Heat units-based potential yield assessment for cotton production in Uzbekistan

Gianni Montanaro[1], Vinay Nangia[1*], Prasanna Gowda[2], Shukhrat Mukhamedjanov[3], Azamat Mukhamedjanov[3], Mira Haddad[1], Tulkun Yuldashev[4], Weicheng Wu[5]

(1. *International Center for Agricultural Research in the Dry Areas (ICARDA), Rabat Instituts, Rue Hafiane Cherkaoui, Rabat, Morocco*;
2. *Forage and Livestock Production Research Unit, USDA-ARS Grazinglands Research Laboratory, El Reno, OK 73036, USA*;
3. *Scientific-Information Center of the Interstate Coordination Water Commission of the Central Asia (SIC ICWC), Tashkent, Uzbekistan*;
4. *International Water Management Institute, Tashkent, Uzbekistan*;
5. *Key Laboratory of Digital Land and Resources, East China Institute of Technology, Nanchang 330013, China*)

Abstract: Cotton yields in Uzbekistan are significantly lower than those in similar agro-climatic regions, requiring the estimation of crop potential and baseline yield to track progress of production enhancement efforts. The current study estimated potential cotton development and baseline yield (maximum given no production constraints) using total heat units (THU) and potential cotton yield (PCY), respectively. Calculations were based on heat units (HU) for a 30-year (1984-2013) period. Long-term average THU and PCY, as well as PCY at three different exceedance probabilities (p=0.99, p=0.80, and p=0.75), were calculated for 21 selected weather stations across cotton-growing areas of Uzbekistan. After confirmation that the current planting date (April 15) is optimal, a comparison of THU with the accepted cotton production cutoff threshold (1444℃) suggested that areas with lower elevations and latitudes are more appropriate for cotton production. Yield gap analysis (relative difference between long-term average PCY and actual yields) confirmed that Uzbekistan cotton production is below potential, while the spatial distribution of yield gaps outlined where efforts should be targeted. Areas near the stations of Nukus, Kungrad, Chimbay, and Syrdarya should be further investigated as benefit/cost ratio is highest in these areas. A comparison between state-set yield targets and PCY values, taking into account climatic variability, suggested that all areas except Jaslyk, Nurata, and Samarkand have safe, appropriate targets. These results present a starting-point to aid in strategic actions for Uzbekistan cotton production improvement.

Keywords: cotton, potential cotton yield, yield gap, heat unit, Uzbekistan, agriculture, climatic variability, target
DOI: 10.25165/j.ijabe.20211406.4803

Citation: Montanaro G, Nangia V, Gowda P, Mukhamedjanov S, Mukhamedjanov A, Haddad M, et al. Heat units-based potential yield assessment for cotton production in Uzbekistan. Int J Agric & Biol Eng, 2021; 14(6): 137–144.

1 Introduction

Cotton is the major industrial, irrigated crop grown under state control in Uzbekistan, contributing significantly to the country's GDP, exports, and rural employment[1,2]. The country's dry continental climate and low annual precipitation result in a heavy reliance on irrigation, with 40% of irrigated lands used for cotton production , supported primarily by the Amu Darya and Syr Darya rivers[2-4].

Cotton production in Uzbekistan has declined in recent years, due to both political and environmental factors[1,4]. Water management and availability are considered the main constraints to cotton production in the country[1], with reduced physical availability, inter-country water disputes, lack of coordination, insufficient infrastructure, and increased demand by other users amongst the main reasons[1,4,5]. These problems, as well as inefficient use and overexploitation of irrigation water, have resulted in excessive water applications leading to waterlogging and salinity problems, further exacerbating declines in yield and incurring severe environmental, social, and economic consequences. While efforts are being made to address these issues, determination of those areas least suited to cotton production, as well as baseline yield (e.g. potential cotton yield), should be determined to aid the Government of Uzbekistan in its continued actions to convert cotton fields to other crops[6,7] and to track progress of efforts.

Rates of cotton development are related to growing season air temperature[8-10], which can be expressed as accumulated (total) heat units or growing degree days. A heat unit (HU) is a measure of the amount of heat energy a plant encounters each day during the growing season. Crop growth and development of cotton are directly related to accumulated heat units (or total heat units, THU) when other environmental factors are not limiting[10], and thus can

Received date: 2019-12-12 **Accepted date:** 2020-10-20
Biographies: Gianni Montanaro, MSc, Research Assistant, research interests: agriculture water management, Email: Gianni.Montanaro.90@gmail.com; **Prasanna Gowda**, PhD, Associate Area Director of USDA, research interests: agriculture water management, Email: Prasanna.Gowda@ARS.USDA.GOV; **Shukhrat Mukhamedjanov**, PhD, Associate Professor, research interests: water resource management, irrigation, Email: shuhrat.shakir@mail.ru; **Azamat Mukhamedjanov**, MSc, Irrigation Specialist Consultant of World Bank, research interests: water and land management, Email: azamatm.84@mail.ru; **Mira Haddad**, MSc, Research Assistant, research interests: sustainable land management, Email: M.Haddad@cgiar.org; **Tulkun Yuldashev**, MSc, Water Management Consultant of IWMI, research interests: irrigation and water management, Email: tulkun_yuldashev@mail.ru; **Weicheng Wu**, PhD, Professor, research interests: remote sensing, soil and water management, Email: wuwch@ecit.cn.

***Corresponding author: Vinay Nangia**, PhD, Research Leader, research interests: soil, water, agronomy, and agriculture water management. International Center for Agricultural Research in the Dry Areas (ICARDA), P.O.Box 6299, Rabat Instituts, Rue Hafiane Cherkaoui, Rabat, Morocco. Tel: +212-668853777, Email: V.Nangia@cgiar.org.

be used as a method for determining the most suitable areas for crop production.

Potential cotton yield (PCY) is defined as the yield that can be achieved based on available thermal heat units assuming no other production constraints, such as salinity and waterlogging, unavailability of water and nutrients, and disease and pests[11]. Previous studies have calculated PCY using a variety of methods, at various spatial scales and locations. Simulation models have been used to estimate large-scale[12,13] and smaller-scale PCY[14]. Percentile-based methods have also been used from global to local scales, using yields at a given percentile under given conditions to determine potential yield[15,16]. Another common method has been the use of yields attained on fields where cotton is grown under optimal conditions[16]. Other methods have also been found in the literature[12,17,18]. No studies were found that estimated PCY at the Uzbekistan national scale, using a heat units-based method.

PCY can be compared with actual yield to determine yield gaps, which are useful when determining areas with obstacles to production[12]. Yield gap is defined as the difference between potential yield, under non-limiting conditions, and average actual yield for a specific area and time period[16,19]. Locations with larger yield gaps are more likely to experience inadequate management practices or other non-climatic constraints to production[16]. These areas have higher potential for yield improvement as compared to areas with lower yield gaps. In addition, comparing PCY with yield targets established by the Uzbekistan Government (target gap analysis) allows an evaluation of state-set targets.

The main objectives of this study were to (1) verify which areas in Uzbekistan are more suitable for cotton production, through the analysis of THU; (2) estimate PCY in various areas using a temperature-based heat units method; and (3) compare PCYs with actual and state target cotton yields to determine regions where production or targets can be improved.

2 Materials and methods

2.1 Study area

Approximately 60% of the country is in semi-desert conditions, characterized by hot summers and cold winters similar to the Texas High Plains in the United States, and an annual average rainfall gradient between 100-300 mm from west to east[3]. This places high importance on irrigation for Uzbekistan's agricultural sector. Cotton production comprises approximately 40% of Uzbekistan's irrigated lands, covering approximately 1.17 million hm^2 in 2018-2019[2,7]. The crop is under state control, with the Government of Uzbekistan dictating the amount of surface area dedicated to cotton production, and setting production targets and national market prices[1,20].

2.2 Database development

Maximum and minimum daily air temperatures from 21 weather stations (Figure 1) located across Uzbekistan, and belonging to the Uzbekistan Meteorological Department, were used to calculate THU and PCY. These stations were selected based on the availability and continuity of daily observations for a 30-year period (1984-2013), as well as their extensive spatial coverage of cotton-producing areas across the country. In the case of missing values, data from the nearest neighboring weather station was used.

Figure 1 Selected weather station locations, topography, and location of the Amu Darya (lower) and Syr Darya (upper) rivers, within Uzbekistan

2.3 Seasonal boundary conditions

Properly selecting planting date can have a significant effect on cotton yield and quality[21,22]. The effect of planting date on potential cotton yield was analyzed to determine whether planting later to avoid low soil temperatures[3,23] resulted in negligible differences, and to determine optimal planting date. In Uzbekistan, planting dates range between mid- to late April[3,6], and served as the basis for this study. Four different planting dates were considered: April 15, May 1, May 15 and June 1. A harvesting date of October 15 was used with all four planting dates, despite the fact that cotton is harvested more than once during a growing season. However, in Uzbekistan, producers usually harvest by the second week of October, thus validating choice of harvest date for this study.

2.4 Heat units and potential cotton yield

Heat units (HU) are calculated from daily maximum and minimum air temperature values as:

$$HU = (T_{max} + T_{min})/2 - T_t \quad \text{when} \quad HU > 0.0 \tag{1}$$

where, T_{max} is daily maximum air temperature, ℃; T_{min} is daily minimum air temperature, ℃; and T_t is threshold temperature, ℃.

This concept of heat units resulted from observations that plants do not grow below a threshold temperature (T_t), with T_t for cotton equal to 15.6 ℃[3]. Accumulated heat units, or total heat units (THU), refer to the sum of daily heat units (calculated using Equation (1)) between planting and harvest dates, and is the basis for calculations of PCY. Cotton requires approximately 1444 ℃ THU from planting to maturity for proper development[24]. Therefore, areas unsuitable for cotton production can be identified by comparing long-term average THU with a cutoff threshold of 1444 ℃.

For each station in this study, annual available THU between cotton planting and harvesting dates were calculated by summing daily HU values obtained using Equation (1), assuming no cotton cultivar response to base temperature. Daily temperatures were capped at a maximum of 35 ℃ when calculating THU, due to the fact that ambient temperatures exceeding 35 ℃ negatively affect cotton growth and yield[25,26]. Potential cotton yield without seeds (kg/hm^2) was calculated as[11]:

$$PCY = 0 \quad \text{when} \quad THU \leq 800°C \tag{2}$$

$$PCY = \left[\frac{THU - 800}{41.7}\right] \times 112.5 \quad \text{when } 800°C < THU \leq 1000 ℃ \tag{3}$$

$$PCY = \left[5 + \frac{THU - 1000}{41.7}\right] \times 112.5 \quad \text{when THU} > 1000 ℃ \tag{4}$$

where, THU is the total heat units accumulated (℃) during the growing season in a given year.

The proposed equations are based on three assumptions: (1) PCY is equal to zero when THU is less than 800 ℃; (2) with 1000 ℃ heat units accumulated, the cotton plant will have one open boll with 4 more bolls at 85 percent maturity level and produces approximately 560 kg/hm^2 of cotton lint under irrigated conditions; and (3) with every additional 41.7 ℃ heat unit accumulation, cotton produces one more harvestable boll. Equations (2), (3) and (4) were used to estimate PCY without seeds for stations with THU less than 800 ℃, in the range of 800 ℃-999 ℃, and above 999 ℃, respectively.

Climatic variability from year-to-year affects total plant available heat energy during the growing season, and thus cotton yield. It should be taken into account when setting realistic yield targets and planning appropriate management practices. Therefore, the PCYs for each station were ranked in decreasing order and the exceedance probability (P) was calculated as:

$$P = \frac{N}{(n+1)} \tag{5}$$

where, N is the rank of the annual estimated value and n is the total number of years[11]. In this study, n is equal to 30.

The exceedance probability of an event is defined as the probability that an event of equal or greater magnitude will occur in any given year. The return period (RP) is the inverse of P. For example, an event with p= 0.25 has 25% likelihood to occur in any given year or should occur at least once in 4 years. Intuitively, producers would want to know the lowest possible PCY that can be expected in their region in any given year (p=0.99). The next thing producers would want to know is the probability of achieving higher yields with some risk involved. Some scenarios that may be of interest to producers would be a PCY at p=0.85 (4 out of 5 years) or p=0.75 (3 out of 4 years) at which producers can expect a PCY higher than the minimum. The PCY for p= 0.99 is the probability that a PCY of equal or greater magnitude can be expected every year (or with 99% chance of occurring in a single year), while p= 0.75 and p= 0.80 signify potential yields that can be expected every 3 out of 4 years (or with a 75% chance of occurring in a single year) and 4 out of 5 years (or 80% likelihood of occurring in any given year), respectively. A set of tables and maps were generated to illustrate the spatial distribution of THU and PCY over the study area. They included long-term average total heat unit and potential cotton yield maps, and PCY maps with exceedance probabilities of 0.99 (every year), 0.80 (4 out of 5 years) and 0.75 (3 out 4 of years), for each of 21 selected weather stations.

The current study analyzed the effect of planting date and feasibility to grow cotton at the 21 study locations. To determine if later planting dates would result in negligible yield increases, long-term average PCY for each planting date scenario was compared for each weather station, using an analysis of variance at p<0.05[27]. To determine suitability to grow cotton for the various weather stations, long-term average THU for each location was compared with a cutoff threshold THU of 1444 ℃. Subsequently, yield gap analysis suggested those areas where non-climatic constraints to production greatly affect yield, and thus where investments would most likely result in greater yield improvements. For this, long-term average PCY was compared with regional long-term average actual yield (1984-2012) for each location, using a single-tailed t-test assuming two samples of unequal variance (p<0.05). Target gap analysis compared regional-level state-mandated production targets[6,28] with potential cotton yield at different exceedance probabilities, in order to take into account climatic variability. Secure yield targets are those which can be expected to be attained or surpassed every year (i.e. exceedance probability p= 0.99). However, this assumes that actual yields are comparable to PCYs at p= 0.99, which may not always be the case. For the purposes of this study, comparisons of state-set yield targets were compared with potential cotton yields, so as to comment on the possibility of attaining such targets given no constraints to production. State-set targets were obtained from literatures[6,8] for Namangan, at regional levels by dividing total seed-lint cotton output targets by planting area. For yield and target gap analyses, actual yield and yield targets included seed mass; thus potential PCY required a conversion (divided by 35%) for comparison[3]. It should be noted that PCY data, calculated for each weather station in this study, is assumed to represent a larger area when compared to regional-scale data, and is a limitation to the current analysis.

3 Results and discussion

Long-term (1984-2013) daily maximum and minimum air temperature data from 21 weather stations were used to calculate THU and PCY for each year, during growing seasons. Four different planting dates (April 15, May 1, May 15 and June 1) and a harvesting date of 15 October were used for calculations. The elevation above sea level of selected weather stations varied from 64 m (Kungrad) to 678 m (Samarkand). Weather stations with higher elevations such as Tashkent, Fergana, and Samarkand were generally located in the eastern part of Uzbekistan, while stations with lower elevations were generally found in the western part (Figure 1).

3.1 Optimal planting date

An ANOVA analysis[27], $p<0.05$, analyzed the effect of planting date on long-term average PCY for each of 21 selected weather station locations (Table 1). Significant differences between normal and late planting dates were apparent, with normal planting dates occurring from mid- to late April in Uzbekistan[3,6]. PCY decreased substantially with later planting dates, indicating that earlier planting dates are necessary to maintain higher yield levels, with highest potential yields for all weather stations occurring with 15 April planting date, validating the current planting period. For example, a 15 d and 30 d delay from April 15 reduced long-term average PCY by 8% and 22%, respectively. For 6 weather stations, PCY was similar between April 15 and May 1 planting dates; however, even in such cases the maximum potential yields occurred with mid-April planting date. April 15 was chosen as the planting date for all subsequent analyses in this study as it proved to be the overall optimal planting date, confirming current practices in Uzbekistan[3,6].

Table 1 Comparisons of long-term average potential cotton yield (1984-2013) between normal and late planting date scenarios for each study location

Station name*	15-Apr		01-May		15-May		01-Jun	
	Long-term average PCY/(kg hm^{-2})**	SS (p<0.05)***	Long-term average PCY/(kg hm^{-2})**	SS (p<0.05)***	Long-term average PCY/(kg hm^{-2})**	SS (p<0.05)***	Long-term average PCY/(kg hm^{-2})**	SS (p<0.05)***
Ak-Baital	1895	a	1783	a	1608	b	1274	c
Andizhan	1678	a	1542	b	1362	c	1044	d
Bukhara	2045	a	1873	b	1651	c	1279	d
Buzaubay	2529	a	2383	b	2166	c	1779	d
Chimbay	1418	a	1315	a	1151	b	836	c
Dzhizak	1637	a	1509	b	1339	c	1020	d
Fergana	1689	a	1560	b	1388	c	1084	d
Jaslyk	1231	a	1164	ab	1045	b	770	c
Karshi	2370	a	2179	b	1936	c	1534	d
Khiva	1865	a	1726	b	1521	c	1160	d
Kungrad	1459	a	1356	a	1192	b	873	c
Namangan	2005	a	1848	b	1648	c	1303	d
Navoi	1837	a	1680	b	1480	c	1141	d
Nukus	1677	a	1564	b	1385	c	1049	d
Nurata	1432	a	1324	b	1171	c	883	d
Samarkand	1317	a	1212	ab	1072	b	810	c
Syrdarya	1453	a	1327	b	1148	c	829	d
Tashkent	1593	a	1473	b	1314	c	1028	d
Tamdy	2459	a	2305	b	2078	c	1682	d
Termez	2885	a	2616	ab	2308	bc	1837	c
Urgench	1590	a	1470	b	1284	c	948	d

Note: *Planting dates with different letters are significantly different (p<0.05). Letters are to be compared for specific locations only; not between locations. **PCY = Potential cotton yield. ***SS = Statistical significance (p<0.05)

3.2 Total heat unit-based feasibility assessment

Long-term average THU, assuming a growing season from April 15 to October 15, ranged from 1248℃ (Jaslyk) to 1861℃ (Termez), with an average THU of 1463℃ (Figure 2). Of the 21 weather stations, 9 surpassed the cutoff threshold of 1444℃, located mostly in the center and southern regions of the country. According to this study, these locations are considered appropriate for cotton-growing, while those with long-term average THU values below 1444℃ are not.

For any given longitude within the study area, the THUs were generally higher for weather stations located in the southern part of Uzbekistan as they receive more solar energy. Weather stations in the east that experienced lower than threshold THU values could be explained by higher elevations, resulting in lower soil and air temperatures. These weather stations are at elevations at or above the median elevation for all study locations.

The Uzbekistan Government has been targeting cotton-growing areas with lower yields for conversion to other crops, such as vegetables and fruits[7]. During 2018-2019, cotton planted area was reduced by 35 000 hm^2, resulting in approximately 1.17 million hm^2 nationally. Areas at higher elevations have been amongst those targeted, which agree with the results of this study. These results are useful in further guiding the government's actions in converting those areas less suitable for cotton production, based strictly on climate.

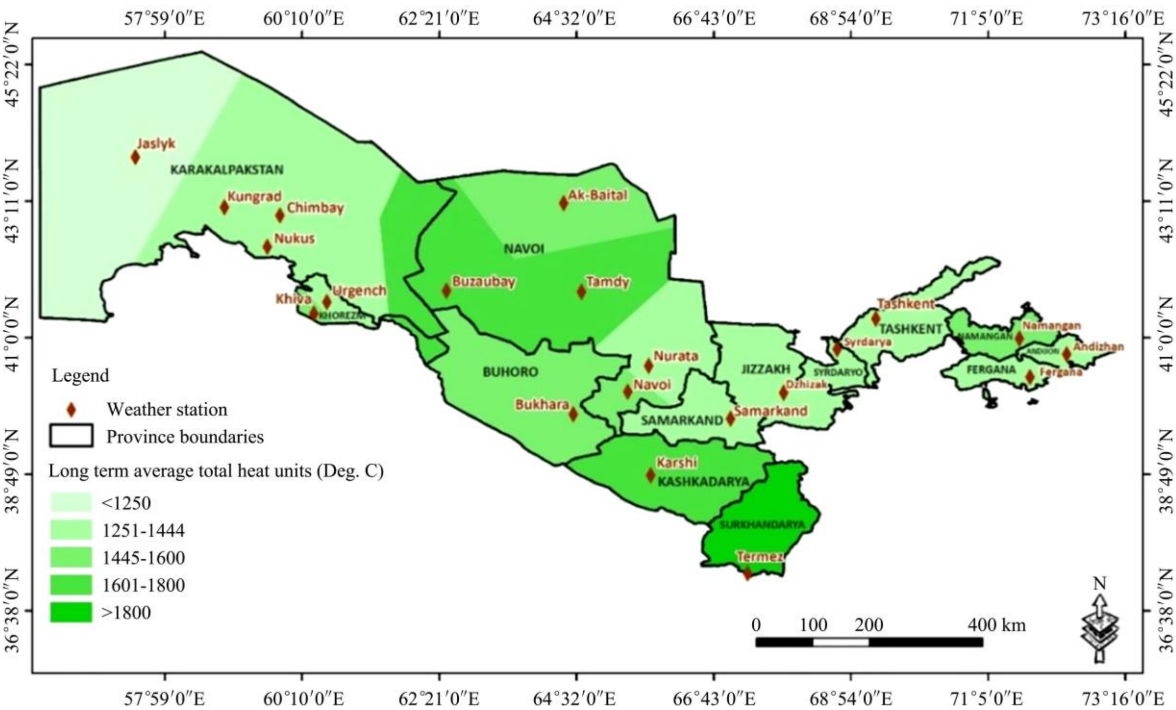


Figure 2 Long-term average total heat units (°C) (THU) for each weather station location (planting date April 15)

3.3 Potential cotton yield

Figure 3 presents long-term average PCY as well as PCYs at three different exceedance probability levels (p=0.75, 3 out of 4 years; p=0.80, 4 out of 5 years; p=0.99, every year), with April 15 planting date. PCY maps follow a similar spatial distribution as long-term average THU (Figure 2). With a planting date of 15 April, long-term average PCYs in Figure 3 varied from 1231 kg/hm^2 in Jaslyk to 2885 kg/hm^2 in Termez. This trend continued at three different p levels, at different magnitudes. Minimum values of PCY at different exceedance probabilities were found at Jaslyk, 1037 kg/hm^2 (p=0.75), 964 kg/hm^2 (p=0.80), and 418 kg/hm^2 (p=0.99); and maximum values were recorded in Termez, 2499 kg/hm^2 (p=0.75), 2386 kg/hm^2 (p=0.80), and 2177 kg/hm^2 (p=0.99).

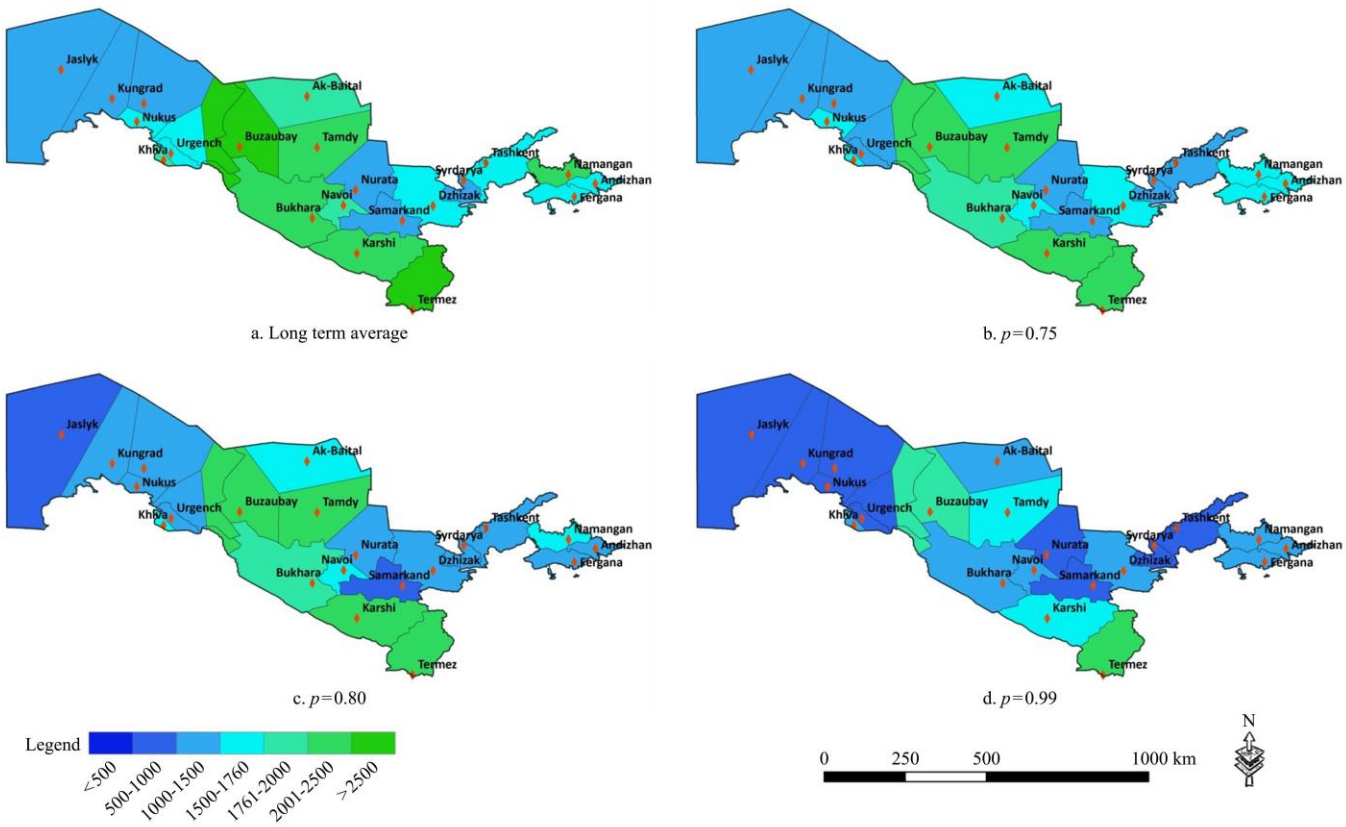


Figure 3 Long-term average potential cotton yield (kg/hm^2) (PCY), as well as PCY at various exceedance probabilities, for each weather station location (April 15 planting date)

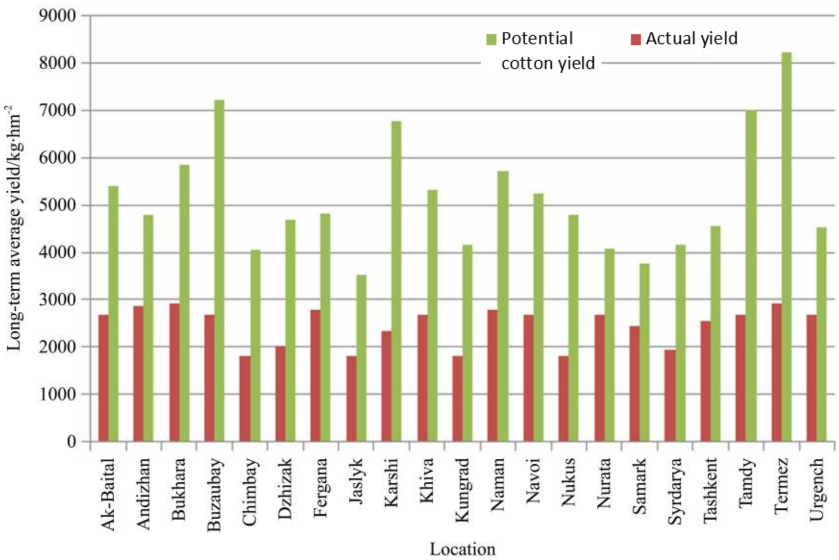
With regards to exceedance probabilities, the higher the *p* value, the lower the yield risk, and vice-versa (Figure 3). PCYs for Uzbekistan increased as *p* values decreased, and were less than the long-term average PCY. With 15 April planting date, producers can expect to achieve an average PCY of at least 1124 kg/hm^2 every year (p=0.99). However, there is 75% chance of achieving a PCY of at least 1631 kg/hm^2 (i.e. 3 out of 4 years), or 80% chance of achieving at least 1549 kg/hm^2 per year (i.e. 4 out of 5 years) (averages of all locations). This is about 45% and 37% more, respectively, than the PCY that can be expected every year, indicating that producers may have a better chance to increase their profit with yield goals that can be attained in 3 out of 4 or 4 out of 5 years. However these require higher risk and the current situation in Uzbekistan does not encourage farmers to improve production beyond what is required by state-set quotas[1]. A detailed assessment of agricultural input costs with different yield goals is needed for this evaluation and is beyond the scope of this study.

3.4 Yield gap analysis

Long-term average PCY (1984-2013) with April 15 planting date was compared with long-term average actual yield (1984-2012), as shown in Figure 4. PCY values required a conversion to simulate seed-lint mass. Lint mass in Uzbekistan is approximately 35% of seed-lint mass[3], thus PCY values were divided by 35%. All study locations had potential yields significantly higher than actual yields (Figure 4), confirmed with a single-tailed t-test assuming two samples of unequal variance (p<0.05), signifying a gap between potentially attainable maximum yields and currently attained yields. The highest yield gap among study locations was found at Karshi, with a 190% difference between actual and potential yields, while the lowest yield gap was found at Nurata weather station, with 53% difference. Current cotton yields in Uzbekistan are significantly lower than those in similar agro-climatic regions[1,2], as confirmed by this study.

The reasons for the spatial distribution of yield gaps seen in Figure 4 are beyond the scope of this study, as they are caused by a complex, interrelated relationship of social-economic-political-natural factors. Soil salinity and waterlogging are two major problems reducing yield in Uzbekistan and cover approximately 60% of irrigated lands in the country, resulting in 30% crop yield reductions[29]. Poor water management, lack of water availability, and inadequate infrastructure are contributing factors to the problem[5,30,31]. There are also many socio-political reasons that are responsible for the decline of cotton production, such as post-independence management of farm land, resource management, and outdated infrastructure[1,29].

Despite the many potential reasons for yield gaps, those areas with a relatively larger yield gap (Figure 4) signify areas where management actions are most likely to have the greatest effect in bridging the gap between potential and actual yields (e.g. Karshi). By contrast, those areas with a relatively smaller gap (e.g. Nurata) demonstrate that actual yields are relatively close to potential yields, and thus there is little room for improvement. It is in the former (larger yield gaps) that investments are most likely to have the greatest benefit/cost ratio and thus should be targeted to address non-climatic yield constraints, such as management actions. Investments in land rehabilitation are particularly promising, as the benefit/cost ratio can be as high as 4:1 over a 30-year period[4]. According to reference [4], the regions of Karakalpakstan, Buhoro, and Syrdaryo would have the highest benefit/cost ratio. The weather stations found in these regions are Nukus, Chimbay, Kungrad, Jaslyk, Bukhara, and Syrdarya. According to Figure 4, Nukus, Kungrad, Chimbay, and Syrdarya in particular have relatively high percent differences between potential and actual yields, and should be further investigated. While this is a preliminary analysis into the areas that should be targeted, a more detailed study into the specific reasons for lower actual yields in each region must be conducted to effectively apply funds, which is beyond the scope of this study.



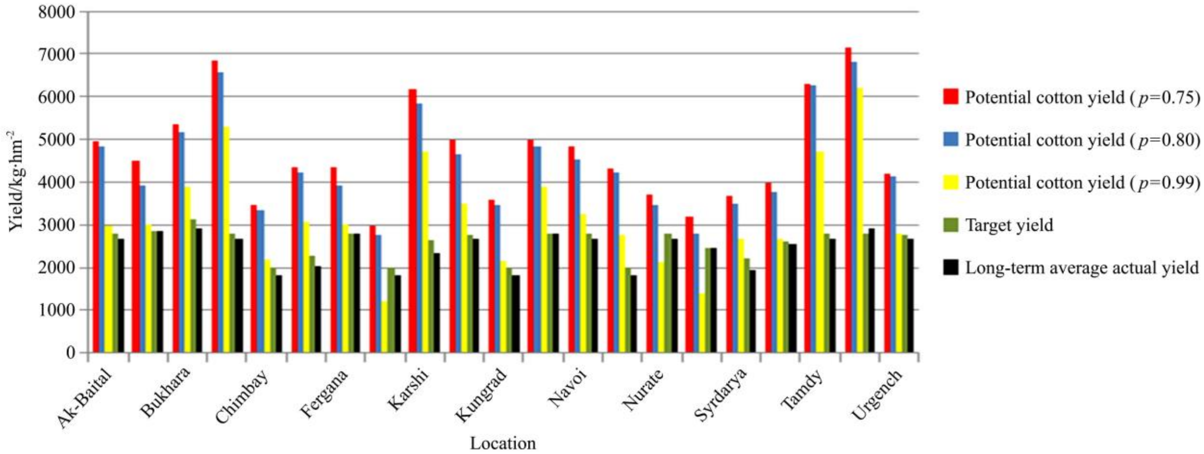
Note: PCY values (1984-2013) were obtained for April 15 planting date scenario and corrected to simulate seed-lint mass. Actual yield data was obtained for the period 1984-2012.

Figure 4 Comparison of long-term average potential cotton yield (PCY) and long-term average actual yield at each location (yield gap analysis)

3.5 Target gap analysis

Three study locations, Jaslyk, Nurata, and Samarkand, reported state-set yield targets that have at least an 80% chance of occurring in any given year, but are not guaranteed to occur every year, as their state-set targets exceed the p=0.99 PCY value (Figure 5). Therefore, it is advised that the government reduces the yield targets for these three locations or establishes that current targets be achieved in 4 out of 5 years. All other weather stations were within regions reporting yield targets that fell below yearly expected cotton yields (p=0.99) and should thus be easily attainable.

When comparing long-term average actual yields with yield targets, it can be seen that state-set targets are reasonable for all locations, as the values match closely. However, such long-term average values (actual yields) do not take into account climatic variability, which is important when setting realistic targets. Thus, taking into consideration exceedance probabilities and climatic variability/risk, as was done in this study, would be more prudent in setting targets.



Note: Government of Uzbekistan production targets were obtained from [6], except values for Namangan[28]. Target yields were calculated by dividing regional production targets (kg) by regional planting area (hm^2). Long-term average actual yields were included for reference.

Figure 5 Potential cotton yields for various exceedance probabilities (p= 0.75, p= 0.80, p= 0.99) at April 15 planting date (1984-2013), corrected to simulate seed-lint mass.

4 Conclusions

This study confirmed that April 15 is the optimal planting date in Uzbekistan, and showed that cotton growing areas located principally at lower elevations and latitudes are most suitable, demonstrated by comparing long-term average total heat units with a cutoff threshold of THU 1444 ℃. Areas considered less suitable for the production of cotton should be the focus of crop conversion efforts by the Uzbekistan Government. Potential cotton yield distributions (for long-term average and exceedance probability levels p=0.99, p=0.80, and p=0.75) were similar to that of THU. Comparing long-term average PCYs with actual yields confirmed that all study locations were performing well-below potential yields. While determining the reasons for the distribution of yield gaps is beyond the scope of this study, those areas with larger yield gaps present greater opportunity for improving yields and should be targeted for future actions. Areas such as Nukus, Kungrad, Chimbay, and Syrdarya are particularly interesting for further investigation, as benefit/cost ratio would be highest. With regards to state-set yield targets, most areas had yield targets lower than potential cotton yields expected every year (p=0.99), suggesting safe targets. Three selected weather stations (Jaslyk, Nurata, and Samarkand) reported targets above the p=0.99 level but below the p=0.80 level, suggesting some risk in attaining the target and requiring revision.

The analyses in this study have limitations as data derived from weather stations were compared to regional data (e.g. actual yield and yield targets) or used to make statements about larger areas. The findings reported in this study offer a preliminary assessment of different aspects of cotton production in Uzbekistan, and should be seen as the starting point for further in-depth studies and revisions to current practices. Future research into reasons for relatively larger yield gaps is needed as this would help target funds to obtain greatest returns for investments.

Acknowledgements

This work was undertaken as part of, and funded by, the CGIAR Research Program on Dryland Systems led by the International Center for Agricultural Research in the Dry Areas (ICARDA). Dryland Systems is supported by these donors (http://drylandsystems.cgiar.org/partner-focus).

The opinions expressed here belong to the authors, and do not necessarily reflect those of Dryland Systems, ICARDA, or CGIAR.

[References]

[1] Shtaltovna A, Hornidge A-K. A comparative study on cotton production in Kazakhstan and Uzbekistan. Bonn: Center for Development Research (ZEF), 2014; 42p.

[2] Abduraupov R. Analysis of cotton production dynamics in Uzbekistan using a system approach. Int Financ Account, 2019. Available: https://uzjournals.edu.uz/interfinance/vol2019/iss2/3/. Accessed on [2018-07-20].

[3] Ibragimov N, Evett S R, Esanbekov Y, Kamilov B S, Mirzaev L, Lamers J P A. Water use efficiency of irrigated cotton in Uzbekistan under drip and furrow irrigation. Agric Water Manag, 2007; 90(1-2): 112–120.

[4] Aw-Hassan A, Korol V, Nishanov N, Djanibekov U, Dubovyk O, Mirzabaev A. Economics of land degradation and improvement in Uzbekistan. In: Nkonya E, Mirzabaev A, von Braun J, editors. Economics of land degradation and improvement – A global assessment for sustainable development. Basel: Springer International Publishing, 2016; pp.651–682.

[5] Ibrakhimov M, Khamzina A, Forkutsa I, Paluasheva G, Lamers J P A, Tischbein B, et al. Groundwater table and salinity: Spatial and temporal distribution and influence on soil salinization in Khorezm region (Uzbekistan, Aral Sea Basin). Irrig Drain Syst, 2007; 21(3-4): 219–36.

[6] USDA Foreign Agricultural Service. Uzbekistan: Cotton and products annual. GAIN Report, Office of Agricultural Affairs, Ankara, 2016. Available: https://www.fas.usda.gov/data/uzbekistan-cotton-and-products-annual-0. Accessed on [2018-07-20].

[7] USDA Foreign Agricultural Service. Uzbekistan: Cotton and products annual. GAIN Report No. TR8011, Office of Agricultural Affairs, Ankara. 2018. Available: https://www.fas.usda.gov/data/uzbekistan-cotton-and-products-annual-2. Accessed on [2018-07-20].

[8] Luo Q, Bange M, Clancy L. Temperature increase and cotton crop phenology. In: 20th International Congress on Modeling and Simulation, Adelaide, Australia, 2013; pp.607–613.

[9] Hinchliffe D J, Meredith W R, Delhom C D, Thibodeaux D P, Fang D D. Elevated growing degree days influence transition stage timing during

cotton fiber development resulting in increased fiber-bundle strength. Crop Sci, 2011;51(4): 1683–1692.
[10] Wanjura D F, Upchurch D R, Mahan J R, Burke J J. Cotton yield and applied water relationships under drip irrigation. Agric Water Manag, 2002; 55(3): 217–237.
[11] Gowda P H, Baumhardt R L, Esparza A M, Marek T H, Howell T A. Suitability of cotton as an alternative crop in the Ogallala Aquifer Region. Agron J, 2007; 99(6): 1397–1403.
[12] Constable G A, Bange M P. The yield potential of cotton (*Gossypium hirsutum* L.). F Crop Res, 2015; 182: 98–106.
[13] Hengsdijk H, Langeveld J W A. Yield trends and yield gap analysis of major crops in the world. WOt-werkdocument 170, Wettelijke Onderzoekstaken Natuur & Milieu, Wageningen, 2009; 60p.
[14] Angella G, Vila M G, Lopez J M, Barraza G, Salgado R, Angueira S P, et al. Quantifying yield and water productivity gaps in an irrigation district under rotational delivery schedule. Irrig Sci, 2016; 34(1): 71–83.
[15] Licker R, Johnston M, Foley JA, Barford C, Kucharik C J, Monfreda C, et al. Mind the gap: How do climate and agricultural management explain the ‘yield gap’ of croplands around the world? Glob Ecol Biogeogr, 2010; 19(6): 769–782.
[16] van Ittersum M K, Cassman K G, Grassini P, Wolf J, Tittonell P, Hochman Z. Yield gap analysis with local to global relevance—a review. F Crop Res, 2013; 143: 4–17. doi: 10.1016/j.fcr.2012.09.009
[17] Bruinsma J. The resource outlook to 2050: By how much do land, water and crop yields need to increase by 2050? In: Proceedings of the Expert Meeting on How to Feed the World in 2050, Food and Agriculture Organization of the United Nations, Rome, 2009; pp. 118–150.
[18] Tittonell P, Giller K E. When yield gaps are poverty traps: The paradigm of ecological intensification in African smallholder agriculture. F Crop Res, 2013; 143: 76–90. doi: 10.1016/j.fcr.2012.10.007
[19] Aggarwal P K, Hebbar K B, Venugopal M V, Rani S, Bala A, Biswal A, et al. Quantification of yield gaps in rain-fed rice, wheat, cotton and mustard in India. Patancheru: International Crops Research Institute for the Semi-Arid Tropics. Colombo: Comprehensive Assessment of Water Management in Agriculture. Pusa: Indian Agricultural Research Institute, 2008; 30p.
[20] Djanibekov N, Sommer R, Djanibekov U. Evaluation of effects of cotton policy changes on land and water use in Uzbekistan: Application of a bio-economic farm model at the level of a water users association. Agric Syst, 2013; 118: 1–13.
[21] Killi F, Bolek Y. Timing of planting is crucial for cotton yield. Acta Agric Scand Sect B-Soil Plant Sci, 2006; 56(2): 155–160.
[22] Khan A, Wang L, Ali S, Tung S A, Hafeez A, Yang G. Optimal planting density and sowing date can improve cotton yield by maintaining reproductive organ biomass and enhancing potassium uptake. F Crop Res, 2017; 214: 164–174.
[23] Steiner J J, Jacobsen T A. Time of planting and diurnal soil temperature effects on cotton seedling field emergence and rate of development. Crop Sci, 1992; 32(1): 238–244.
[24] Waddle B A. Crop growing practices. In: Kohel R J, Lewis C F, editors. Cotton. Madison, WI.: ASA, CSSA, and SSSA; 1984. p. 234–264.
[25] Asha R, Lal A M. Screening of cotton genotypes for heat tolerance. Int J Bio-resource Stress Manag, 2013; 4(4): 599–604.
[26] Bibi A C, Oosterhuis D M, Gonias E D, Bourland F M, Keiser A R. High temperature effect on physiology and biochemistry of cotton. In: Beltwide Cotton Conference. San Antonio, Texas; 2006. pp. 5–9.
[27] R Core Team. R: A language and environment for statistical computing. Vienna: R Foundation for Statistical Computing. 2017. Available: https://www.r-project.org/. Accessed on [2018-07-20].
[28] USDA Foreign Agricultural Services. Uzbekistan: Cotton and products update. GAIN Report, Office of Agricultural Affairs, Ankara. 2014. Available: https://www.fas.usda.gov/data/uzbekistan-cotton-and-products-update-0. Accessed on [2018-07-20].
[29] Abdullaev I, Giordano M, Rasulov A. Cotton in Uzbekistan: Water and Welfare, 2005; 244(2): 239–244.
[30] Yusupov N, Muminov S, Ibragimov I, Gojenko B. Present problems of water management and agrarian reforms in Uzbekistan. Agric Sci., 2012; 3(4): 524–530.
[31] Pereira L S, Paredes P, Cholpankulov E D, Inchenkova O P, Teodoro P R, Horst M G. Irrigation scheduling strategies for cotton to cope with water scarcity in the Fergana Valley, Central Asia. Agric Water Manag, 2009; 96(5): 723–735.