Ecological Indicators 124 (2021) 107383

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Use of growing degree indicator for developing adaptive responses: A case study of cotton in Florida

Anjali Sharma [a], R. Deepa [b], Sriramana Sankar [c], Mikela Pryor [b], Briyana Stewart [b], Elijah Johnson [a], Aavudai Anandhi [b,*]

[a] School of the Environment, Florida Agricultural and Mechanical University, Tallahassee, FL 32307, USA
[b] Biological Systems Engineering, Florida Agricultural and Mechanical University, Tallahassee, FL 32307, USA
[c] Department of Biomedical Engineering, John Hopkins University, Baltimore, FL, MD 21218, USA

ARTICLE INFO

Keywords:
Climate variability and change
Temperature change
Phenological stages
Adaptation and mitigation strategies
Driver-Pressure-State-Impact-Responses (DPSIR) framework

ABSTRACT

Significant variabilities in planting and harvesting dates of crops have been observed throughout Florida in recent decades, indicating a change in their phenology. This study innovatively uses an agroecosystem indicator, growing degree days (GDD), to understand the change in cotton crop phenology throughout the region and develop adaptation strategies using the Driver-Pressure-State-Impact-Response (DPSIR) framework. GDD is the amount of heat absorbed by the growing stages of cotton. It is computed from temperature simulations obtained from the 21 models participating in the Coupled Model Inter-comparison Project Phase 5 (CMIP5) for the historical (1950–2005) and future scenarios (Representative concentration pathway (RCP) 8.5, 2006–2100) at a spatial resolution of 0.125°x0.125°. The future projections from the 21 models show an increase in surface temperature ranging from 3.5 °C to 5.5 °C. Additionally, the variability in dates for the different phenological stages shows an early occurrence of the simulation's growth stages. Historically, the minimum and maximum ranges of trend shift towards the funnel's negative side in the RCP 8.5 scenarios. The trends are estimated for two time-periods during historical (1950–1975 and 1976–2005) and future (2006–2050 and 2015–2100) periods of time. They ranged from −3.5 to 3.4 days per decade and −3.6 to 0 (no change) days per decade, respectively, among the six stages namely: emergence stage, the appearance of the first square, the appearance of the first flower, peak blooming, first open boll, and defoliation. Warming accelerated plant growth and shortened the growing period, which is translated to develop adaptation strategies for a climate-resilient crop production system, using casual chain/loops and the DPSIR framework. Identifying the multiple adaptation strategies for levels of adaptation and degree of climate change and variability can be used by different stakeholders and policymakers as a guide for making decisions to adapt cotton to climate change better. Although this methodology is applied to the cotton crop in Florida, it can be used for other crops and regions of the world.

1. Introduction

Cotton is a perennial, annual crop grown in both tropical and subtropical regions. It is the most widely used textile globally, accounting for 25% of total fiber use (USDA-E, 2019). The United States (USA) is the third-largest cotton producer after China and India (Johnson et al., 2014) and a leading cotton exporter, accounting for one-third of raw cotton's global trade. The US cotton industry accounts for more than $21 billion in products and services annually. Additionally, it generates more than 125,000 jobs in the industrial sectors spanning from farms to textile mills (USDA, 2019). *Gossypium hirsutum*, or Upland cotton, comprises the bulk of cotton growth worldwide. In the United States, 95% of cotton grown is Upland cotton, while the rest is Pima cotton. Florida was ranked among the top 15 cotton-producing states in 2016 (USDA, 2017). The cotton production in Florida largely overlies the panhandle region (northwestern part of Florida). Santa Rosa and Jackson counties have the highest cotton production, accounting for 115,200 bales (25,081,344 kg) in 2016 (USDA, 2017).

The productivity of crops like cotton depends on the plant's favorable nourishment via soil moisture and atmospheric conditions. Atmospheric conditions impact the plant phenology and play a vital role as the stressor on plant growth/development and ultimately yield (Doherty

* Corresponding author.
E-mail address: anandhi@famu.edu (A. Anandhi).

https://doi.org/10.1016/j.ecolind.2021.107383
Received 23 January 2019; Received in revised form 18 November 2020; Accepted 7 January 2021
Available online 6 February 2021

et al., 2003). Agriculture is highly vulnerable to climate variabilities due to atmospheric conditions such as temperature, sunshine, and soil moisture. A *meta*-analysis of 32 studies demonstrated the surface temperature change from 1950 to 2100 in Florida is between −3 °C to 6 °C (Anandhi et al., 2018). Changes in the phenological stage can further increase the vulnerability of ecological systems in the region.

The cotton crop is considered drought-tolerant (Esparza et al., 2007), such that temperatures in the range of 32.2 °C to 35 °C (90°F to 95°F) are considered near ideal for cotton growth. However, very little change occurs below 15.5 °C (60°F) or above 37.7 °C (100°F), especially if soil moisture is low (Wright et al., 2005). Multiple factors, such as light, rainfall, relative humidity, winds, soil, pests, etc. affect the cotton crop's productivity. A warmer environment provides favorable conditions to increase pests' growth rate and thus decreases the overall crop productivity (Hatfield and Prueger, 2015). This knowledge creates an urgent need to adapt cotton production to take advantage of the benefits of changes while reducing its adverse impacts.

The changes in the phenological stages create an immediate effect of temperature change on the cotton crop. Studies have observed temperature changes accelerated the phenological stages inhibiting maximum boll weight development in cotton (Doherty et al., 2003). Moreover, the number of days to reach maturity for cotton also differs according to the temperature zones. In Florida, cotton takes 130 to 160 days to reach maturity (Wright et al., 2005). The USDA's plant hardiness zone maps show the year 2012 differs from 1990 and displays the northwards movement zone, indicating the zones are getting warmer (Daly et al., 2012). In short, the changes in phenological stages and hardiness zones due to climate change and variability are also vital for understanding adaptation and mitigation responses (Wyman and Flint, 1967).

There are many numerical models studied both globally (Luo et al., 2013; Voloudakis et al., 2015; Yang et al., 2014a, 2014b) and regionally (Doherty et al., 2003; Esparza et al., 2007; Reddy et al., 2002) relating crop yield to climate variability (Table 1). However, only a few studies have been conducted for cotton within the Florida region, creating the necessity to understand if any changes in phenological stages exist for cotton observed in the context of climate change. Thus, this study's first objective is to assess the change in cotton phenology by GDD using Coupled Model Inter-comparison Project Phase5 (CMIP5) in Florida. The second is to develop the causal loop and chain with the DPSIR framework's help, which can be utilized by the stakeholders for management decisions and developing responses.

2. Definitions, study area, datasets used, and methodology

The methodology section involved a six-step process: definition of GDD; the study scope; data set used; estimation of mean temperature followed by determination of change; development of spatial, temporal plots using MATLAB programming; and finally, development of causal chain and loops with the help of DPSIR framework. Moreover, scenarios are studied for the growing degree days for the cotton crop in Florida to develop a DPSIR framework to draw responses or adaptation strategies.

2.1. Definition: Growing degree days (GDD)

Growing Degree Day (GDD), also known as heat units (HUs) or thermal time concept, is one of the most essential indicators in understanding the cotton plant phenology. GDDs are used as a phenological and climatic measurement to signify the difference in temperature change related to the cotton crop (Anandhi, 2016). To produce a high-yield, high-quality cotton crop, it is evident that a proper understanding of the growth and development of the cotton plant is necessary. The equation for GDD uses air temperature (McMaster and Wilhelm, 1997) as follows:

$$HU = \sum_{i=1}^{n} GDD_i \tag{1}$$

Table 1
Previous studies that relate the effects of climate change on cotton crops worldwide.

Author	Region	Model	Data	Changes in plant growth/ development
Yang et al. (2014a), Yang et al. (2014b)	Northwest China	APSIM- Oz Cot crop growth model and HadCM3 GCM (A2, A1B, B1)	Observed (1951–2012) Projected 20-year future periods centered on 2030, 2050, 2070, and 2090	Simulations showed shorter growing seasons
Voloudakis et al. (2015)	Greece	FAO aqua crop simulation model	Data from three periods, 1961–1990, 2021–2050, and 2071–2100	Lower increases in temperature caused reduction of the length of the growing period (2021–2050 & 2071–2100)
Reddy et al. (2002)	Mississippi Delta	GCM	1964–1993	Rise in CO_2 decreased cotton production in normal years
Luo et al. (2013)	Australia	CCAM model	Baseline (1980–1999) and a future period (2020–2039)	Advanced growth in future compared to baseline. Crops planted 10 days earlier (emergence earlier). Crops planted 10 days later (harvesting delayed)
Doherty et al. (2003)	SEUS	GCM and RCM	1960–1995	The changes in climate hastened phenological processes. Does not allow for maximum boll weight development due to relatively warmer temperature.

$$GDD = MAX\left[0, \left(\frac{(T_{max} + T_{min})}{2} - T_b\right)\right] \tag{2}$$

$$T_{max} = \left\{ \begin{array}{ccc} T_{max} & if & 37.7^{\circ}C > T_{max} > T_b \\ 37.7\ ^{\circ}C & if & T_{max} \geqslant 37.7^{\circ}C \\ T_b & if & T_{max} \leqslant T_b \end{array} \right\} \tag{3}$$

$$T_{min} = \left\{ \begin{array}{ccc} T_{min} & if & 37.7^{\circ}C > T_{min} > T_b \\ 37.7\ ^{\circ}C & if & T_{min} \geqslant 37.7^{\circ}C \\ T_b & if & T_{min} \leqslant T_b \end{array} \right\} \tag{4}$$

In Eq. (1), i is an index for each growing day in the crop growing duration (season's length) for n (days). In Eq. (2), T_{max} and T_{min} are the maximum and minimum daily air temperatures. T_b is the crop's base temperature (15.6 °C), defined as the temperature below which plant growth and development stops (Wright et al., 2005). 37.7 °C is the upper threshold temperature because plant roots have difficulty taking in water for growth and development (Wright et al., 2005). Eq. (2) describes the heat units or thermal time concept received by the cotton crop over a given time by integrating the area under the diurnal temperature curve and summing the daily heat units accumulated by the cotton crop in a given time period.

2.2. Study area

Florida is the selected region for this study (Fig. 1). It is popularly known as the "Sunshine State" as summers throughout the state are long, very warm, and humid (Henry and Portier, 1994), whereas winters are mild. The Florida peninsula (25°N to 31°N) makes it a diverse climatic region characterized by differences in frost occurrence, chill accumulation, growing degree accumulation, and solar radiation affecting crop growth (Her et al., 2017). Agriculture in Florida notably contributes to the economy. It ranked first in the USA for cucumber, grapefruit, oranges, squash, sugarcane, fresh market snap beans, and fresh market tomatoes production values (FDACS, 2017). Exposure of the agriculture crops in this changing climate is critical since it can prolong the growing season length, increase pests and diseases, and ultimately disturb the region's environmental system. Crops in Florida are irrigated frequently, especially in winter. Florida has the most extensive acreage of wet sandy soil with an organic-stained subsoil, Myakka, which is dark with some being acidic and others being rich in organic matter (USDA, 2019; Watts and Collins, 2008). The soil differs in the southern portion of the state, though, where bogs and marshes are more common.

2.3. Dataset used

21 CMIP5 downscaled models for the surface temperature (maximum and minimum) are downloaded for historical (1950–2005) and Representative Concentration Pathways (RCPs) (2006–2100) (Maurer et al., 2002) and plotted. The RCPs are future projections with the mitigation scenario that assume policy actions to reduce emission targets. These RCPs are consistent with high emission scenarios (RCP 8.5) (Taylor et al., 2011). The RCP 8.5 combines assumptions about high population and relatively slow income growth with modest rates of technological change and energy intensity improvements, leading in the long term to high energy demand and increased greenhouse gas (GHG) emissions in the absence of climate change policies (Riahi et al., 2011). This data is available at 0.125° × 0.125° grid resolution for the entire United States, which is further extracted for the Florida domain (i.e., 856 grids). The list of all 21 models is shown in Table S1. We utilize data analysis from only one future scenario, RCP 8.5. This is because RCP 8.5 follows the present forcing of the global CO_2 emissions, which continue to track this emission's high end (Bhardwaj et al., 2018; Misra et al., 2019; Peter et al., 2013). Moreover, observed monthly precipitation and temperature data are downloaded from the Climate Prediction Center (CPC) of the National Centers for Environmental Prediction (NCEP) (Kalnay et al., 1996). Precipitation datasets are available globally over the land surface at 0.5 × 0.5 spatial resolution from 1979 to 2018 (Chen et al., 2008; Xie et al., 2007). The dataset is used to compute the climatology of the precipitation and monthly surface temperature over Peninsular Florida.

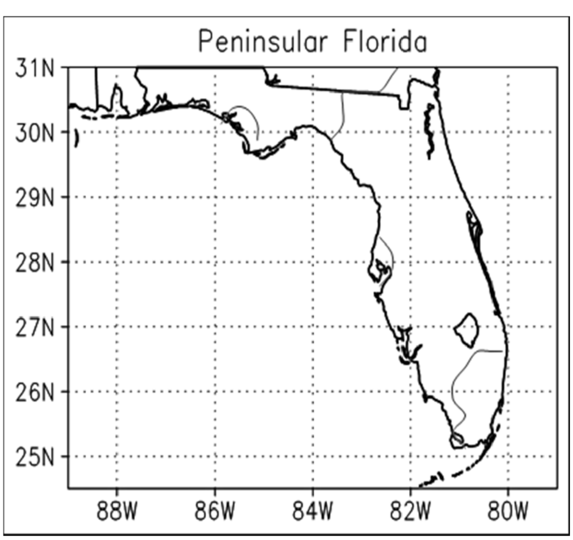

Fig. 1. Study Domain.

2.4. Methodology

In this methodology section, steps are well-defined for the analyses done for the GDD, spatial, and temporal plots in Florida and, finally, to develop adaptation strategies from the DPSIR framework. These steps, also illustrated in Fig. S1, are necessary because they clearly define the terms and concepts of the GDD to develop the plan and analyze it.

Step 1: Analysis of literature for cotton production, phenology, and planting and harvesting dates: Cotton crop production data is downloaded from the National Agricultural Statistics Service (USDA/NASS, 2018) from 1960 to 2018. Documentation of information is done to know the causes behind the gradual decrease/increase in cotton production. Additionally, an intensive literature review is conducted to identify the number of stages with GDD value and different planting dates across the United States. This study, May 1, is chosen as the planting date to compute Florida's heat units. A discussion of this step is provided in section 4.1 (Fig. S4).

Step 2: Data analysis with CMIP5 models: Data analysis with 21 CMIP5 for historical (1950–2005) and RCP 8.5 (2006–2100) is used to analyze and compare the mean variability in maximum and minimum surface temperatures. Annual scenarios are illustrated, consisting of one temperature value for each year and corresponding for each simulation model for historical and RCP 8.5 time periods.

Step 3: Calculate GDD and cumulative GDD: Data analysis of CMIP5 models is performed with daily minimum and maximum temperatures to compute the daily GDD values using Eq. (1) for historical and future simulations. To compute GDD, t_{max} and t_{min} are selected for the cotton crop, i.e., 37.5 °C for maximum threshold. Eqs. (3) and (4) clearly interprets that if $t_{max} < T_b$, then $T_{max} = T_b$ and if $T_{min} < T_b$, then $T_{min} = T_b$. The detailed interpretation of GDD calculation is given in (McMaster and Wilhelm, 1997). The daily GDD values from May 1 of each year are accumulated at each grid point of the Florida domain (Table 3).

Step 4: Estimate the day of the year to reach each growth stage and duration of each stage: The day when the approximate cumulative GDD is reached for each of the six growth stages is documented. The duration of each growth stage is calculated as the number of days between two growth stages.

Step 5: Estimate trends: For each crop stage, least-squares linear trends are fitted to the day of the year, and the growth stage's duration using linear regression. Significance test of trends: A variant of the *t*-test is used to calculate the trend's significance and account for the serial autocorrelation in the time series. This method is based on Anandhi, 2016, and is described briefly in the Supplementary material.

Step 6: Estimate the variability in the dates of different cotton stages: For each stage, the selected CMIP5 model's mean values from 856 grid points are portrayed as a box plot to check increasing or decreasing trends. Each boxplot shows the 21 CMIP5 models for the area average for each stage. The Julian days for each stage that range between two time-periods both in historical (1950–1975, 1975–2005) and RCP8.5 (2006–2050, 2050–2100) are tabulated.

Step 7: Estimate the spatial variability of trend lines: For each stage, the average trend values from 856 grid points in Florida are for three periods both for historical (1950–1975, 1975–2005, 1950–2005) and RCP 8.5 (2006–2050, 2050–2100, 2006–2100) for 21 models. The minimum and maximum trends across 856 grids for each of the time-periods are tabulated. Similarly, for each cotton stage and model, the slope value change for three time-periods both for historical (1950–1975, 1975–2005, 1950–2005) and RCP 8.5 (2006–2050, 2050–2100, 2006–2100) is shown. The statistical significance is tested with a *t*-test at a confidence interval of 90%.

Step 8: Temporal variability in each stage: For each stage, the trend values from each of 856 grid points in Florida for two time-periods, historical (1950–1975, 1975–2005) and RCP 8.5 (2006–2050, 2050–2100), for the 21models are plotted. Scenario funnels provide a dynamic view of the future by exploring various change paths in variables (Anandhi et al., 2018). Thus, displaying slope for combinations of grids, time-periods, and GCM can be inventive. For the funnel plot, lines are drawn between years, showing a change in trend values. Each scenario line is plotted between the start and end year of the known change. Hence, the scenario funnel plot is derived by combining one or more scenario lines. The changes in trends observed in the cotton phenological stages in CMIP5 simulations with years are plotted to generate the funnel plot. The x-axis in funnel plots represents the time (years), whereas the y-axis represents the trends in each stage's Julian days.

Step 9: Develop the causal chain and loop using the DPSIR framework: The DPSIR (Driver-Pressure-State-Impact-Response) framework was developed in the late 1990 s and proposed by the Organization of Economic Co-operation and Development (OECD, 2003). This framework's primary purpose was to structure and organize indicators in a meaningful way for the decision-makers. Later, the DPSIR framework was adopted by the European Environmental Agency (EEA) in 1995 (Gabrielsen and Bosch, 2003). Furthermore, in the DPSIR framework (Fig. S2): the "Driver" refers to significant social and economic processes outlining human activities having a direct impact on the environment; "Pressure" results from the driving force which impacts the environment; "State" refers to the condition of the environment that is not static; "Impacts" are the changes in the states; and "Responses" refer to formal efforts to address changes in state, as prioritized by impacts. DPSIR is a casual chain link to inspect the most critical root of vulnerability, identifying where and how different drivers and pressures interact and lead to vulnerability, as well as the available capacities to cope with threats. Those responses (e.g., adaptation strategies) are defined as the general plan or some action for addressing the impact of climate change, including climate variability and extremes, which includes various policies and measures with a specific objective to reduce vulnerability (Biesbroek et al., 2010).

Adaptation is a crucial feature of sustainable ecological, social, and agricultural systems (Anandhi, 2017). Adaptation is also considered a policy response to the impacts of drivers and pressures (Smit and Skinner, 2002) and can involve decision-making by stakeholders and producers. Increasing temperatures have shortened crop duration with fewer days for growth and development and reduced yield (Anapalli et al., 2016). Different levels of adaptation strategies are shown in Fig. 7 for the changing climate. These include incremental adaptation, system adaptation, and transformational adaptation, as discussed. These are defined as 1) Incremental strategies are the practices and technologies with minor changes (such as changing planting dates) within existing fields; 2) System adaptation strategies are the significant changes in existing agricultural areas (such as precision agriculture); and 3) Transformational strategies include robust change (such as land-use change) in a new field rather than the existing one (Anandhi, 2016). Hence, applying the DPSIR framework for decision making and for the development of GDD to develop adaptation strategies for the trends is innovative in this study.

3. Results

3.1. Analysis of literature for cotton production, phenology, and planting/harvesting dates

In the early 1970s, due to widespread pest problems, there was a decline in yield growth, falling to 4.8% from 1974 to 1978 (Cooke and Sundquist, 1991). Cotton was a significant "power" crop in Florida's early 80's (Hering, 1954) where St. Marks, Port Leon, Newport, and Apalachicola were the important cotton ports with dockside warehouses. In the early 1980s, productivity was increased by 5.6% as farmers adopted shorter season production systems, improved pest management practices, and suspended production on marginal acreage (Cooke and Sundquist, 1991). The USDA dissipated the cotton crop in the early 1990s because of its susceptibility to the boll weevil. In the 1990s, production rose rapidly by the use of advances in technology (seed varieties, fertilizers, pesticides, and machinery) and production practices (Fig. S3). In 2016, Florida ranked 14th out of the 17 states reporting cotton statistics. In 2016, Florida produced 196,000 bales (41,388,800 kg) of cotton (USDA, 2017). According to the special projects from UF/IFAS Communications, almost all of Florida's cotton crop had been damaged, with losses totaling around $51 million, due to Hurricane Michael in 2018 (Nordlie, 2018). The five studies with growing degree units for each of the phenological stages of cotton obtained from the literature review are synthesized in Table 2. The table shows that the number of phenological stages with GDD heat units varied from 5 to 7 among the studies. A range of heat units for a phenological stage in cotton was observed. In this study, the six phenological stages of cotton-based on Wright et al., 2005 are used. The six phenological stages of cotton are emergence, the first square's appearance, the appearance of the first flower, peak blooming, appearance of first boll, and defoliation (Fig. S4). In three of the six stages, the number of days in each stage was available and documented (Table 3).

Table 2
Studies showing the Different Growing Degree Days (GDD) stages for cotton.

Author	Region	Base Temperature	GDD stages and values (Days)
Oosterhuis (1990)	Mid-south	60 °F	Seed emergence- 50–60 Nodes up- 45–65 First square emergence- 425–475 Square to white flower- 300–350 Planting to first flower- 775–850 White flower to open boll- 850 Planting to harvest- 2600
Ritchie et al. (2004)	Georgia	60 °F	Emergence- 50 First square- 550 First flower- 950 Open ball- 2150 Harvest- 2600
Wright et al. (2005)	Southeast United States	60 °F	Emergence- 45–130 First square- 440–530 First flower- 780–900 Peak Blooming- 1350–1500 First open boll- 1650–1850 Defoliation- 1900–2600
Tsiros et al. (2009)	Greece	15.6 °C	Sowing to emergence- 50 First leaf- 450 Square to bloom- 330 Bloom to open bolls- 950 Normal crop production- >2800
Hutmacher et al. (2004)	California	60 °F	Emergence to the first flower- 425–500 Emergence to first bloom- 750–900 Emergence to peak bloom- 1350–1500 Emergence to first open boll- 1650–1850 Emergence to 60% open boll- 2200–2350

Table 3
Approximate accumulated growing degree days (GDD) or heat units in Fahrenheit required for the cotton crop to reach different growth stages from the time of planting (May 1).

Growth stage	Days	Heat units (DD60s) *
Emergence	7	45–130 (87.5)
Appearance of first square	39	440–530 (485)
Appearance of first flower	62	780–900 (840)
Peak blooming	n.a	1350–1500 (1425)
First open boll	n.a	1650–1850 (1750)
Defoliation	n.a	1900–2600 (2250)

*Source: Adapted from Wright et al., 2005. The values in parenthesis are values used in this study. n.a. refers to not available.

Variability in the planting and harvesting dates for the Southeastern Unites States (SEUS), i.e., Florida, Georgia, Alabama, Mississippi, Tennessee, North Carolina, and South Carolina were taken from USDA 2010 and 1997 (Fig. S5). In the figure, green and blue represent the most active planting and harvesting dates. Among the states, the planting dates for Mississippi and North Carolina during 1997 are similar, while Alabama shows the earliest planting date. In 2010, Florida marked the earliest planting date with Alabama and Mississippi showing similar dates. The harvesting dates for the year 1997 display the earliest dates for Alabama and Florida's latest date. Mississippi has the earliest harvesting date from 2010, while Georgia and Alabama have similar harvesting dates. With that being said, the focus of this study is on the state of Florida.

It is clear from Fig. S5 that the planting and harvesting dates for Florida changed from 1997 to 2010. For 1997 the planting dates were from April 1 to June 15, while it changed from April 15 to June 15 for 2010. Similarly, the harvesting dates for 1997 were from September 15 to December 1, while for 2010, they changed to September 20 to December 15. In some studies, it is shown that if planting dates are changed or modified due to climate impacts, it will advance or delay harvesting, ultimately impacting crop yield (Luo et al., 2013). Since cotton crop originated in a warm climate (Reddy et al., 1992) and its growth is dependent on a certain thermal threshold, we can attribute the change in cotton crop planting and harvesting dates to the interannual or decadal changes in surface temperatures, which affect the phenological stages. Therefore, in the following sections, we examine a significant trend in surface temperature in Florida during the 1950 to 2100 periods from climate model simulations.

3.2. Analysis of surface temperature of Florida

Temperature plays a critical role in the growth and development of the cotton crop. The continuing rise in global atmospheric carbon dioxide and greenhouse gases is expected to cause a rise in atmospheric temperatures. The principal effect of an increase in carbon dioxide is an increase in photosynthesis (Baker et al., 1990) and the partial closure of stomata that leads to reduced leaf transpiration (Jones et al., 1985). This results in an increase in tissue temperature. Thus, we can predict considerable alterations in plant phenology with climate change due to the rise in CO_2 and the corresponding temperature increase. Therefore, in this section, Florida's temporal variability of surface temperature is analyzed using CMIP5 model simulations. The annual average maximum and minimum surface temperatures of Florida from 21 CMIP5 models for the historical and RCP 8.5 scenarios are shown in Fig. 2. The RCP 8.5 scenario is a baseline scenario in which the greenhouse emissions and concentration increase considerably over time. Surface maximum temperature change ranges from 3.5 to 5 °C, whereas surface minimum temperature change ranges from 3.5 to 5.5 °C. Thus, one can anticipate changes in the phenological stages of the cotton crop in Florida. The monthly mean climatology from 1979 to 2017 is shown in Fig. S6. A maximum temperature of 28 °C is recorded for July, and a minimum temperature of 14 °C is recorded for January.

3.3. Variability in the dates of the different crop stages for cotton in CMIP5 simulations

The variability in the dates for six phenological stages for the cotton crop is shown in Fig. 3. The historical simulation shows the variability in the cotton crop dates from 21 models for the period 1950–2005 for each phenological stage. The x-axis represents the years, and the y-axis represents the days for each stage, represented as Julian days. A Julian day is the number of elapsed days since the beginning of the year. Each boxplot shows the 21 CMIP5 models for the area average for each stage. The emergence stage starts on average after 127 Julian days, meaning it emerges five days after planting. It requires approximately 153 Julian days or 27 days from emergence for the first square to appear. The first flower appears at an average of 173 Julian days, meaning it requires 20 days from the first square. For the peak blooming, it took an average of 202 Julian days, meaning it requires approximately 47 days from the first flower. The first open ball emerged 44 days from the first flower, which took nearly 217 Julian days. The defoliation stage takes on average 244 Julian days, meaning it takes 117 days to reach maturity.

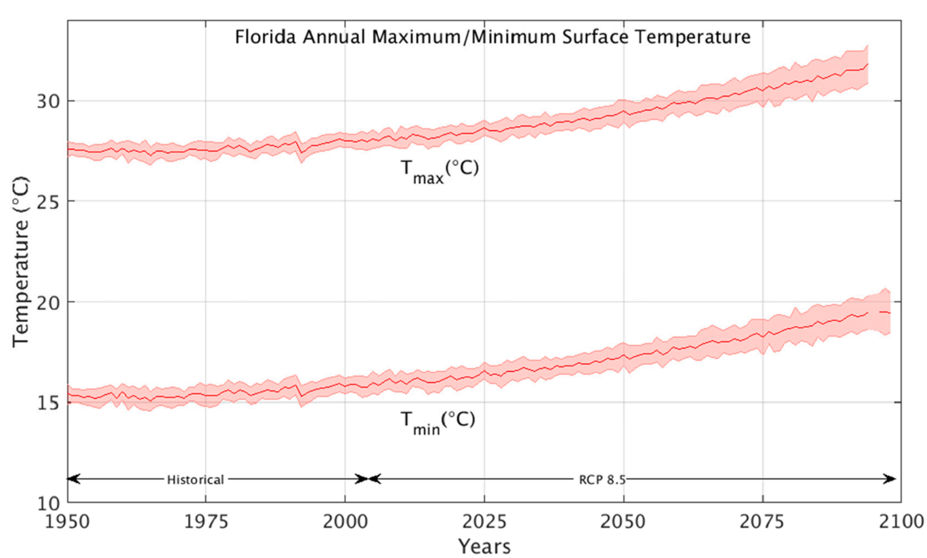

Fig. 2. Comparison of Florida mean variability in maximum and minimum surface temperatures from climate models during 1950–2100.

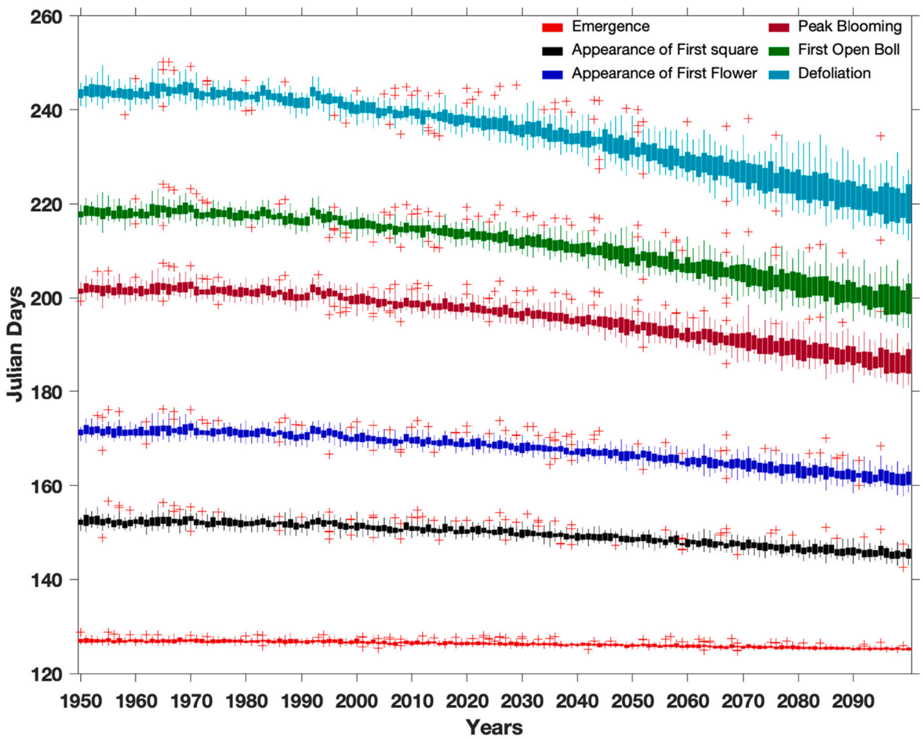

Fig. 3. Variability in the dates of the different crop stages studied from the 21 models for historical (1950–2005) and RCP 8.5 (2006 to 2100). Different boxplots in different colors are for six phenological stages: Emergence (Red); Appearance of the first square (Black); Appearance of first flower (Blue); Peak blooming (Dark red); First open boll (Green); Defoliation (greenish-blue). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

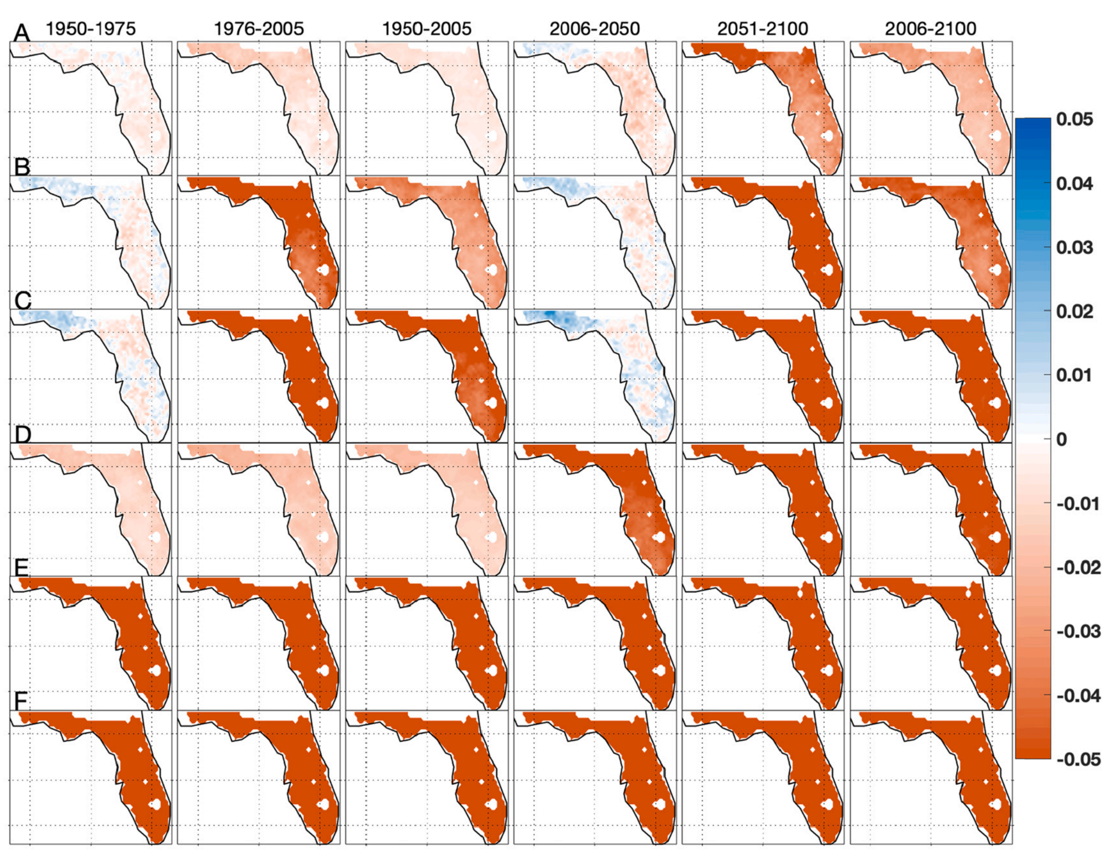

Fig. 4. Spatial changes in the cotton (a) emergence, (b) appearance of first flower, (c) peak blooming, (d) first open boll, (e) appearance of first ball, and (f) defoliation across Florida for historical (1950–2005, first three columns) and RCP 8.5 (2005–2100, last three columns). Statistical significance was tested with a *t*-test at a confidence interval of 90%.

Table S4 shows the approximate days to reach maturity after planting. In the next section, we investigate how these stages will change in the future from RCP 8.5 simulations. Wright et al., 2005 observed that it takes 130 to 160 days for the crops to reach maturity, while our results indicate 117 days, meaning it takes less time to reach maturity. The historical simulations from the CMIP5 models show the various phenological stages are starting earlier, and maturity is achieved in fewer days than in previous studies.

However, the RCP 8.5 scenario shows the variability in the cotton crop dates in 21 CMIP5 models from 2006 to 2100 for each phenological stage. The emergence stage starts on average at 125 Julian days, meaning it emerges on the 4th day after planting. The appearance of the first square appears at 144 Julian days. It requires 19 days from the emergence for the first square to appear. The cotton's first flower appears at an average of 163 Julian days, 19 days from the first square. The peak bloom requires approximately 26 days from the first flower and occurs at an average of 189 Julian days. The first open boll appears after 205 Julian days, requiring 42 days from the first flower. The defoliation stage is reached an average in 220 Julian days, thereby taking 95 days to reach maturity. The range of each phenological stage in Julian days is presented in Table S2. Similarly, it is seen from the study that each stage between the time-period 2006 to 2100 is going to reach maturity very early, specifically in 95 days. The occurrences of the six stages observed from the 21 CMIP5 models over Florida are also shown in Table S2.

3.4. Spatial changes in the cotton phenological stages for 21 CMIP5 models

Spatial plots (Fig. 4) show the variability in trends (days per year) of each phenological stage for all 21 CMIP5 models at each grid point of Florida for historical and RCP 8.5 scenarios for all stages (A, B, C, D, E, and F). For the emergence stage (A), trends show a negative change in slope revealing early emergence (0 to −0.02) from 1950 to 2005. From 2006-2050, +0 to 0.01 days/year change in slope is shown for panhandle regions. Overall, the emergence stage shows 0 to −0.05 days/year from 2006 to 2100, which clearly indicates early emergence. For the appearance of the first flower (B), the panhandle region shows the positive range of 0–0.02 days/year from 1950 to 1975 and 2006 to 2050. Overall, this stage shows a 0 to −0.05 days/year slope value, which means the first flower's early formation. The peak blooming shows a slope value of 0 to −0.05 days/year from 1950 to 2021, but from 1950 to 1975 and 2006 to 2050 it shows delaying in a stage near the panhandle region and southern Florida. The fourth stage shows a negative slope from 1950 to 2005 in the range of 0 to −0.02 days/year, whereas it shows −0.02 to −0.05 days/year for the later time period. For the last two stages, i.e., the appearance of first ball and defoliation, it shows the range from 0 to −0.05, explicating these stages early appearances. The interesting point to note here is the last three stages are affected most due to increasing temperature causing them to show early. Moreover, the spatial variability in the length of each stage of cotton is discussed and plotted for historical (1950–2005) and RCP 8.5 (2006–2100) (Figs. S7–S27) due to the huge volume of figures. Interestingly, the common fact is noted that all stages of the cotton crop show a negative slope, i.e., all stages will be early in the future. Thus, it is clear from the analysis that temperature increase is the primary factor affecting the shift in the length of phenological stages. As a result, this information helps the stakeholders and other managers use this information and results for decision making.

3.5. Temporal variability in each stage of the cotton crop

Temporal variability of the trends in Julian days for the six stages of the cotton crop from historical simulations (1950–1975 and 1976–2005) is illustrated in Fig. 5. The historical simulation during 1950–2005 is

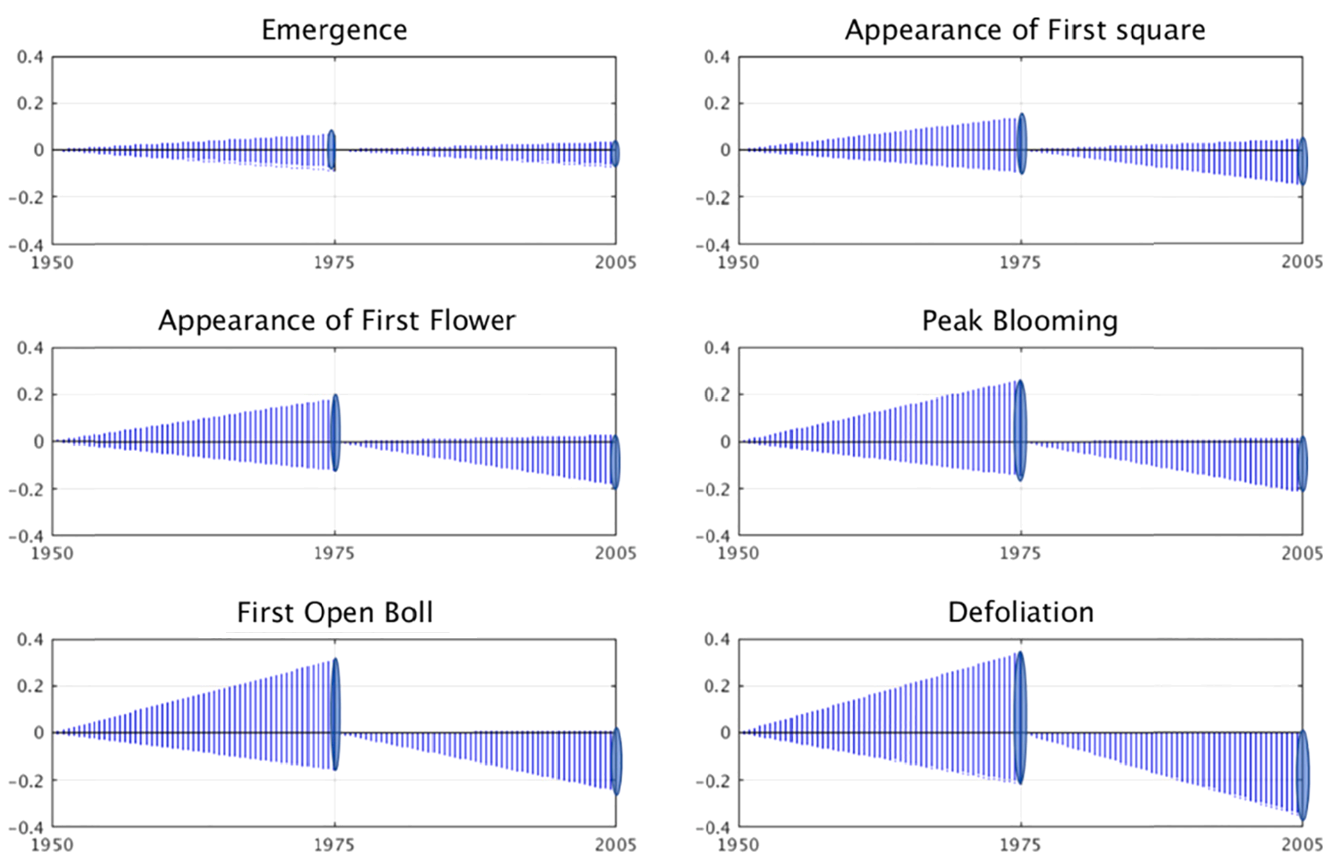

Fig. 5. Development of scenario funnel plots for the trends from 1950 to 1975 and 1976 to 2005, in which x-axis in funnel plots represented the time (years) whereas y-axis represents the changes in trends (°C). Statistical significance was tested with a *t*-test at a confidence interval of 90%.

symmetric funnel scenario until the appearance of the first flower stage. The funnel spread has increased in the direction of a positive trend in the remaining stages, marking the delay in reaching maturity. Whereas for the rest of the period, 1976–2005, the funnel is asymmetrically showing the spread towards the negative values. As the stages go on, the spread increases to higher negative values. This indicates the cotton crop's phenological stages are starting earlier. Similarly, Fig. 6 is the representation of the future funnel scenario for RCP 8.5, from 2006 to 2050 and 2050 to 2100. The early period of 2006 to 2050 depicts a near-zero trend pattern for the emergence stage. The trend pattern shows negative values slowly increasing its extent in the succeeding stages. The late period, 2051 to 2100, shows more negative trends indicating the stages will be earlier nearing 2100 compared to the 2050s. These changes in the phenological stages can alter crop production. From this study, the analysis of the stages with different GCMs for the historical and RCP 8.5 scenarios shows both delay and early occurrence in stages of the cotton for historical simulations and early occurrence in the future scenario.

3.6. Development of a causal chain/loop using the DPSIR framework

To utilize the benefits of increasing temperature and reduce its impact, several adaptation strategies can be developed (Anandhi, 2017; Anandhi et al., 2016) by applying the DPSIR framework. The framework is widely used in multiple ecosystems, such as marine ecosystems, coastal ecosystems, and agroecosystems (Anandhi and Kannan, 2018). In this study, climate change is considered the driving force and temperature change is the pressure affecting the cotton plants. An increase in the number of pests and extreme events such as hurricanes are also considered pressure. The cotton plant's state is represented using a growing degree day indicator that represents the plant's growth and development. The pressures eventually impact phenological stages, crop quality, and crop yield. Responses are made through different adaptation strategies. The DPSIR framework developed for the cotton crop for other pressures such as temperature change, extreme events (Hurricane, tornado, etc.), and the number of pests are documented in Figs. S28–S30.

The DPSIR framework helps in demonstrating the cause-effect relationship between environmental and human systems. Using the DPSIR framework in the agricultural sector can be beneficial for the stakeholders and farmers so a decision can be made with proper adaptation strategies, which could be one of the above three levels of adaptation strategies. Incremental strategies in literature have little effectiveness and benefits (Fig. 7) other than the transformational adaption strategies. Additionally, there will be an increase in intricacy, cost, and risks in action while moving from incremental to transformational change (Howden et al., 2007; Kates et al., 2012; Stokes and Howden, 2010). When developing adaptation strategies, the multidisciplinary nature of adaptive management of ecosystems and knowledge gaps existing when translating the biophysical information into adaptation strategies may limit our understanding of how to adapt with regards to ecosystems purposes (Anandhi et al., 2018; Prokopová et al., 2019).

4. Discussion

This study is an improvement of a previous study by the corresponding author in which the use of GDD was demonstrated as an effective ecosystem indicator for changing diurnal temperatures and their impact on corn growth stages in Kansas (Anandhi, 2016). In the present work, GDD is used to develop a causal loop using the DPSIR framework to provide adaptation strategies. The usefulness of GDD is demonstrated using observations and CMIP5 model simulations for historical and future scenarios.

For 2100 an increase of ~5 °C day and nighttime temperatures were simulated from 21 CMIP5 models. A *meta*-analysis of published surface temperature change from 1950 to 2100 in Florida showed an increase of 6 °C by 2100 (Anandhi et al., 2018). Experiments on cotton plants revealed developmental stages occurred much more quickly with increased temperature. There were decreases in the number of days to the appearance of the first square (flower-bud), first flower, and mature open boll (Reddy et al., 1997). Similar results were observed in the

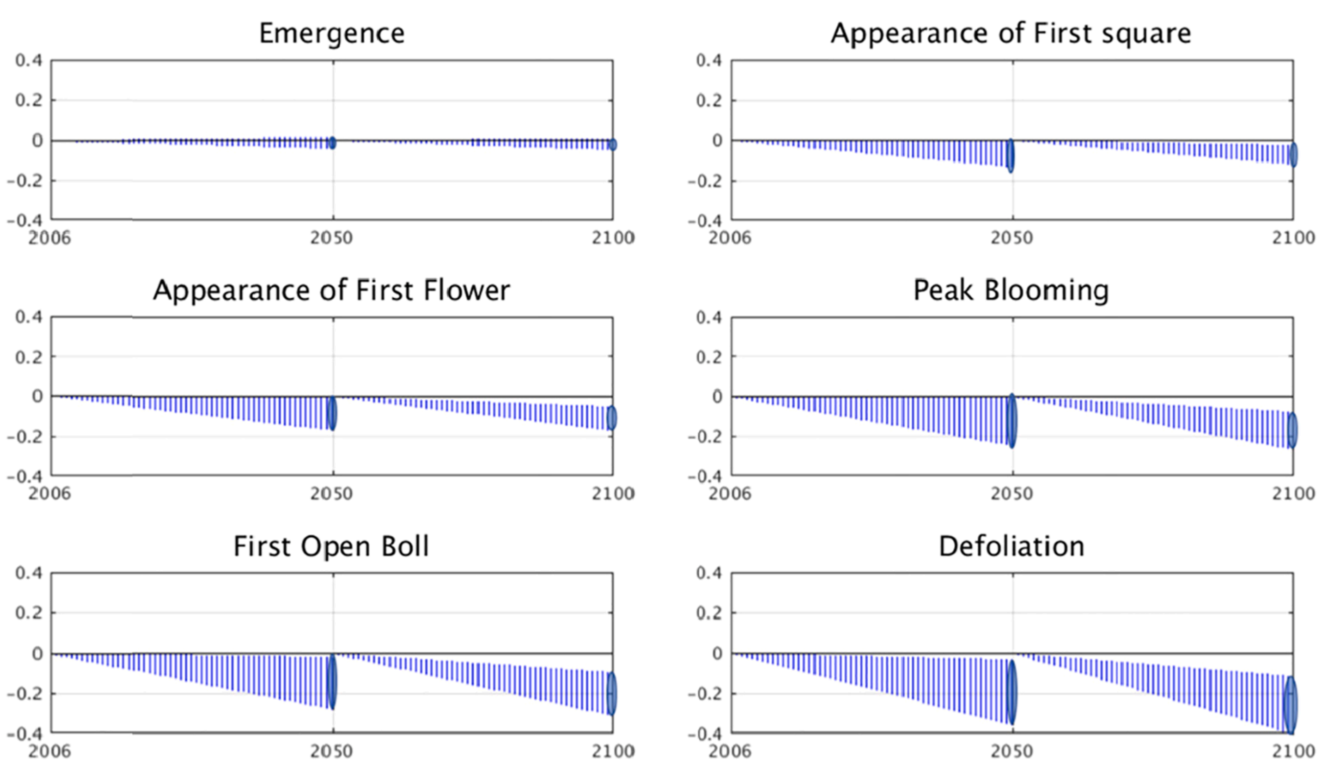

Fig. 6. Development of scenario funnel plots for the trends from 2006 to 2050 and 2051 to 2100, in which x-axis in funnel plots represented the time (e.g., years) whereas y-axis represented the changes in trends (°C). Statistical significance was tested with a *t*-test at a confidence interval of 90%.

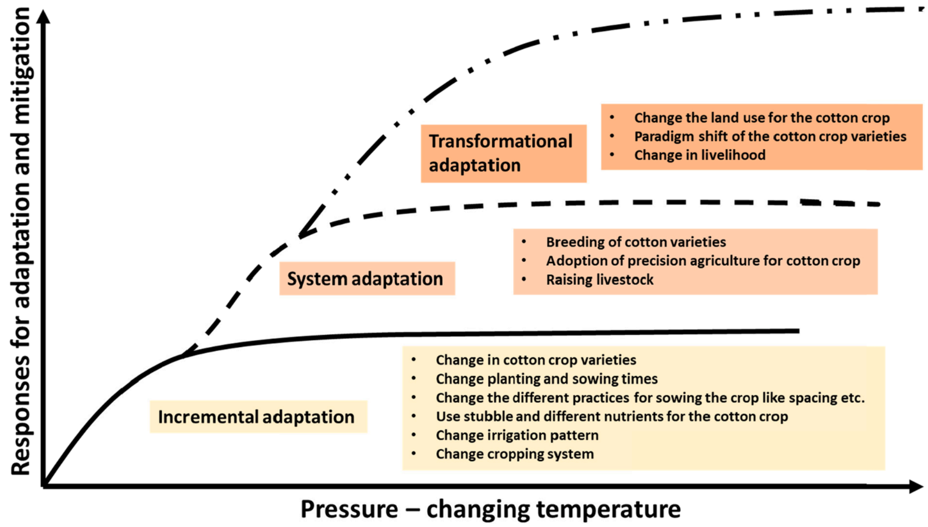

Fig. 7. The potential adaptation to changing GDD with increasing climate variability. This was adapted from Strokes et al, 2010.

developmental stages from model simulations in this study. Although both day and night temperatures influence cotton bolls' production, it was found that nighttime temperature was more influential on boll maturation (Viator et al., 2005). Higher temperatures cause early maturity of the cotton bolls resulting in a severe decrease in seed and cotton yield and shorter growing season length (Chen et al., 2019; Yang et al., 2014a, 2014b). Yield loss of up to 16% by 2080 under RCP 8.5 was predicted (Anapalli et al., 2016; Chen et al., 2019; Voloudakis et al., 2015). The decrease in the number of days between stages will reduce crop yields and affect cotton fiber quality.

Fiber-quality is impacted during the different phenological stages of fiber development. These include the period of peak rates of elongation post-anthesis, a transitory period, and secondary cell wall bio-synthesizing phase (8–10 days, 12–16 days, and up to ~ 35 days post-anthesis for a cotton variety, respectively) (Hinchliffe et al., 2011). High-temperatures in cotton cause luxuriant vegetative growth due to premature boll abscission, hastening development, especially during the boll-filling period, resulting in smaller bolls and lower yields with poor lint quality (Reddy et al., 2002). In addition to temperature, other abiotic stressors such as soil moisture (from rainfall/irrigation) and CO_2 levels impact cotton production (Williams et al., 2015). As sunlight is essential to cotton plants for photosynthesis, the climatic extremes can reduce photosynthesis and cause the fruit to shed. Evaporative cooling keeps the temperature of the plant below 90°F. If the soil moisture is insufficient for cooling to occur, the boll may shed.

On the other hand, excess soil moisture can reduce photosynthesis, causing the fruit to shed. Thus, the production in cotton varies among different regions depending on their climate and soil moisture. The variability in surface temperature can also affect the soil moisture content, which leads to changes in the phenological stages of the cotton crop (Hatfield and Prueger, 2015; Sement, 1988).

Cultural practices such as earlier planting may be used to avoid the negative impacts of high temperatures during mid to late summer (Reddy et al., 2002). Earlier planting can be a useful adaptation strategy to mitigate cotton yield reduction due to future temperature increase (Chen et al., 2019). The optimum temperature for cotton growth, boll development, and retention is around 28 °C to 32 °C (critical for yield), while at about 35 °C the reproductive growth stops completely (Anapalli et al., 2016). Earlier planting could decrease cotton yield reduction due to future temperature increase (Chen et al., 2019). Marek and Bordovsky (2006) suggested planting must occur when soils are warm enough for rapid growth early in the growing season in Texas. No-tillage practices with cover cropping would increase the lint yield by more than 10% (Delaune et al., 2019).

Climate change studies for cumulative GDD and Florida trends were limited, but it has been estimated for different areas. For example, USDA estimated the planting and harvesting dates in 2010 were April 15 to June 15 and September 20 to December 15. They changed from April 1 to June 15 and September 15 to December 1 in 1997 in Florida. The decrease in dates between planting and harvest could be contributed to changing temperatures, shorter period cotton varieties, improved pest management, and agricultural practices. It was estimated that cotton development between planting and squaring ceases below 11.4 °C in New South Wales. A delay of one week in planting decreased the planting to the emergence phase by 0.9 days, the emergence to squaring phase by 2.2 days, and the squaring to the flowering stage by 0.4 days (Constable, 1976). DeTar (2008) shows deficit irrigation of cotton on sandy soil can significantly reduce yield. (Reddy et al., 1992) observed time to the first square was more sensitive to a temperature of 27 °C than other phenological stages, boll-filling period became shorter as temperatures increased, and boll size was reduced at temperatures above or below 26 °C. Schaefer et al. (2018) observed that mid to late-season irrigation improved yield and fiber quality between 525 and 750 GDD. Viator et al. (2005) observed that DD3017 (30 and 17 as thresholds) provided the best results with the cotton yield.

The results presented in this study are subjective to the following assumptions. Firstly, in this study, a commonly used threshold temperature of 15.6 °C (Wright et al., 2005) was used. However, several studies were using other threshold temperatures, namely: 17 °C degree day (Viator et al., 2005), 16.5 °C (Chen et al., 2019), and 15.5 to 16 °C (Yfoulis and Fasoulas, 1978). The results are subjective to the threshold temperatures used. Although the planting dates can vary, planting is considered May 1 in this study.

Additionally, the accumulated heat units for a cotton crop variety to reach different growth stages from the time of planting are used. The current study utilizes 21 CMIP5 models that link climate impacts research with adaptation planning, and management is an essential aspect of this study. The DPSIR framework is helpful because it focuses on different drivers, their impacts, and possible responses (Poppy et al., 2014). Additionally, it helps identify a vulnerability index's indicators as a cause-effect relationship and provides the feedback of the cause-effect process (Khajuria and Ravindranath, 2012). It also helps identify and describe processes and interactions in human-environmental systems and assess sustainable agricultural development (Zhou et al., 2013). However, one of the disadvantages of this framework is its lack of specifically illustrating transparent cause-effect relationships for environmental problems (Carr et al., 2007). Developing a decision support tool will help in evaluating and comparing decision outcomes.

Implementing adaptation options significantly reduces vulnerability, improves resilience to future changes, and has a higher potential for well-being (Brooks and Adger, 2005). In addition to the three levels of adaptation strategies (incremental, system, and transformation adaptation strategies) used in the study, other classifications of adaptation strategies available in literature can also be used.

This study (trends and duration of the stages) and adaptation strategies can provide quantitative information for crop breeders. Researchers to develop new genetically modified crops, i.e., system adaptation strategies, can mitigate the adverse effect of climate. Managers, crop advisors, and producers can use this information to select genetically modified varieties of cotton from existing ones (e.g. early to late maturity varieties), which is incremental adaptation, or can decide to change the cotton crop landscape, i.e., transformational adaptation.

5. Conclusion

This study is innovative because GDD is used to develop causal loops using DPSIR to link pressure (changing temperatures) to response (adaptation strategies). The method is demonstrated for the cotton crop in Florida. Subsequently, the methodology can be applied to other crops and regions of the world. The study investigated the increasing trend in temperature on the phenological phases of cotton crop using historical and RCP 8.5 simulations from 21 CMIP5 models. The historical simulations (during 1950–2005) show an increase in the length of emergence, first flower appearance, peak blooming, first open boll, and defoliation stages of cotton across Florida. The future simulations (RCP 8.5) from 2006 to 2010 exhibit early occurrence for all the stages.

Additionally, the trend analysis provides quantitative values to develop the causal loop. Finally, adaptation strategies to cope with the increase in temperature have been drawn from the DPSIR framework. The use of multiple adaptation strategies for different adaptation levels, specifically incremental adaptation, system adaptation, and transformational adaptation, address various changes in trend values. The incremental adaptation involves changing the planting and sowing times and developing new cultivars that need higher GDD requirements according to the future temperature rise. System adaptation devises the adoption of precision agriculture for the cotton crop. Transformational adaptation is the most efficient and relevant to agricultural adaptation to climate change, but it can be tricky. As this article has demonstrated, this study improves the linkage between climate impacts on cotton's phenological stages and develops adaptation strategies for future planning and management studies for stakeholders to use for their practices and work.

Overall, this study found that 1) due to the increase in temperature during historical and RCP 8.5 scenarios, the quality of cotton and production will decline 2) the phenological stages of the cotton crop is shortened that affects the flower and boll stage maturity, and 3) adaptation strategies can reduce the effects of climate at different levels (incremental, system, and transformational strategy). In the future, it is suggested that this study is applicable to other regions and crops. Moreover, this work can be 'refined' with an improved version of data models by exploring the implications of these changes on crop yield and quality and comparing the differences with model simulations (past and future) for sustainable agricultural production.

CRediT authorship contribution statement

Anjali Sharma: Formal analysis. **R. Deepa:** Reviewing, Visualization. **Sriramana Sankar:** Validation. **Mikela Pryor:** Validation. **Briyana Stewart:** Methodology. **Elijah Johnson:** Reviewing. **Aavudai Anandhi:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This material is based upon work partially supported by the USDA-NIFA capacity building grant 2017-38821-26405, USDA-NIFA Evans-Allen Project, Grant 11979180/2016-01711, USDA-NIFA grant No. 2018-68002-27920, and National Science Foundation under Grant No. 1735235 awarded as part of the National Science Foundation Research Traineeship. Dr. Bhardwaj's support in data processing. Further, support of committee members Drs. Ibeanusi, Misra, and Gragg are acknowledged. Additionally, the authors would like to acknowledge Ms. Goodman for editorial services in the early stages and Ms. Emily Kelley for the editorial services, including copyediting, proofreading and scientific & scholarly editing of this draft. Finally, the authors express their gratitude to the anonymous reviewers for their constructive comments and suggestions on the earlier drafts of the paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2021.107383.

References

Anandhi, A., 2016. Growing degree days–Ecosystem indicator for changing diurnal temperatures and their impact on corn growth stages in Kansas. Ecol. Indic. 61, 149–158.

Anandhi, A., 2017. CISTA-A: Conceptual model using indicators selected by systems thinking for adaptation strategies in a changing climate: Case study in agro-ecosystems. Ecol. Model. 345, 41–55.

Anandhi, A., Kannan, N., 2018. Vulnerability assessment of water resources–Translating a theoretical concept to an operational framework using systems thinking approach in a changing climate: Case study in Ogallala Aquifer. J. Hydrol. 557, 460–474.

Anandhi, A., Steiner, J.L., Bailey, N., 2016. A ' 'system's approach to assess the exposure of agricultural production to climate change and variability. Clim. Change 136, 647–659.

Anandhi, A., Sharma, A., Sylvester, S., 2018. Can meta-analysis be used as a decision-making tool for developing scenarios and causal chains in eco-hydrological systems? Case study in Florida. Ecohydrology 11, e1997.

Anapalli, S., Fisher, D., Reddy, K., Pettigrew, W., Sui, R., Ahuja, L., 2016. Vulnerabilities and adapting irrigated and rainfed cotton to climate change in the lower mississippi delta region. Climate 4, 55.

Baker, J.T., Allen, L.H., Boote, K.J., Jones, P., Jones, J.W., 1990. Rice photosynthesis and evapotranspiration in subambient, ambient, and superambient carbon dioxide concentrations. Agron. J. 82, 834–840.

Bhardwaj, A., Misra, V., Mishra, A., wootten, A., Boyles, R., Bowden, J.H., Terando, A.J., 2018. Downscaling future climate change projections over Puerto Rico using a non-hydrostatic atmospheric model | SpringerLink.

Biesbroek, G.R., Swart, R.J., Carter, T.R., Cowan, C., Henrichs, T., Mela, H., Morecroft, M.D., Rey, D., 2010. Europe adapts to climate change: Comparing National Adaptation Strategies. Glob. Environ. Change, Govern. Complex. Resilience 20, 440–450.

Brooks, N., Adger, W.N., 2005. Assessing and enhancing adaptive capacity. Adapt. Policy Framew. Clim. Change Dev. Strateg. Policies Meas. 165–181.

Carr, E.R., Wingard, P.M., Yorty, S.C., Thompson, M.C., Jensen, N.K., Roberson, J., 2007. Applying DPSIR to sustainable development. Int. J. Sustain. Dev. World Ecol. 14, 543–555.

Chen, M., Shi, W., Xie, P., Silva, V.B.S., Kousky, V.E., Higgins, R.W., Janowiak, J.E., 2008. Assessing objective techniques for gauge-based analyses of global daily precipitation. J. Geophys. Res. Atmospheres 113.

Chen, X., Qi, Z., Gui, D., Gu, Z., Ma, L., Zeng, F., Li, L., 2019. Simulating impacts of climate change on cotton yield and water requirement using RZWQM2. Agric. Water Manag. 222, 231–241.

Constable, G.A., 1976. Temperature effects on the early field development of cotton. Austr. J. Experim. Agric. 16, 905–910.

Cooke, S.C., Sundquist, W.B., 1991. Measuring and explaining the decline in US cotton productivity growth. J. Agric. Appl. Econ. 23, 105–120.

Daly, C., Widrlechner, M.P., Halbleib, M.D., Smith, J.I., Gibson, W.P., 2012. Development of a new USDA plant hardiness zone map for the United States. J. Appl. Meteorol. Climatol. 51, 242–264.

DeLaune, P.B., Mubvumba, P., Lewis, K.L., Keeling, J.W., 2019. Rye cover crop impacts soil properties in a long-term cotton system. Soil Sci. Soc. Am. J. 83, 1451–1458.

DeTar, W.R., 2008. Yield and growth characteristics for cotton under various irrigation regimes on sandy soil. Agric. Water Manage. 95, 69–76.

Doherty, R.M., Mearns, L.O., Reddy, K.R., Downton, M.W., McDaniel, L., 2003. Spatial scale effects of climate scenarios on simulated cotton production in the southeastern USA. Clim. Change 60, 99–129.

Esparza, A.M., Gowda, P.H., Baumhardt, R.L., Marek, T., Howell, T.A., 2007. Heat unit availability for cotton production in the Ogallala Aquifer region of the United States. J Cotton Sci 11, 110–117.

FDACS, 2017. Florida Department of Agriculture and Consumer Services, Florida Agriculture overview and statistics.

Gabrielsen, P., Bosch, P., 2003. Environmental indicators: typology and use in reporting. EEA Cph.

Hatfield, J.L., Prueger, J.H., 2015. Temperature extremes: Effect on plant growth and development. Weather Clim. Extrem. 10, 4–10.

Henry, J.A., Portier, K.M., 1994. The climate and weather of Florida. Pineapple PressInc.

Her, Y.G., Boote, K.J., Migliaccio, K.W., Fraisse, C., Letson, D., Mbuya, O., Anandhi, A., Chi, H., Ngatia, L., Asseng, S., 2017. Climate Change Impacts and Adaptation in ’ ‘Florida’s Agriculture. Fla. Clim. Chang. Var. Amp Impacts.

Hering, J., 1954. Plantation Economy in Leon County, 1830–1840. Fla. Hist. Q. 33, 32–47.

Hinchliffe, D.J., Meredith, W.R., Delhom, C.D., Thibodeaux, D.P., Fang, D.D., 2011. Elevated growing degree days influence transition stage timing during cotton fiber development resulting in increased fiber-bundle strength. Crop Sci. 51, 1683. https://doi.org/10.2135/cropsci2010.10.0569.

Howden, S.M., Soussana, J.-F., Tubiello, F.N., Chhetri, N., Dunlop, M., Meinke, H., 2007. Adapting agriculture to climate change. Proc. Natl. Acad. Sci. 104, 19691–19696. https://doi.org/10.1073/pnas.0701890104.

Hutmacher, R.B., Travis, R.L., Rains, D.W., Vargas, R.N., Roberts, B.A., Weir, B.L., Wright, S.D., Munk, D.S., Marsh, B.H., Keeley, M.P., 2004. Response of recent Acala cotton varieties to variable nitrogen rates in the San Joaquin Valley of California. Agron. J. 96, 48–62.

Johnson, J., MacDonald, S., Meyer, L., Norrington, B., Skelly, C., 2014. The world and United States cotton outlook, in: Agricultural Outlook Forum 2014. United States Department of Agriculture.

Jones, P., Allen, L.H., Jones, J.W., Valle, R., 1985. Photosynthesis and transpiration responses of soybean canopies to short-and long-Term CO2 Treatments 1. Agron. J. 77, 119–126. https://doi.org/10.2134/agronj1985.00021962007700010029x.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K.C., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., Joseph, D., 1996. The NCEP/NCAR 40-Year Reanalysis Project. Bull. Am. Meteorol. Soc. 77, 437–472.

Kates, R.W., Travis, W.R., Wilbanks, T.J., 2012. Transformational adaptation when incremental adaptations to climate change are insufficient. Proc. Natl. Acad. Sci. 201115521.

Khajuria, A., Ravindranath, N.H., 2012. Climate change vulnerability assessment: Approaches DPSIR framework and vulnerability index. J. Earth Sci. Clim. Chang. 3.

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

Marek, T., Bordovsky, D., 2006. Performance of ten cotton varieties in the Northern Texas High Plains. Texas J. Agric. Nat. Resour. 19, 48–61.

Maurer, E.P., Wood, A.W., Adam, J.C., Lettenmaier, D.P., Nijssen, B., 2002. A long-term hydrologically based dataset of land surface fluxes and states for the conterminous United States. J. Clim. 15, 3237–3251.

McMaster, G.S., Wilhelm, W.W., 1997. Growing degree-days: One equation, two interpretations. Agric. For. Meteorol. 87, 291–300.

Misra, V., Mishra, A., Bhardwaj, A., 2019. A coupled ocean-atmosphere downscaled climate projection for the peninsular Florida region. J. Mar. Syst. 194, 25–40.

Nordlie, tom, 2018. UF/IFAS Economists: Hurricane Michael Caused $158 Million in Florida Agricultural Production Losses. UFIFAS News. URL http://blogs.ifas.ufl.edu/news/2018/10/26/uf-ifas-economists-hurricane-michael-caused-158-million-in-florida-agricultural-production-losses/ (accessed 6.3.19).

Oosterhuis, DMM, 1990. Growth and development of a cotton plant. American Society of Agronomy.

Organisation for Economic Co-operation and Development (OECD). 2003. OECD Environmental Indicators –Development, Measurement and Use, Paris: OECD.

Peter, G.P., Andre, R.M., Boden, T., Canadell, J.G., Ciais, P., Quere, C.L., Marland, G., Raupach, M.R., Wilson, C., 2013. The challenge to keep global warming below 2 °C | Nature Climate Change.

Poppy, G.M., Jepson, P.C., Pickett, J.A., Birkett, M.A., 2014. Achieving food and environmental security: new approaches to close the gap. The Royal Society.

Prokopová, M., Salvati, L., Egidi, G., Cudlín, O., Vceláková, R., Plch, R., Cudlín, P., 2019. Envisioning present and future land-use change under varying ecological regimes and their influence on landscape stability. Sustainability 11 (17), 4654.

Reddy, K., Hodges, H., Reddy, V., 1992. Temperature effects on cotton fruit retention. Agron. J. 84, 26–30.

Reddy, K.R., Hodges, H.F., McKinion, J.M., 1997. A comparison of scenarios for the effect of global climate change on cotton growth and yield. Funct. Plant Biol. 24, 707–713.

Reddy, K.R., Doma, P.R., Mearns, L.O., Boone, M.Y., Hodges, H.F., Richardson, A.G., Kakani, V.G.G., 2002. Simulating the impacts of climate change on cotton production in the Mississippi delta. Clim. Res. 22, 271–281.

Riahi, K., Rao, S., Krey, V., Cho, C., Chirkov, V., Fischer, G., Kindermann, G., Nakicenovic, N., Rafaj, P., 2011. RCP 8.5—A scenario of comparatively high greenhouse gas emissions. Clim. Change 109, 33.

Ritchie, J.W., Abawi, G.Y., Dutta, S.C., Harris, T.R., Bange, M., 2004. Risk management strategies using seasonal climate forecasting in irrigated cotton production: A tale of stochastic dominance. Aust. J. Agric. Resour. Econ. 48, 65–93.

Schaefer, C.R., Ritchie, G.L., Bordovsky, J.P., Lewis, K., Kelly, B., 2018. Irrigation timing and rate affect cotton boll distribution and fiber quality. Agron. J. 110, 922–931.

Sement, G., 1988. Cotton. The Tropical Agriculturalist. CTA. MacMillan, 88p.

Smit, B., Skinner, M.W., 2002. Adaptation options in agriculture to climate change: A typology. Mitig. Adapt. Strateg. Glob. Change 7, 85–114.

Stokes, C., Howden, M., 2010. Adapting agriculture to climate change: Preparing Australian agriculture, forestry and fisheries for the future. CSIRO publishing.

Taylor, K.E., Stouffer, R.J., Meehl, G.A., 2011. An Overview of CMIP5 and the Experiment Design. Bull. Am. Meteorol. Soc. 93, 485–498.

Tsiros, E., Domenikiotis, C., Dalezios, N.R., 2009. Assessment of cotton phenological stages using agroclimatic indices: An innovative approach.

USDA, 2017. USDA – National Agricultural Statistics Service - Florida [WWW Document]. URL https://www.nass.usda.gov/Statistics_by_State/Florida/index.php (accessed 6.3.19).

USDA, 2019. Soils | NRCS Florida. Soil. URL https://www.nrcs.usda.gov/wps/portal/nrcs/main/fl/soils/ (accessed 6.17.19).

USDA-E., 2019. USDA ERS - Cotton & Wool. URL https://www.ers.usda.gov/topics/crops/cotton-wool/#otherpublications (accessed 6.3.19).

USDA/NASS, 2018. USDA/NASS QuickStats. U. S. Dep. Agric. Natl. Agric. Stat. Serv. URL https://quickstats.nass.usda.gov/ (accessed 6.3.19).

Viator, R.P., Nuti, R.C., Edmisten, K.L., Wells, R., 2005. Predicting cotton boll maturation period using degree days and other climatic factors. Agron. J. 97, 494–499.

Voloudakis, D., Karamanos, A., Economou, G., Kalivas, D., Vahamidis, P., Kotoulas, V., Kapsomenakis, J., Zerefos, C., 2015. Prediction of climate change impacts on cotton yields in Greece under eight climatic models using the AquaCrop crop simulation model and discriminant function analysis. Agric. Water Manag. 147, 116–128.

Watts, F.C., Collins, M.E., 2008. Soils of Florida. ASA-CSSA-SSSA.

Williams, A., White, N., Mushtaq, S., Cockfield, G., Power, B., Kouadio, L., 2015. Quantifying the response of cotton production in eastern Australia to climate change. Clim. Change 129, 183–196.

Wright, D.L., Sprenkel, R.K., Marois, J.J., 2005. Cotton growth and development. Univ. Fla. Agron. Dep. Fla. Coop. Ext. Serv. IFAS Ext. Publ. SSAGR-238 Gainsville FL.

Wyman, D., Flint, H.L., 1967. Plant hardiness zone maps. Arnoldia 27, 53–56.

Xie, P., Chen, M., Yang, S., Yatagai, A., Hayasaka, T., Fukushima, Y., Liu, C., 2007. A gauge-based analysis of daily precipitation over East Asia. J. Hydrometeorol. 8, 607–626.

Yang, K., Wu, H., Qin, J., Lin, C., Tang, W., Chen, Y., 2014a. Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: A review. Glob. Planet. Change 112, 79–91.

Yang, Y., Yang, Y., Han, S., Macadam, I., Li Liu, D., 2014b. Prediction of cotton yield and water demand under climate change and future adaptation measures. Agric. Water Manag. 144, 42–53.

Yfoulis, A., Fasoulas, A., 1978. Role of minimum and maximum environmental temperature on maturation period of the cotton Boll 1. Agron. J. 70, 421–425.

Zhou, S., Mueller, F., Burkhard, B., Cao, X., Hou, Y., 2013. Assessing agricultural sustainable development based on the DPSIR Approach: Case study in Jiangsu. China. J. Integr. Agric. 12, 1292–1299.