (maize, rice, soy beans, and wheat) to weather indicates that global maize and wheat production declined by 3.8 and 5.5%, respectively, relative to a counterfactual without climate trends [*Lobell et al.*, 2011]. However, their modeling study considered only the effect of temperature on a large scale region. Although, they refer to a precipitation effect, they reported no significant finding regarding this effect. In fact, they assimilated climate and growing season from nearby countries (i.e., Pakistan), which may have skewed the results. Thus, we believe that a study of specific regional AOD, T, P and crop yield (CrY) correlation is essential for an understanding of the impact of these factors.

Our goal is to investigate the statistical correlations in order to better understand the climate and aerosol impact on major crop production in specified regions of CAS. To better understand the phenomenon, we raise the questions: How has increased temperature affected crop production yield in Central Asia during the last decade (2000-2010)? What is the correlation of crop yield with AOD and climate in the five countries of CAS? Does the effect of precipitation in agricultural areas vary from one region to another or does it have an equal effect on all four major crops in all the countries of CAS? Does the correlation differ between temperatures, precipitation, AOD, and crop yield in the countries that have more rain-fed (RF) and less irrigation-fed (IF) agricultural regions of CAS?

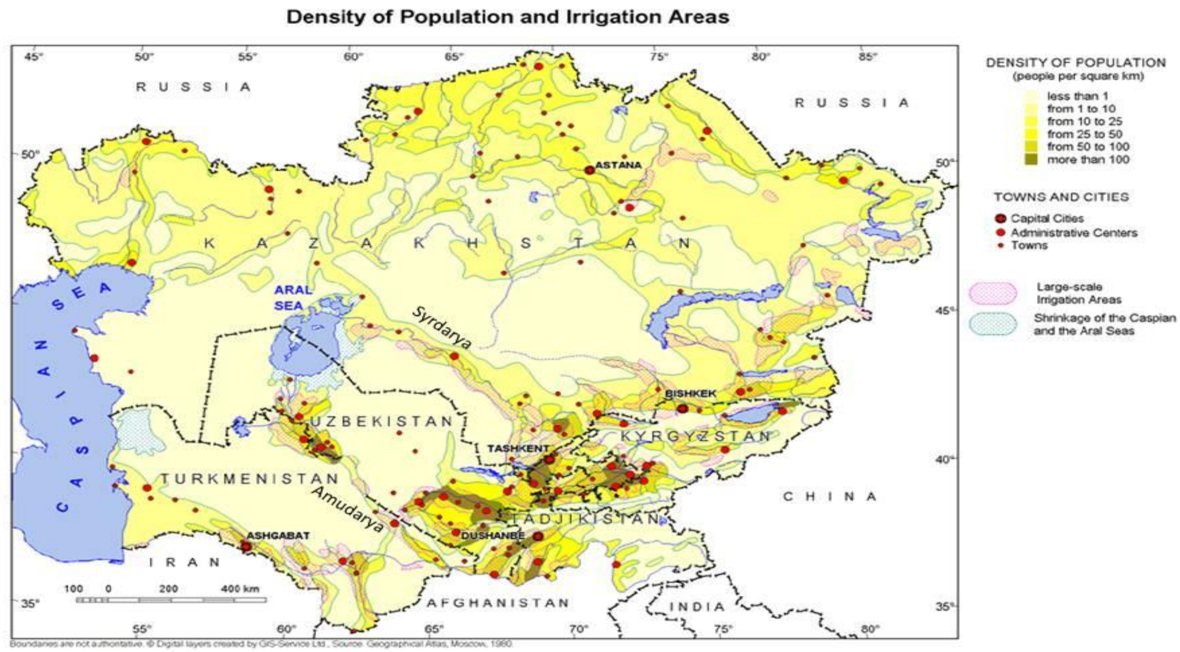
Our approach is to perform the Pearson's Correlation Coefficient analysis, to observe the empirical linkages between crop yield (CrY)-AOD, T-CrY, P-CrY, and T-AOD, P-AOD for each specified agricultural regions in CAS. We used the NASA GIOVANNI website tools, as well as retrieved T, P and AOD time series to strengthen our analysis. We focus particularly on four major crop (maize, rice, wheat, and cotton) yield changes in the five Central Asian countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan) during the last decade (2000-2010)

METHOD

Our goal is to better understand the impact of recent climate change on regional agriculture in CAS, with particular consideration of the effect of aerosol. Investigation of the correlation between AOD, T, P and CrY for specified regions, therefore, is critical for an understanding of the impact of these factors in CAS. In order to observe the correlation between AOD, T, P and CrY, we employed the Pearson Correlation Coefficient (bivariate) on the SPSS statistical analysis. We also used climate, AOD, and crop production time series and online analysis tools to strengthen our analysis.

A Brief Overview of Study Region

The five central Asian countries formed in December 1991 after the break-up of the former USSR -- Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan, -- cover an area of about 3.5 million km^2 with a combined population of more than 63 million people [*PRB*, 2011]. Most of the population is concentrated around the two biggest water sources, the Amudarya and Syrderya Rivers (Figure 1). More than 95% of Turkmenistan and more than one half of Uzbekistan and Kazakhstan are covered by deserts. Additionally, the entire Turan Low-land and the southern border of the Kazakh Hills, which is bounded by the Middle Asian Mountains (up to 7450 m) on the southeast, consists of arid lands. In the southwest, the lower mountains of the Kopet Dagh (2000 m) allow monsoon precipitation to reach the western slopes of the Tian Shan and Pamiro-Altai mountain ranges. In the north, the Turanian plain descends northward and westward, expanding towards the Caspian Sea. The deserts and semi-deserts of CAS have a typical continental climate and can be divided into two climate sub-regions, the Northern (primarily Kazakhstan) and the Southern (Iran-Turanian) [*Lioubimtseva and Cole*, 2006].



http://www.envsec.org/centasia/proj/ferghana/img/kyr/density_eng.gif

Figure 1: Density of population and irrigation areas of CAS. A total of 63 million people live in about a 3.5 million km2 area. Most of the population settled around the two biggest water sources, the Amudarya and Syrderya Rivers.

Data and Method

We determined the most rain-fed and irrigated agricultural areas in the region from reference maps (Kariyeva & van Leeuwen, 2011). Since each country has different growing seasons for each particular crop, the growing period for each crop had to be determined for all countries. Because some biases existed in the research [*Conrad et al.*, 2011; *de Beurs and Henebry*, 2004; *Ehammer et al.*, 2010; *Kariyeva et al.*, 2011; *Monfreda et al.*, 2008; *Neumann et al.*, 2010; *Ramankutty et al.*, 2008; *Sacks et al.*, 2010; *Tondel*, 2011], we relied primarily on the reference crop calendar utilized by the United States Department of Agriculture [*http://www.pecad.fas.usda.gov/*, 2010] (http://www.fas.usda.gov/pecad/weather/Crop_calendar/crop_cal.pdf). Thus, we created a crop calendar from models, which were initialized by average start of season data derived from national crop reports [*http://www.pecad.fas.usda.gov/*, 2010], with adjustments for particular crop calendars for certain regions [*Conrad et al.*, 2011; *de Beurs and Henebry*, 2004]. Crop growing seasons run from planting dates to harvesting dates. Because some crops are planted in the middle of the month and because climate and AOD data generally are available only on a monthly basis, adjustments to the growing seasons were necessary in order to create appropriate time series. Accordingly, we considered the whole month as a growing season even where the season did not start at the beginning of the month.

Our maps were formed by overlapping layers using Google Earth, Photoshop and other similar programs. The first layer consists [*Kariyeva et al.*, 2011] of a map of the study area, showing the three regional landscape vegetation responses assessed through modeling of their pheno-metrics, i. e., steppe, mountainous, and desert regional landscape, and designated on the map by different colors (Figure 2). This map also shows the location of the rain-fed and irrigated agricultural regions (ARs) considered in our analysis. The second layer reflects $1^{o}x1^{o}$ resolution gridded-cells of CAS. We then applied the political boundaries of the CAS countries. Finally, we overplayed maps of the four major crop regions (maize, rice, wheat, and cotton) of CAS (Figure 3). (Higher resolution copies of these maps are shown in Appendices A, B, C, and D.) The majority of the crop maps were obtained from one source [*Aldaya et al.*, 2010],but where particular information was not available, we used additional maps from appropriate sources [*http://www.pecad.fas.usda.gov/*, 2010; *Monfreda et al.*, 2008; *Muminjanov*, 2008; *Sacks et al.*, 2010],

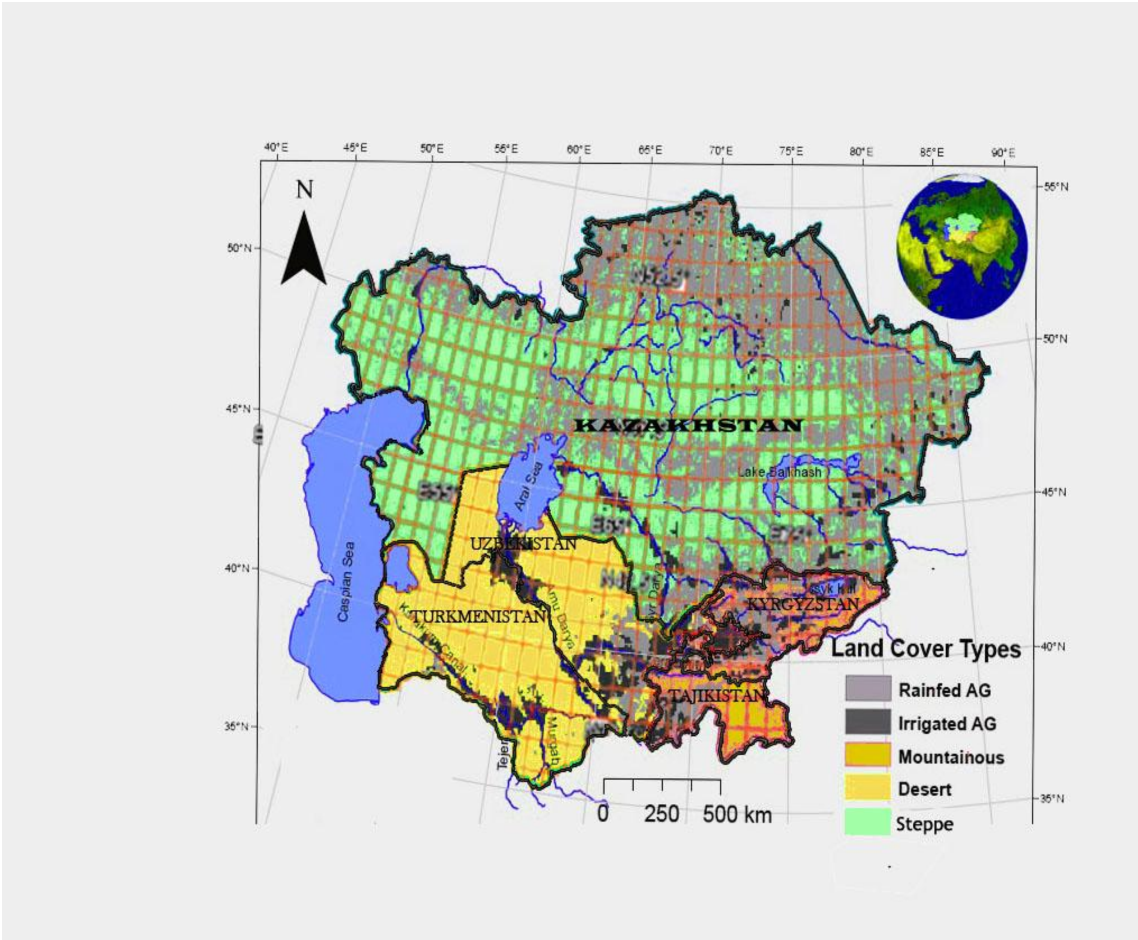


Figure 2: Main map of Agricultural area [Kariyeva et al., 2011]. Map of study area showing areas of the three regional landscape vegetation responses evaluated through modeling of their pheno-metrics: steppe (green); mountainous (orange); and desert regional landscapes (yellow). The map also shows the location of the rain-fed and irrigated agricultural areas in grey and black colors, respectively.

we used the superimposition of each crop region and agricultural area as our study areas, dividing the crop areas into two different categories: rain-fed (RF) and irrigated (IR) crop regions. Thus, we distinguished crop regions by RF and IR for each country and grid-by-grid cell. We then derived a total of 54 RF and IR agriculture regions (ARs), including 22 in Kazakhstan (six of which were IR), six in Kyrgyzstan (five of which were IR), four in Tajikistan (three of which were IR), 12 in Turkmenistan (all IR), ten in Uzbekistan (eight of which were IR). Because much of the crop land overlaps, we sometimes employed the same ARs for more than one crop. For example, the AR4 for wheat in Turkmenistan shares the same common area as maize, and we used the same AR for both. The study area included many more overlapping ARs. For example, since almost all crop areas overlapped in Tajikistan, we used the same four ARs for all four crops.

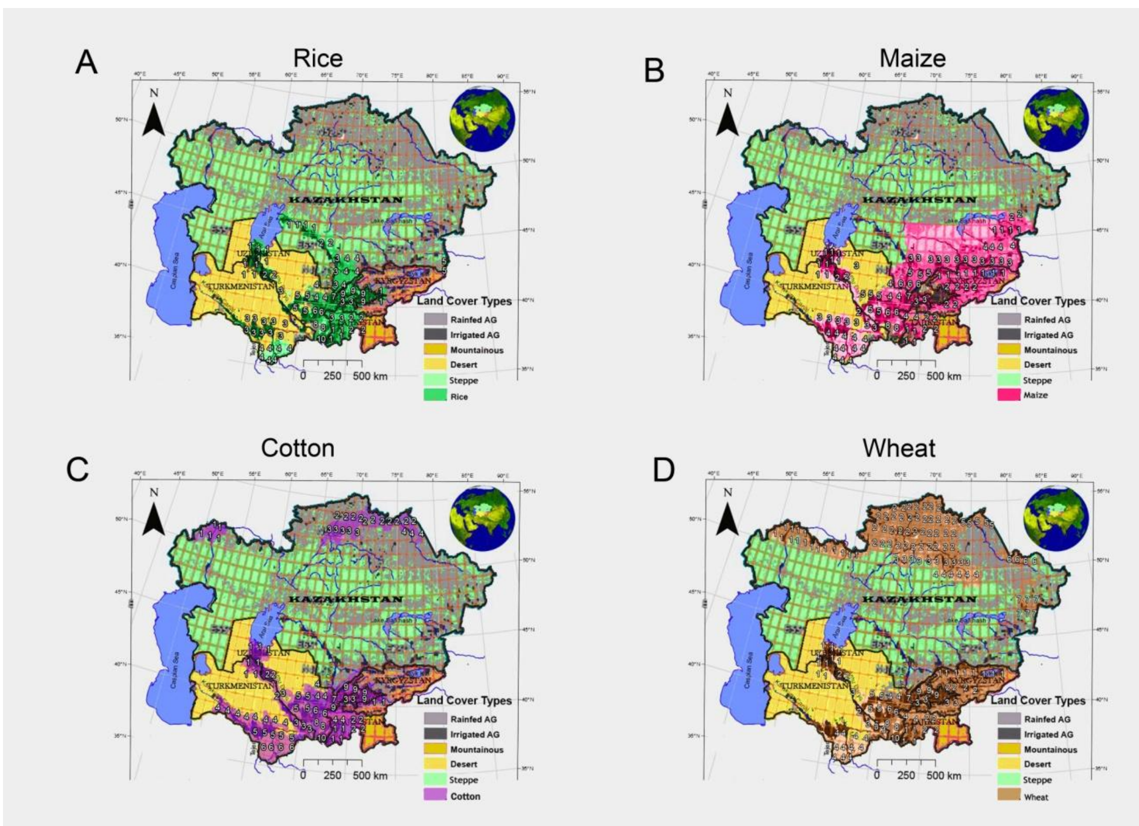


Figure 3: Agricultural regions of the study areas: A) Rice area outlined by the dark-green color; B) Maize area outlined with the pink color*; C) Cotton area outline by the purple color; D) Wheat area outlined by the brown color. At least 1% of the area was covered by each crop where shown. (See Appendices A, B, C, and D for higher resolution).**

*Note 1: * The maize area of Kazakhstan is indicated in a different manner than the other countries' crops. The maize area for Kazakhstan reflects an area averaged by crop production of 10,000 and above for each oblast. Thus, three oblasts were indicated as the maize area for Kazakhstan. The number-free maize area in Kazakhstan reflects a conflict between two maps, one of which [Kariyeva et al., 2011]indicated the area as a steppe while in the other[http://www.pecad.fas.usda.gov/, 2010]maize was counted as oblast-averaged. Thus, we excluded this area from the maize map.*

*Note 2:** Although we obtained the majority of cotton maps from a single source [Aldaya et al., 2010], we considered the cotton area in Kazakhstan as uncertain due to a conflict between information from two separate reports. [Monfreda et al., 2008] and USDA [http://www.pecad.fas.usda.gov/, 2010].*

We ultimately identified a combination of 105 crop areas in the Central Asia countries, and then employed several tools to apply gridded variables to the crop areas on these maps. Average annual precipitation in northern Kazakhstan is about 580 mm, which is barely enough for crops that are seldom irrigated. Kazakhstan crop production suffers from serious drought two out of every five crop seasons [*http://faostat.fao.org/*]. Since virtually none of the wheat is irrigated, yield and production are marked by sharp year-to-year fluctuations.

Another Central Asia country with a large amount of rain-fed crops is Kyrgyzstan with about a 20% rain-fed crop area. In Tajikistan, Turkmenistan, and Uzbekistan most of crops are irrigated: 94%, 95%, and 90% respectively. The average annual precipitation amount per year for Kyrgyzstan and Tajikistan is 530 mm and 700 mm, respectively. In Uzbekistan the overall average annual rainfall is 400 mm and in Turkmenistan, it is 210 mm. Most of the agricultural regions in Uzbekistan and Turkmenistan, however, are quite arid, with an average annual rainfall amount between 100 and 200 mm [*http://faostat.fao.org/*, 2010]. For purposes of analysis, we created three different types of data sets: (1) individual crop regions, (2) average of RF and IR ARs for each country, and (3) each country's annual mean (growing seasons-averaged) of T,P, and AOD including an analysis of CrY variables.

Monthly time series do not include the entire year but only the months of the growing season for the crop areas in each country. The crops in CAS have similar growing seasons except for Kazakhstan, which has shorter growing seasons due to its climatic conditions. Therefore, we applied a growing season from May to August for Kazakhstan and from May to September for all of the other southern CAS countries. Most of the maize is grown in the three oblasts (states) of Kazakhstan: Zhambyl, South Kazakhstan and Almaty. We considered only the oblasts producing 10,000 tons or more of maize as maize production regions. In the case of Kazakhstan, therefore, we used the oblasts as a whole as the maize ARs because production was reflected as an area averaged per oblast in the source material [*http://www.pecad.fas.usda.gov/*, 2010]. The steppe areas indicated in our sources [*Kariyeva et al.*, 2011], however, were excluded from the cotton-growing areas. We then divided Kazakhstan into six ARs: two of which were IR and four of which were RF. Monthly variables are reflected as gridded data sets composed of three spatiotemporal resolution data points on the same agricultural areas: (1) the Rainfall Analyses Tool Monthly Global Precipitation (GPCP) [*http://disc2.nascom.nasa.gov/Giovanni/tovas/rain.GPCP.2.shtml*], (2) the daytime surface temperature [*http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=neespi*] and (3) the MISR AOD 550 nm green band Level-3 Data Monthly Global Aerosol Product [*http://gdata1.sci.gsfc.nasa.gov/daac-bin/G3/gui.cgi?instance_id=MISR_Monthly_L3*]. The gridded data resolutions were

2.5^ox 2.5^o, 1^ox 1^o, and 0.5^ox 0.5^o, respectively (Table 1). In the present study, we used a unique spatiotemporal resolution, a one-decade-long satellite-based dataset on crop regions to examine various categories for the yield fluctuation in the CAS countries. Two types of monthly data analyses were done: (1) in the first, we applied all the above variables to each agricultural area separately and (2) in the second, we separated the RF and IR areas for each country and applied the average of both RF and IR for each country.

Annual time series include annual CrY data from the Food and Agriculture Organization of the United States (FAO) [*http://faostat.fao.org/*] besides T, P, and AOD variables. Annual data sets consist of 11-year (2000-2010) time series. Variables include annual averaged growing seasons for each crop in each country. Using annual data sets, we were able to analyze the correlation between the CrY with climate and AOD, using the Pearson correlation coefficient; however, it was not plausible to correlate monthly data including CrY, and we could only create and interpret visual time series of eleven-year data.

Table 1: Data Sources

Data sources	Crop Production	**MISR AOD (555 nm)**	**Climate T, P**
Duration	2000-2010	2000-2010	2000-2010
Data Source	FAO	NASA GIOVANNI	GPCP
Temporal Resolution	Annual	Monthly mean & Annual mean	Monthly mean & Annual mean
Spatial Resolution	Country Level	0.5^ox 0.5^o	1^ox1^o, 2.5^ox2.5^o
Descriptions	Maize, rice, cotton, wheat.	MISR Terra 555 nm L3 Green band	Satellite Gridded Data

The Pearson Correlation is the most commonly-used measure of dependence between two quantities and is obtained by dividing the covariance of the two variables by the product of their standard deviations. The population correlation coefficient $\boldsymbol{\rho_{X,Y}}$ between two random variables *X* and *Y* with expected values μ_X and μ_Y and standard deviations σ_X and σ_Y is defined as:

$$\rho X, Y = \mathrm{corr}(\mathrm{X}, \mathrm{Y}) = \frac{\mathrm{cov}(\mathrm{X}, \mathrm{Y})}{\sigma_X \, \sigma_Y} = \frac{\mathrm{E}[(\mathrm{X} - \mu_\mathrm{X})(\mathrm{Y} - \mu_\mathrm{Y})]}{\sigma_X \, \sigma_Y},$$

where *E* is the expected value operator, *cov* means covariance, and, *corr* is Pearson's correlation.

RESULTS

We expect this study to add to the field's knowledge of the effect of climate change on agriculture in CAS, with particular consideration given to the effects of aerosols. Because our main goal is to examine the yield variation in specified regions, the correlation and analysis of P-CrY, T-CrY, and AOD-CrY becomes significant. Therefore, we present the research results in four separate sections: (1) CrY-P, (2) CrY-T, (3) CrY-AOD, and (4) other correlations (T-AOD, P-AOD) for each country. This section includes **(a** a separate analysis of each AR and each crop in each country and (**b)** a closer look into the RF and IR ARs for each country.

Crop Yield and Precipitation

Kazakhstan's wheat area is mostly rain-fed, and only two of the seven wheat regions are irrigated; therefore, a significant positive correlation (PS-corr) existed between P and wheat yield (WY) (r=.62, p<.05) in Kazakhstan (Table 2).

Table 2: The result represents the mean value of 5 RF and 2 IR W crop areas of Kazakhstan. Significant correlation was found between precipitation and annual wheat yield.

Kazakhstan Wheat				
Pearson's Correlation (N=11)	AOD	T	P	WY
AOD	1	.544	-.570	-.330
T	.544	1	-.700*	-.310
P	-.570	-.700*	1	.617*
WY	-.330	-.310	.617*	1
*. Correlation is significant at the 0.05 level (2-tailed).				

*Note. * = p<.05*

A clear correlation also existed between the P and wheat yield time series, especially in the second half of the decade (Figure 4). In the rice, cotton and maize areas of Kazakhstan, no significant correlation existed between the CrY-P variables. Similarly, no significant correlation was found in the CrY-P in areas of Kyrgyzstan, Turkmenistan, and Uzbekistan.

In Tajikistan, a PS-corr was found (r=.66, p<.05) between cotton yield (CY) and P, and a significant level existed between WY-P (r=.55, p>.05) see (Appendix G).

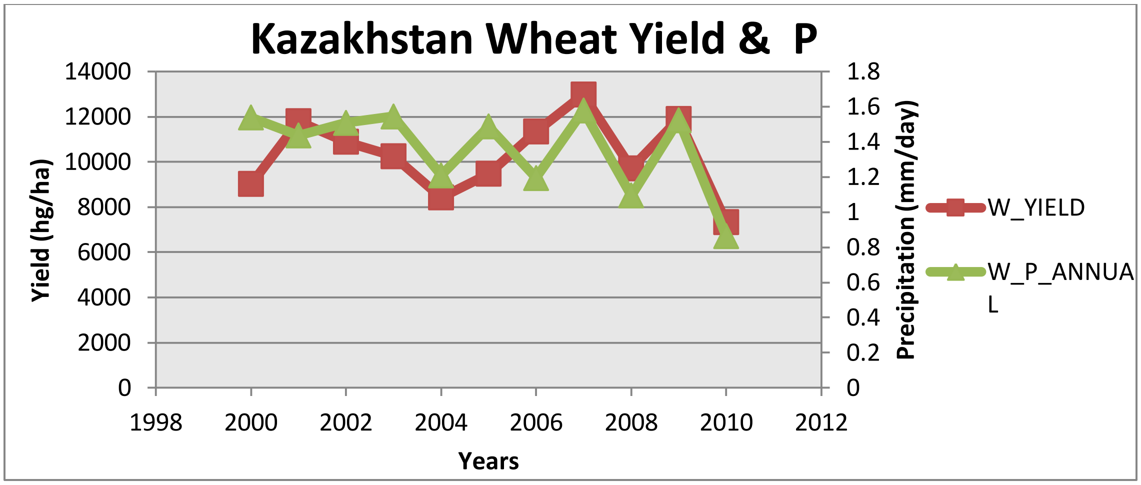


Figure 4: Kazakhstan wheat yield and precipitation time series. The chart shows a clear correlation between P and W yield, especially in the second half of the decade. Significantly, the wheat areas in Kazakhstan are mostly rain-fed, and only a small amount of the wheat area is irrigated.

Crop Yield and Temperature

A negative significant correlation (NS-corr) was found between CY-T (r=.-61, p<.05) and WY-T (r=.-61, p<.05) in Tajikistan's ARs. On the other hand, no correlation was found between RY-T and MY-T in Tajikistan's agricultural areas.

In the crop areas of Kazakhstan, Turkmenistan, and Uzbekistan no significant correlation existed with any of the CrY-T variables. Further, we found that the only relatively significant negative relation in Kyrgyzstan existed between wheat yield (WY) and T. (r=.-60, p=.053) [see (Appendix F)].

Lobell et al. (2011) claim that the warming trends have a certain negative effect on wheat and maize yield[*Lobell et al.*, 2011]. This research showed, however, that the "slowdown in recent yield gains" theory can be valid only for Kyrgyzstan WY and Tajikistan WY and CY. Maize and rice did not show any correlation. Although, no relationship between T and CrY existed in the other Central Asian countries, the correlation demonstrated in Tajikistan and Kyrgyzstan provides an essential basis for our hypothesis.

Crop Yield and AOD

Aerosol does not directly affect crop production. Instead, it affects climate that, in turn, has a direct effect on CrY, which may indicate an indirect effect on CrY. In the rice, cotton, wheat and maize areas of Kazakhstan, Tajikistan, Turkmenistan, and Uzbekistan, no significant correlation was found in the case of CrY-AOD variables. Only a NS-corr existed between maize yield (MY) and AOD (r=.-60, p<.05) for the rest of Kyrgyzstan.

Other Correlations: Annual, and Monthly Growing-Season-Based Correlations between T-AOD and P-AOD

The rest of the evaluations between T and P showed a NS-corr., but because this fact is well known, we did not evaluate this subject in the present study. Instead, we analyzed the correlation between T-AOD and P-AOD.

Annual results

In the cotton areas of Kazakhstan, a PS-corr existed between T and AOD (r=.65, p<.05) and a NS-corr existed between P and AOD (r=.-83, p<.01) see (Table 2). Although, a positive relation existed between T and AOD (r=.54, p>.05), and a negative relation existed between P and AOD (r=.-57, p>.05) in the wheat areas of Kazakhstan, these results were not considered significant according to the Pearson's correlation coefficient. On the other hand, no significant correlation was found in Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan with respect to P-AOD and T-AOD.

Overall, the annual results show little or no correlation in T-AOD and P-AOD, as compared to the monthly results. This effect could be attributable to the lack of data points in the annual time series, which consisted of 11 years (points). To avoid this problem, we also created monthly growing season-based time series, as discussed below.

Growing-seasons based correlations results

Growing season periods vary from country to country and by different crop types. In the present study, the growing seasons were divided into two groups: (1) Kazakhstan (4 months), and (2) all other southern CAS countries (4.5-5 months). The results are based on each AR for each country in CAS.

Kazakhstan: The only NS-corr in cotton areas out of the four regions was between P and AOD in the AR2 in northern Kazakhstan, between the cities of Kostanay and Pavlodar (r=-.-31, p<.5). In the maize areas, however, a PS-corr was found between P and AOD at the AR4 of AR6. (r=.34, p<.5). This area is located in southeast Kazakhstan, between Almaty and Balgash Lake. Remarkably, although both areas are RF ARs, they have opposite P and AOD correlations. This result could be explained by several factors. One possible cause could be latitudinal differences in precipitation types. For instance, in northern Kazakhstan, the weather is much colder and most of P falls as snow or hail [*Rachkovskaya*, 2003]. Another factor could be data conflict between maize and cotton in Kazakhstan (see Figure 3 caption). Out of five rice areas in Kazakhstan, a NS-corr was found at the AR5 between T and AOD (r= -.38, p<.5), and a PS-corr was found between P and AOD (r=.38, p<.5) in the same area. This AR is located east of Altyn Emel National Park, at the edge of the Kyrgyzstan border. At the same time, the mean averaged RF rice area indicated a PS-corr between P and AOD (r=47, p<.1), but no correlation was found in the wheat ARs of Kazakhstan.

Kyrgyzstan's results best express our hypothesis about the P-AOD and T-AOD relationship. In the cotton area of Kyrgyzstan, the correlation between AOD and P is significant (r=.33, p<5), as discussed above. Moreover, in 66% of the maize area (2/3) of Kyrgyzstan, a PS-corr was observed between P and AOD. The correlation observed at the AR1 and AR2 wheat was (r=.55, p<.1) and (r=.61, p<.1), respectively. These ARs are 50% RF and 50% IR. At the same time, a NS-corr between T and AOD was indicated at the AR2 (r=.-31, p<.5). Although a negative relation was seen at the maize AR1, it was not at a significant level. In the rice region, 100% of the rice ARs showed a correlation between P and AOD (2/2). The correlation was (r=.31, p<.5) at the AR1 and (r=.39, p<.1) at the AR2 of rice. Also, a negative relation between T and AOD appeared very close to the significant level (r=.-26, p=.52). As in the maize regions, 66% of the wheat area of Kyrgyzstan reflected a PS-corr between P and AOD. The correlation observed at the AR1 and AR2 was (r=.55, p<.1) and (r=.61, p<.1), respectively.

Tajikistan was divided into four ARs, the AR1 and AR3 of which were IR and the AR2 and AR4 of which were RF areas. Both the RF ARs showed a PS-corr in P-AOD of (r=.45, $p<.1$) and (r=.34, $p<.5$) respectively, while the IR ARs had no correlation. Accordingly, there was a NS-corr in T-AOD at the AR2, a RF region. (r=.-36, $p<.1$). Furthermore, the mean-averaged RF ARs of Tajikistan show a PS-corr in P-AOD (r=.49, $p<.1$) for all crops. Nevertheless, most of the ARs indicated a negative relation between T and AOD, but not at a significant level, according to the Pearson's correlation coefficient. This relationship is a key factor in explaining the T-CrY, P-CrY, and AOD-CrY relationships in Tajikistan. Moreover, as with the T-CrY in Tajikistan, a PS-corr existed in P-AOD in the wheat and cotton regions, and the reverse existed in the T-AOD relationship. In fact, cotton and wheat are the main two crops in Tajikistan; both crops together compose more than 70% of Tajikistan's agricultural product.

Turkmenistan is one of the two countries (together with Uzbekistan) in CAS that had no yield correlation with other variables. This result may be due to the fact that these two countries are located in the vicinity of the two driest deserts in the world, the Kara Kum and Kyzyl Kum deserts, each with an average rainfall of less than 200 mm per year [*Aldaya et al.*, 2010; *Gintzburger et al.*, 2005; *Gintzburger et al.*, 2003; *Yang et al.*, 2009]. The ENSO (El Nino Southern Oscillation) suppresses a strong warm pool signal, associated with a clear extension of positive precipitation anomalies into the Indian Ocean and negative anomalies over CAS [*Barlow et al.*, 2002]. Even so, the available meteorological data show no significant precipitation trend during the last decades in CAS, although slight regional differences exist in the annual precipitation trend (Figure 4). On the other hand, a PS-corr exists between T and AOD (r= .27, p<.5) in the AR1 is common region for all four crop regions, which share approximately the same geographical location. These ARs are located south of the Aral Sea, near the Khorezm Region, where agriculture is restricted to irrigated land [*Conrad et al.*, 2011]and which is considered one of the more substantial agricultural areas in CAS.

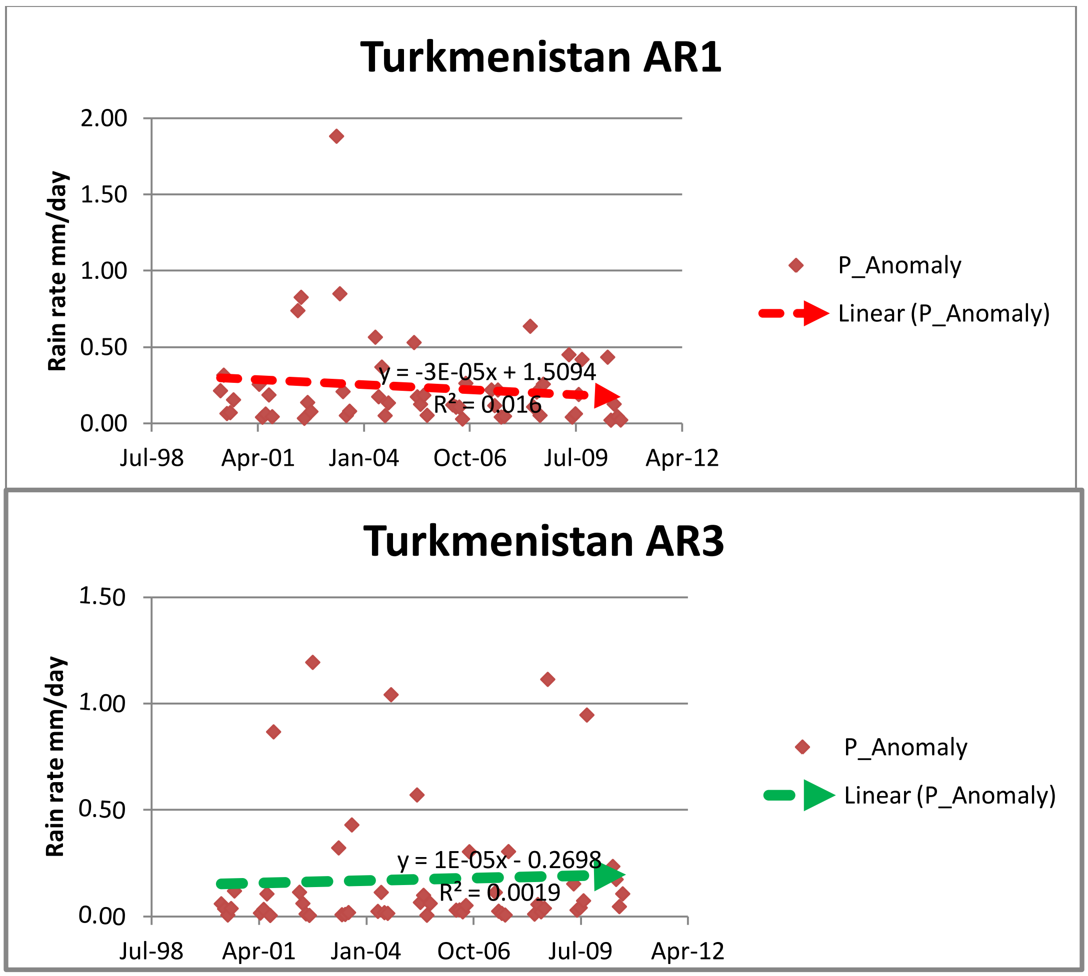


Figure 5: Precipitation Trends in Turkmenistan's AR1 and AR3, located about 200 km south of the Aral Sea. The precipitation rate slightly decreased at the coastal areas along the Aral Sea (upper chart) and increased in the region's inner agricultural areas (lower chart).

Uzbekistan country level analyses did not show any CrY correlation with other variables, although some ARs showed significant T-AOD correlations. Such significant positive T-AOD correlations were found in the AR1 AR, the AR2 AR and AR7 ($r=.27$, $p<.5$), ($r=.37$, $p<.1$), and ($r=.42$, $p<.1$) respectively, which are common ARs for all four crops. Furthermore, the AR10, which is a common AR for rice, wheat, and cotton, showed significant positive T-AOD correlation ($r=.41$, $p<.1$). Additionally, the AR7 that is common for all four crops and the AR9 that is common for rice, wheat, and cotton crops areas denote a significant positive P-AOD correlation (($r=.38$, $p<.1$), ($r=.41$, $p<.1$) respectively). Both T-AOD and P-AOD showed a PS-corr in Uzbekistan. These results distinguish Uzbekistan from most of other countries in CAS. Thus, in most ARs, the relationship between T and AOD is negative. Furthermore, Uzbekistan is the highest cotton producer among the CAS countries. The AR1 in Uzbekistan is especially productive in agriculture. This AR is located at Khorezm, which is 200 km south of the former Aral Sea shore. Khorezm is located on the Amu Darya River, at the transition of the Kara Kum and Kyzyl Kum deserts. Although the area is extremely dry, with about 100 mm in rainfall per year, most of the population relies on agriculture, which is limited to irrigated land. Thus, P is not a major factor in Uzbek agriculture, and T has an inverse effect when compared to RF regions. Due to an Uzbek state order, cotton and wheat dominate the agricultural landscape in spring and summer, respectively [*Conrad et al.*, 2011]. Likewise, rice is another profitable crop for the farmers in Khorezm. The population's income depends on the region's agricultural yields [*Ehammer et al.*, 2010].

CONCLUSION

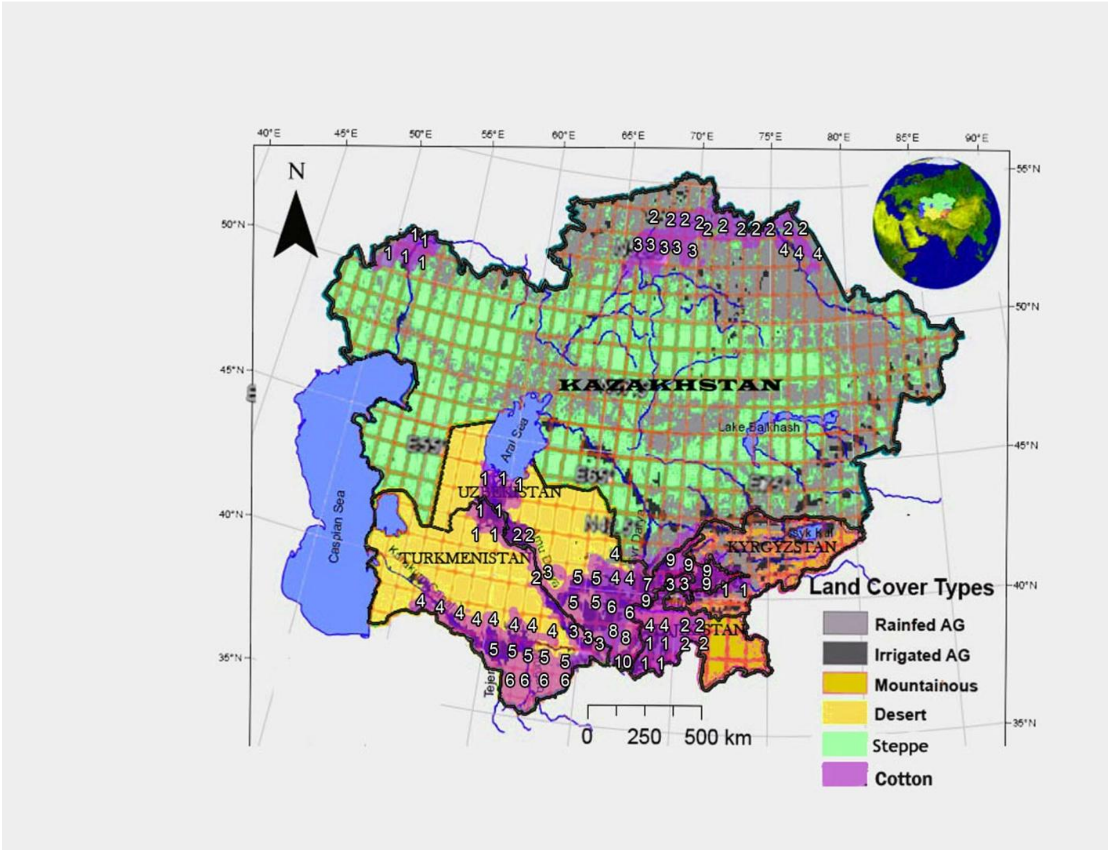
Our goal was to investigate the linkage between aerosol, climate, and major crop production (cotton, maize, wheat, and rice) at specified agricultural regions in CAS countries. In order to better understand the recent climate impact on agriculture in CAS, we investigated climate-yield correlation, considering the effect of aerosol. Although prior research has investigated the climate-yield relationship, no study could be found in the scientific literature considering the aerosol effect along with climate factors from a regional perspective. Our results show that the relation between aerosols (aerosol optical depth, AOD), climate, and crop yield varies not only across countries but also across ARs. Even so, more arid countries with less precipitation (P) rates (Turkmenistan and Uzbekistan) show little or no P-CrY correlation, while countries with higher P rates (Kazakhstan, Kyrgyzstan, and Tajikistan) indicate a PS corr. In some ARs of the more arid countries, T-AOD shows a NS corr, while ARs in other countries show a PS corr. For example, in Kazakhstan there were opposite correlation between P and AOD in two different agricultural regions even though both regions are rain-fed. Furthermore, more arid countries, such as Turkmenistan and Uzbekistan show little or no T and AOD correlation while relatively less arid countries (Kazakhstan, Kyrgyzstan, and Tajikistan) indicated a positive correlation. Another significant finding in is that in the more arid countries (with lower rain rates) of Turkmenistan and Uzbekistan, no correlation exists between CrY-T, CrY-P, and CrY-AOD, while the less arid (with higher rain rate) countries (Kazakhstan, Kyrgyzstan, and Tajikistan) indicate a significant correlation.

Finally, looking at the research from a regional perspective, some important points emerge in the present study. The results show that the relationship between AOD, climate, and crop yield was different in the CAS countries than it was in the previous global or large scale research hypotheses [*Barlow et al.*, 2002; *Lobell et al.*, 2011; *Lobell et al.*, 2012; *D B Lobell et al.*, 2010]. In fact, the results varied dramatically not only across countries but also across specific agricultural regions. On the other hand, the overall results show that more than one half of the ARs in CAS do not indicate any correlation between CrY and other variables. This implies that future studies must address other factors in addition to those included in the present study.

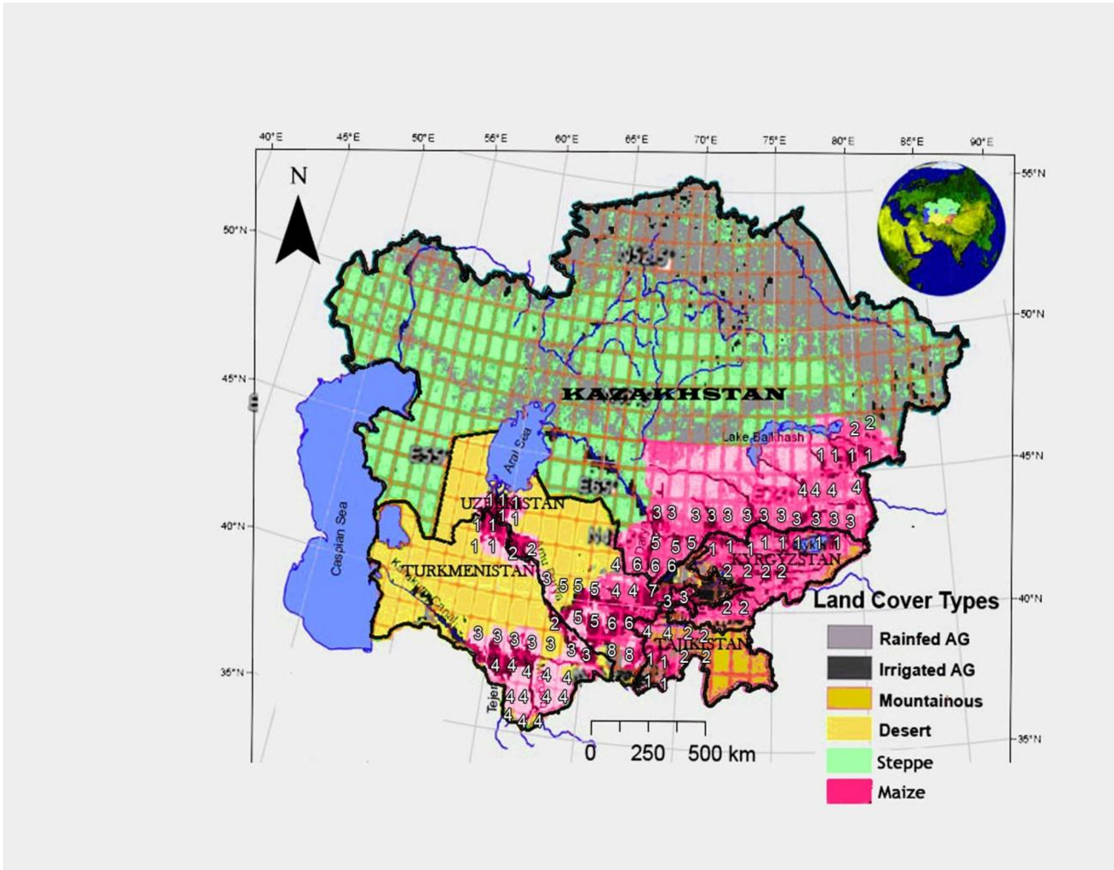
This study emphasizes a more region-specific approach to studying the climate and aerosol effect on crop production than that found in comparable global studies [*Lobell et al.*, 2011]. Nevertheless, many uncertainties remain in analyzing these aspects of CAS due to the limitations we encountered. One technical limitation arose from a substantial bias between source maps. Even though most of cotton maps were obtained from a single source [*Aldaya et al.*, 2010], we question the validity of the information regarding the cotton area in Kazakhstan due to conflicting information in other researches [*http://www.pecad.fas.usda.gov/*, 2010; *Monfreda et al.*, 2008]. Moreover, the climate and aerosol data resolutions used in the present study were not identical. The resolution varied from 0.5x0.5 degree to 2.5x2.5 degree, because the meteorology sites, AOD tools and websites from which we obtained the data quantified essential information in different resolutions. Further, the present study did not estimate the direct effect of elevated CO2 on crop yields. Annual mean global atmospheric CO2 concentrations increased 23.210 ppm from 2000 to 2010, with an increase from 369 ppm to 392 ppm in the last decade (NOAA) [*Conway and Tans*, 2012]. Free-air CO2 enrichment experiments for C_3 crops (i.e. rice, wheat, cotton) show an average yield increase of 14% in 583 ppm CO2 relative to 367 ppm CO2 [i.e., 0.065% increase per ppm [*Li et al.*, 2008]]. This study suggests that the increased CO2 since 2000 would have raised yields slightly. Impacts of higher CO2 on maize production were likely much smaller because its C4 photosynthetic pathway is unresponsive to elevated CO2 [*Leakey*, 2009]. [*Lobell et al.*, 2011] Lobell et al. (2011) argued that the effects of higher CO2 and climate change have possibly been slightly positive for rice and cotton, and negative for wheat and maize. However, we found that climate impact varies from country to country and even among local areas in CAS. Similarly, some regions were affected by T while others by P. Even in the same country, the same climate factors had an adverse effect on the same crop species when combined with other factors. The present study also did not consider soil moisture, which is a substantial component of agriculture. Our study considered variation in the four major crops and some of the factors that could potentially influence them at national and sub-national scales in CAS. Although we analyzed P, T, and AOD in each country of CAS, and in each separate RF and IR AR, we did not calculate the net direct effects of irrigation on agriculture.

Many important components exist beyond those addressed here, and many important factors other than food production are implicated in the CAS agricultural sector. For example, fluctuations in crop production may also result from unstable political environments and government regulation of agriculture in the CAS countries [*Babu and Tashmatov*, 2000; *Muminjanov*, 2008; *Tondel*, 2011]. After the collapse of the former Soviet Union, the resulting governments implemented varying farm policies. Finally, our study provides a valuable framework for further regional research about CAS. One future project would be a comparison of CAS with a region with different climate conditions). We believe that an assessment of the effect of climate trends and aerosol variability on regional crop production can provide useful knowledge for future study

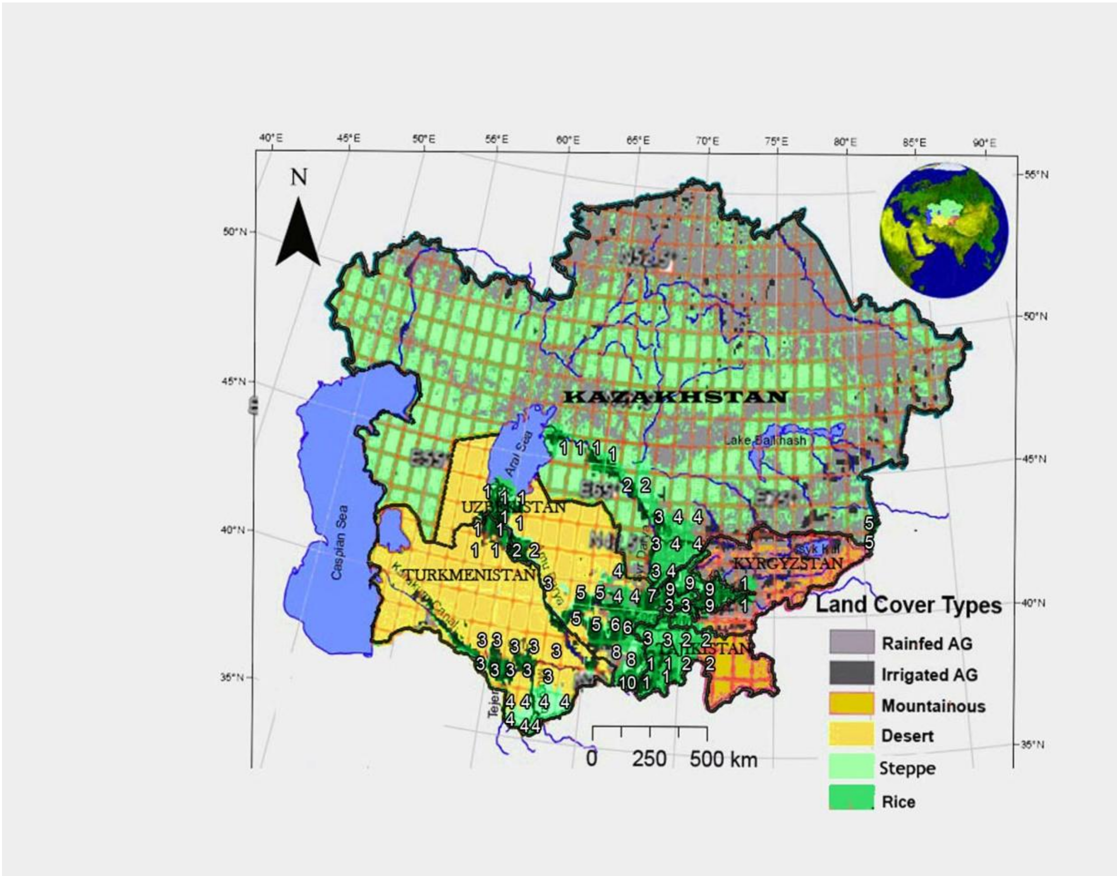
APPENDICES



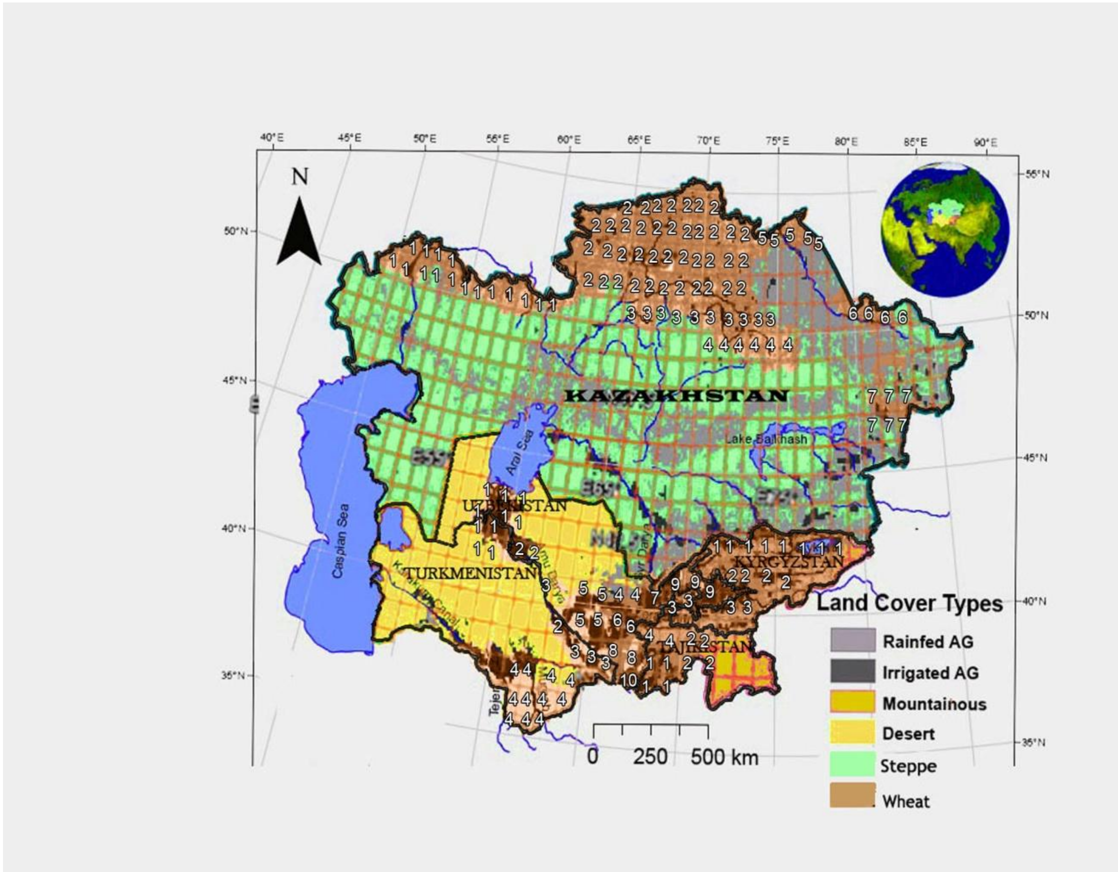
Appendix A: Cotton production regions in CAS [Aldaya et al., 2010; Kariyeva et al., 2011]. Numbers on the map represent ARs' numbers for cotton in each country. Each country has at least one, at most ten IR and/or RF crop regions.



Appendix B: Maize production regions in CAS [Aldaya et al., 2010; http://www.pecad.fas.usda.gov/, 2010; Kariyeva et al., 2011]. Numbers on the map represent ARs' numbers for maize in each country. Each country has at least one, at most ten IR and/or RF crop regions.



Appendix C: Rice production regions in CAS [Aldaya et al., 2010; Kariyeva et al., 2011]. Numbers on the map represent ARs' numbers for rice in each country. Each country has at least one, at most ten IR and/or RF crop regions.



Appendix D: Wheat production regions in CAS [Aldaya et al., 2010; Kariyeva et al., 2011]. Numbers on the map represent ARs' numbers for wheat in each country. Each country has at least one, at most ten IR and/or RF crop regions.

Kazakhstan (108)				
Cotton				
	AOD	T	P	CY
AOD	1	.63*	-.82**	-.33
T	.63*	1	-.74**	-.56
P	-.82**	-.74**	1	.52
CY	-.33	-.56	.52	1
Maize				
	AOD	*T*	*P*	*MY*
AOD	1	-.24	.25	-.04
T	-.24	1	-.94**	.23
P	.25	-.94**	1	-.10
MY	-.04	.23	-.10	1
Rice				
	AOD	*T*	*P*	*RY*
AOD	1	.02	.16	.21
T	.02	1	-.95**	-.08
P	.16	-.95**	1	.15
RY	.21	-.08	.15	1
Wheat				
	AOD	*T*	*P*	*WY*
AOD	1	.54	-.57	-.33
T	.54	1	-.70*	-.31
P	-.57	-.70*	1	.62*
WY	-.33	-.31	.62*	1

Appendix E: The results of Pearson Correlation Coefficient for Kazakhstan.The results of Pearson correlation coefficient between AOD, P (precipitation), T (Temperature), and four different crops' yield: C(Cotton), M(Maize), R(Rice), W(Wheat) , in Kazakhstan during 2000-2010.Note *= p<.05, **= p<.01, N=11

Kyrgyzstan (113)				
Cotton				
	AOD	T	P	CY
AOD	1	.33	-.09	.14
T	.33	1	-.95**	-.07'
P	-.09	-.95**	1	.09
CY	.14	.07	.09	1
Maize				
	AOD	*T*	*P*	*MY*
AOD	1	.38	-.19	-.60*
T	.38	1	-.96**	-.32
P	-.19	-.96**	1	.12
MY	-.60*	-.32	.12	1
Rice				
	AOD	*T*	*P*	*RY*
AOD	1	.26	.-23	.04
T	.26	1	-.97**	-.61*
P	-.23	-.97**	1	.51
RY	.04	-.61*	.51	1
Wheat				
	AOD	*T*	*P*	*WY*
AOD	1	.38	-.19	-.25
T	.38	1	-.96**	-.63*
P	-.19	-.96**	1	.47
WY	-.25	-.63*	.47	1

Appendix F: The results of Pearson Correlation Coefficient for Kyrgyzstan. The results of Pearson correlation coefficient between AOD, P (precipitation), T (Temperature), and four different crops' yield: C(Cotton), M(Maize), R(Rice), W(Wheat) , in Kyrgyzstan during 2000-2010.Note *= p<.05, **= p<.01, N=11

Tajikistan(208)				
Cotton				
	AOD	T	P	CY
AOD	1	.05	.35	.22
T	.05	1	-.82**	-.64*
P	.35	-.82**	1	.66*
CY	.22	-.64*	.66	1
Maize				
	AOD	*T*	*P*	*MY*
AOD	1	.05	.35	.06
T	.05	1	-.82**	-.34
P	.35	-.82**	1	.22
MY	.06	-.34	.22	1
Rice				
	AOD	*T*	*P*	*RY*
AOD	1	.05	.35	.07
T	.05	1	-.82**	-.33
P	.35	-.82**	1	.23
RY	.07	-.33	.23	1
Wheat				
	AOD	*T*	*P*	*WY*
AOD	1	.05	.35	-.12
T	.05	1	-.82**	-.61*
P	.35	-.82**	1	.55
WY	-.12	-.61*	.55	1

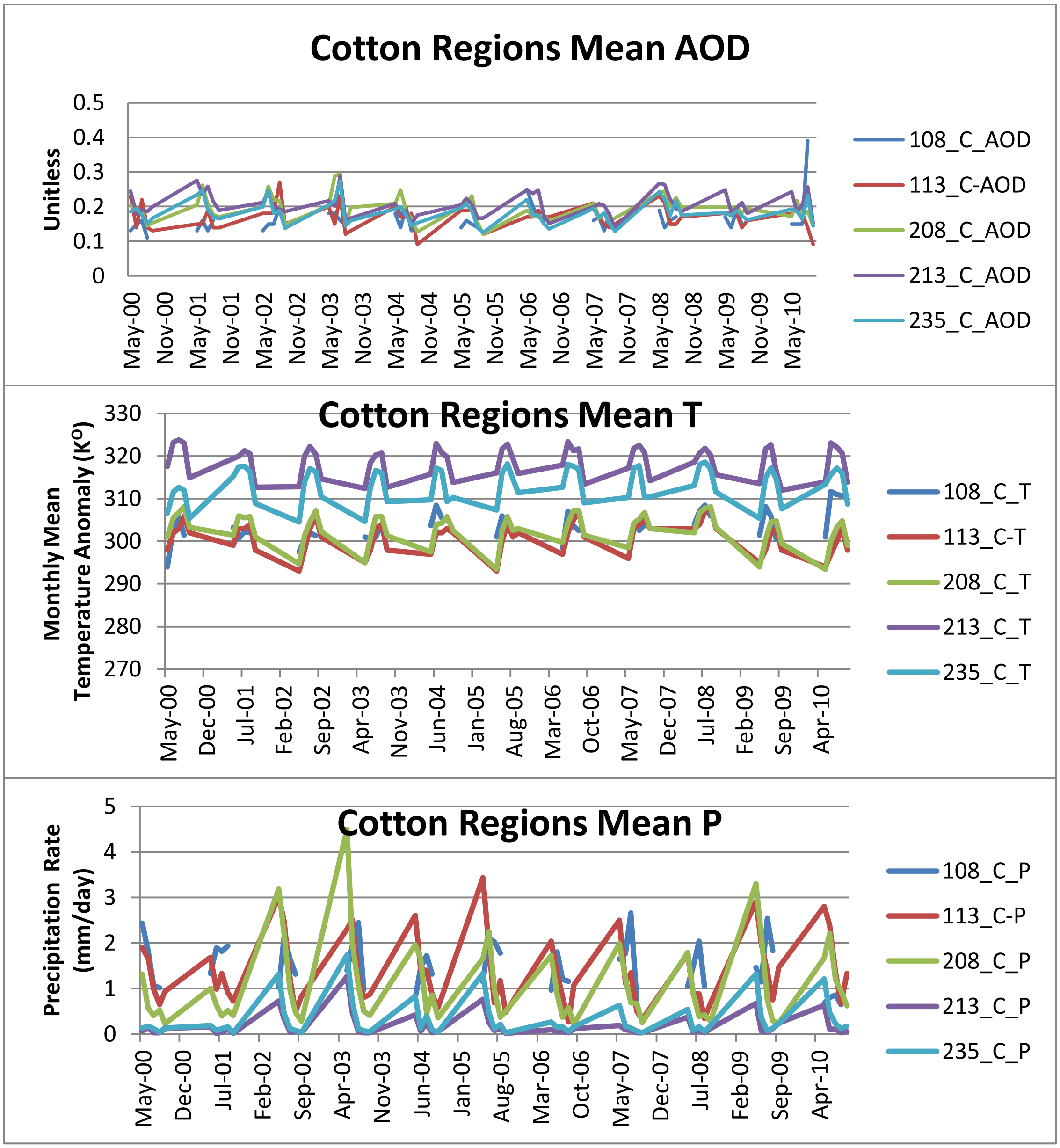
Appendix G: The results of Pearson Correlation Coefficient for Tajikistan.The results of Pearson correlation coefficient between AOD, P (precipitation), T (Temperature), and four different crops' yield: C(Cotton), M(Maize), R(Rice), W(Wheat) , in Tajikistan during 2000-2010.Note *= p<.05, **= p<.01, N=11

Turkmenistan(213)				
Cotton				
	AOD	T	P	CY
AOD	1	-.03	-.17	.19
T	-.03	1	-.79**	.37
P	-.17	-.79**	1	.30
CY	-.19	.37	-.30	1
Maize				
	AOD	*T*	*P*	*MY*
AOD	1	.02	-.26	.26
T	.02	1	-.59	-.51
P	-.26	-.59	1	.37
MY	.45	-.52	.37	1
Rice				
	AOD	*T*	*P*	*RY*
AOD	1	.08	-.29	-.17
T	.08	1	-.62	-.58
P	-.29	-.62	1	.47
RY	-.17	-.58	.47	1
Wheat				
	AOD	*T*	*P*	*WY*
AOD	1	-.001	-.28	-.43
T	-.001	1	-.61*	-.45
P	-.28	-.61*	1	.30
WY	-.43	-.45	.30	1

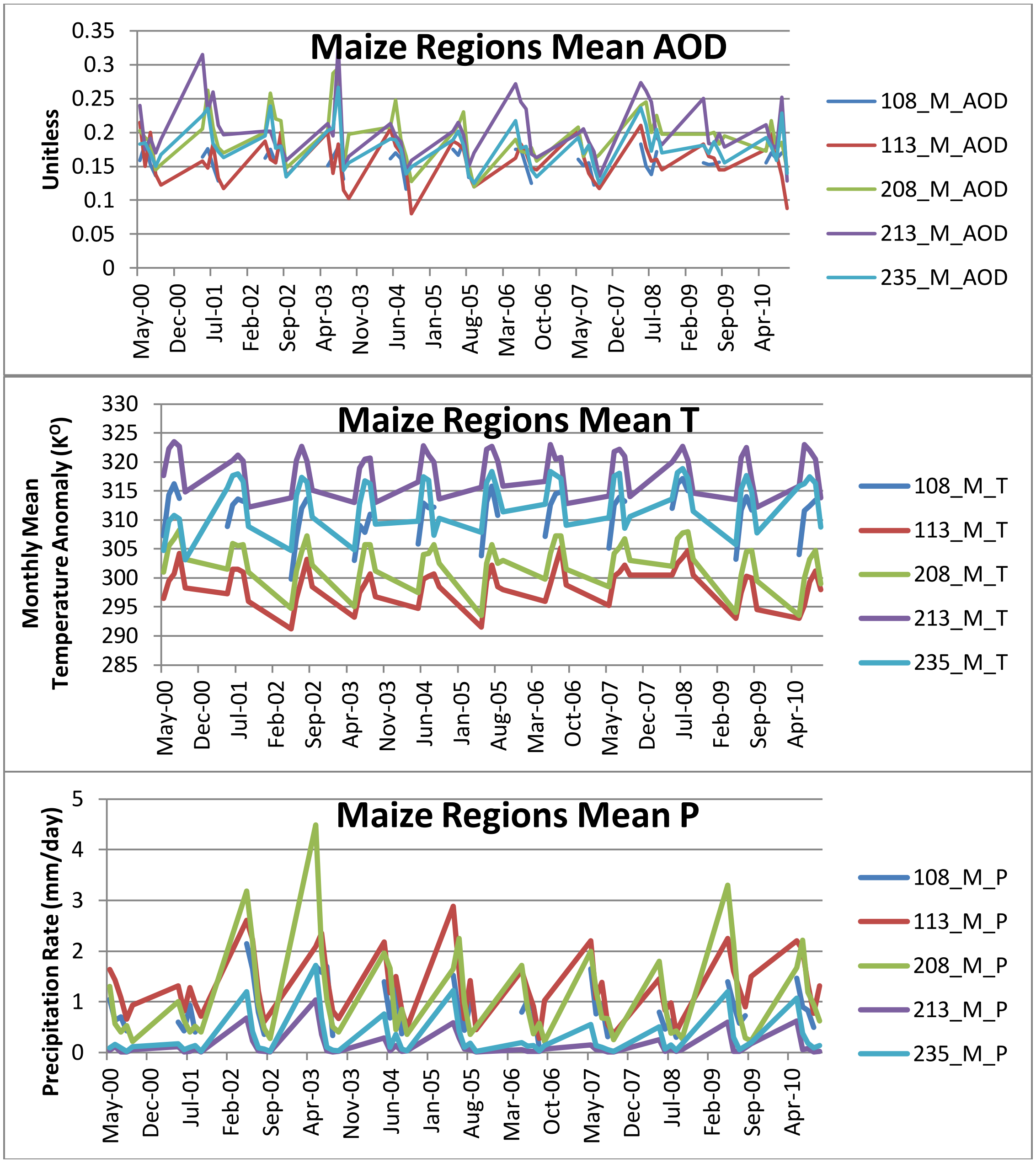
Appendix H: The results of Pearson Correlation Coefficient for Turkmenistan.The results of Pearson correlation coefficient between AOD, P (precipitation), T (Temperature), and four different crops' yield: C(Cotton), M(Maize), R(Rice), W(Wheat) , in Turkmenistan during 2000-2010.Note *= p<.05, **= p<.01, N=11

Uzbekistan(235)				
Cotton				
	AOD	T	P	CY
AOD	1	.08	.16	-.06
T	.08	1	.27	-.23
P	.16	.27	1	-.07
CY	-.06	-.23	-.07	1
Maize				
	AOD	*T*	*P*	*MY*
AOD	1	.08	.14	.21
T	.08	1	.25	-.11
P	.14	.25	1	.05
MY	.21	-.11	.05	1
Rice				
	AOD	*T*	*P*	*RY*
AOD	1	.08	.16	-.13
T	.08	1	.27	.02
P	.16	.27	1	.37
RY	-.13	.02	.37	1
Wheat				
	AOD	*T*	*P*	*WY*
AOD	1	.08	.16	.11
T	.08	1	.27	.05
P	.16	.27	1	.34
WY	.11	.05	.34	1

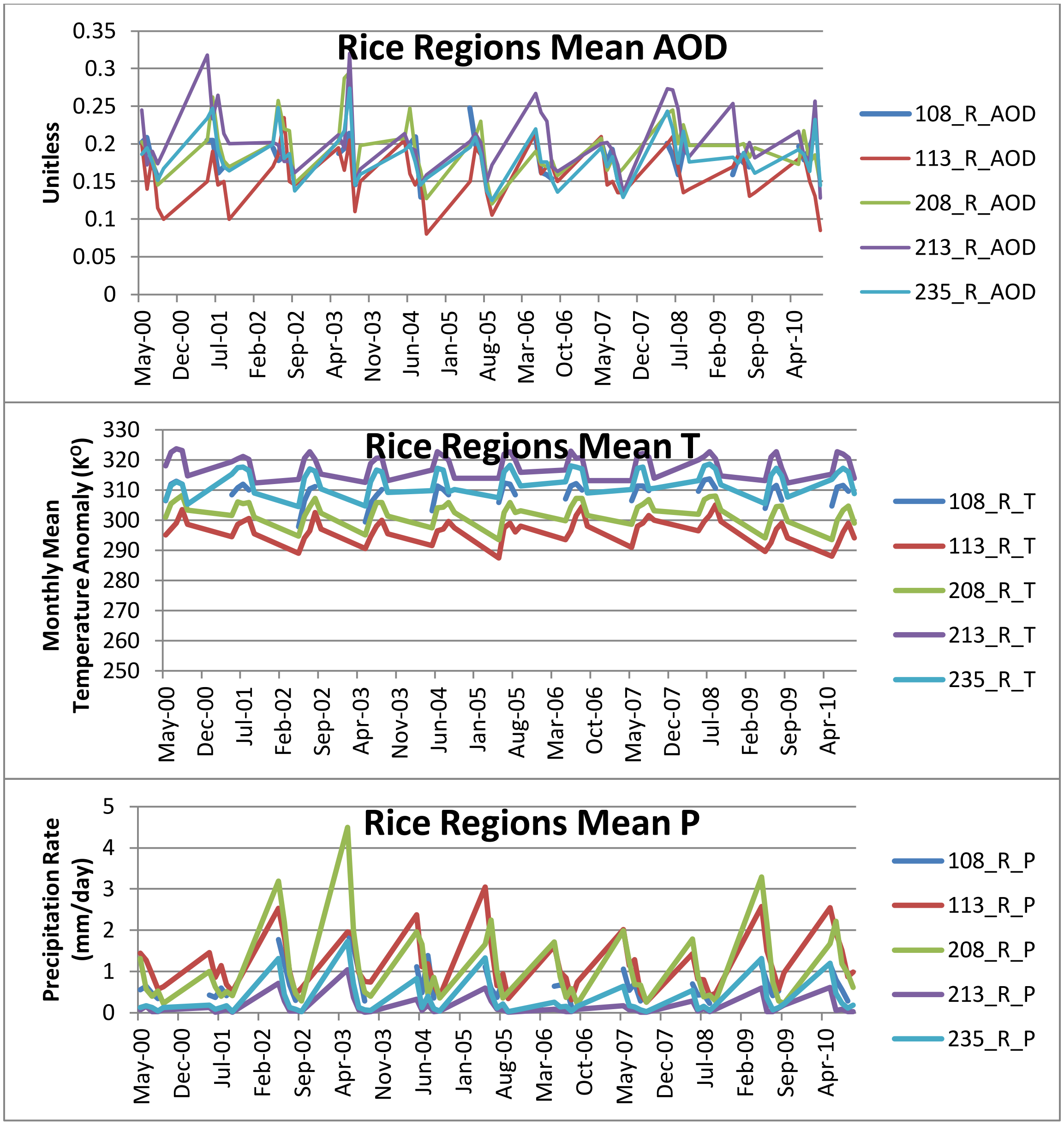
Appendix I: The results of Pearson Correlation Coefficient for Uzbekistan. The results of Pearson correlation coefficient between AOD, P (precipitation), T (Temperature), and four different crops' yield: C(Cotton), M(Maize), R(Rice), W(Wheat) , in Uzbekistan during 2000-2010.Note *= p<.05, **= p<.01, N=11



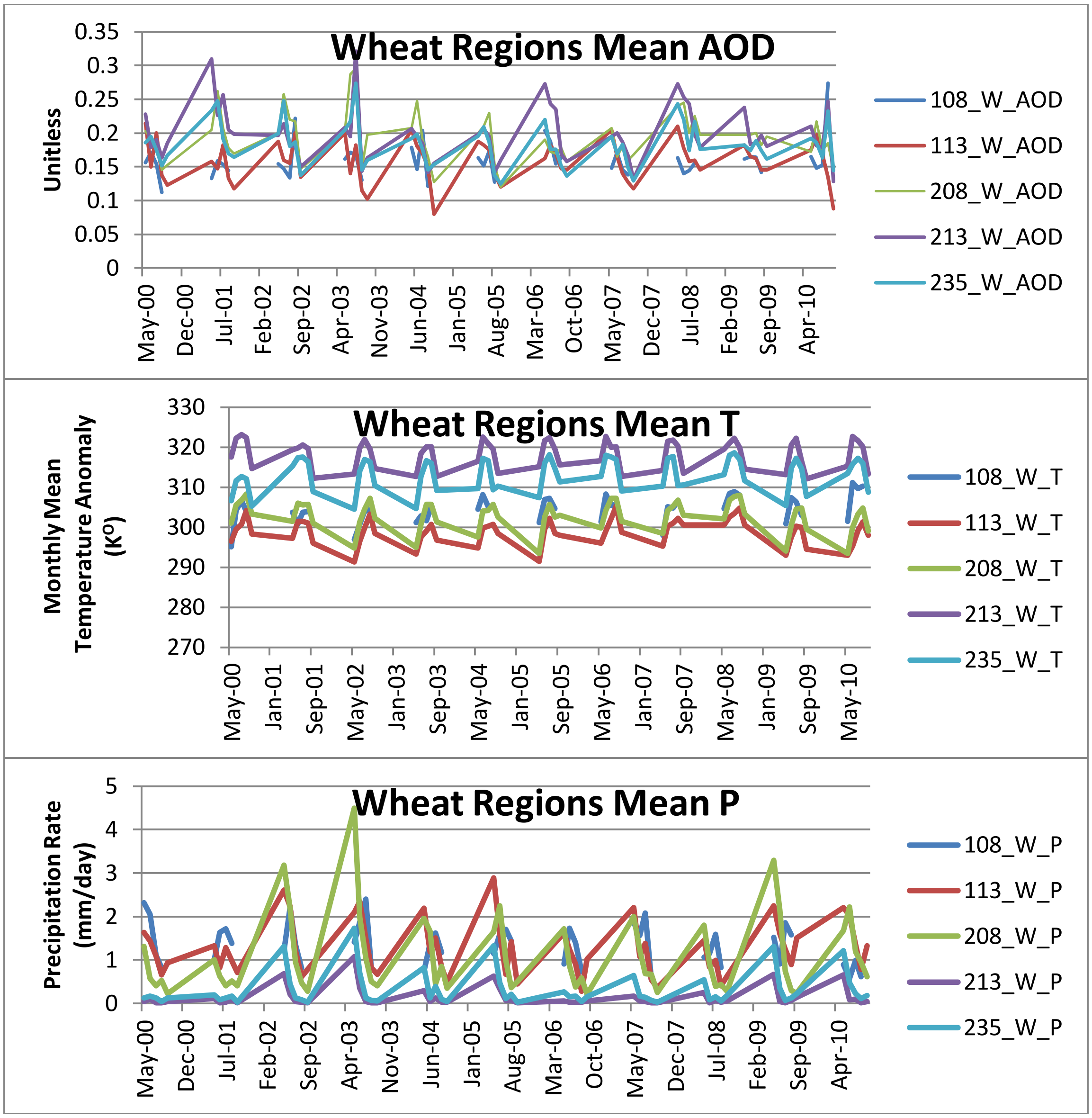
Appendix J: AOD (upper), T (middle), and P (lower) time series of cotton areas in CAS countries: Kazakhstan (108), Kyrgyzstan (113), Tajikistan (208), Turkmenistan (213), and Uzbekistan (235).



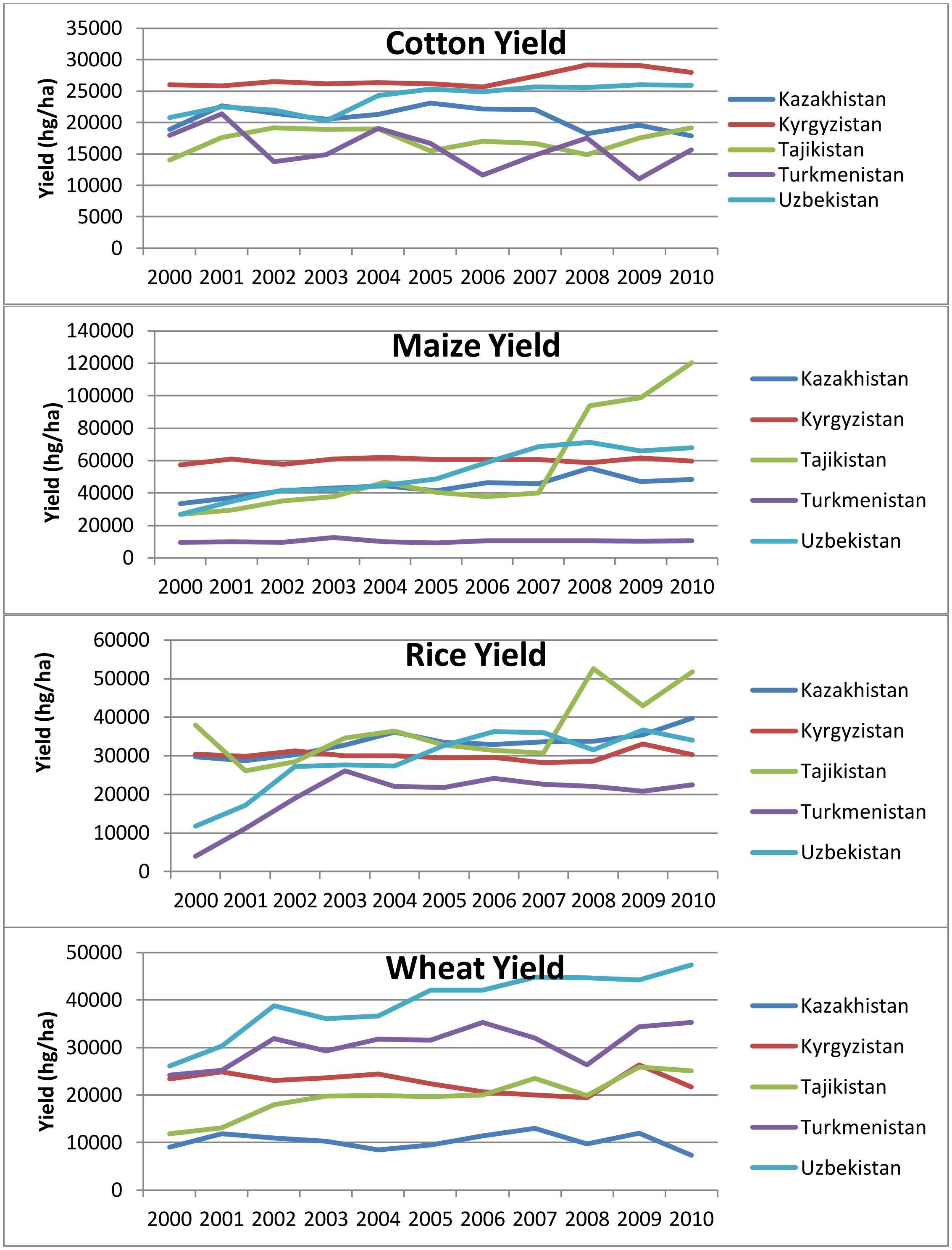
Appendix K: AOD (upper), T (middle), and P (lower) time series of maize areas in CAS countries: Kazakhstan (108), Kyrgyzstan (113), Tajikistan (208), Turkmenistan (213), and Uzbekistan (235).



Appendix L: AOD (upper), T (middle), and P (lower) time series of rice areas in CAS countries: Kazakhstan (108), Kyrgyzstan (113), Tajikistan (208), Turkmenistan (213), and Uzbekistan (235).



Appendix M: AOD (upper), T (middle), and P (lower) time series of wheat areas in CAS countries: Kazakhstan (108), Kyrgyzstan (113), Tajikistan (208), Turkmenistan (213), and Uzbekistan (235).



Appendix N: Central Asian countries cotton maize, rice and wheat yield fluctuation time series during 2000-2010.

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