UNIVERSITY OF THESSALY
SCHOOL OF AGRICULTURAL SCIENCES
DEPARTMENT OF AGRICULTURE - AGROTECHNOLOGY

HOW CLIMATE CHANGE AFFECTS COTTON AND WHEAT CROPS IN GREECE THE LAST FIFTEEN YEARS

by

Rafael-Ioannis Antonopoulos

Bachelor's Thesis

Submitted in partial fulfillment of the requirements for the degree of Diploma in agriculture-agrotechnology at the University of Thessaly

Larissa, 2024

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Date approved: [08/11/2023]

Acknowledgements

I would like to express my sincere and deepest thanks to my thesis supervisor, Assistant Professor Vasilis Liakos, who has guided me to follow the agro-technological field with continuous support and deep faith. His enthusiasm, patience and persistence does not stop there. Professor Liakos has also motivated me to pursue further academic goals by teaching me what innovative science and research means.

I am also grateful to the other members of the examination committee of my thesis, Professors Mr. Panagiotis Vyrlas and Nikolaos Alamanis for their valuable suggestions and their excellent cooperation with me during my studies.

Finally, I am especially grateful to my parents, Athanasios and Dimitra Antonopoulou, for their wholehearted love and support during all these years of continuous effort and struggle. I dedicate this work to my beloved mother, my father and my friends.

HOW CLIMATE CHANGE AFFECTS COTTON AND WHEAT CROPS IN GREECE THE LAST FIFTEEN YEARS

RAFAEL-IOANNIS ANTONOPOULOS
Department of Agrotechnology, University of Thessaly, 2023

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Abstract

Undoubtedly since the past three centuries (18th, 19th and 20th respectively), Earth's temperature has changed. Even though a small change of temperature may seem to have minimal impact at us, as human beings, however, though it has an enormous impact on plant organisms. It has been reported that, due to climate change, already-rare plant species are facing an even higher risk of being disappeared. Climate change and its impact on agriculture and water resources have become a global concern. The implications of extreme weather events on food production and water resource availability are starting to have both social and economic effects worldwide. However, despite that, how does climate change effect common crops, like cotton and wheat?

By utilizing and comparing the data of the temperature of the year 1978 and the latest year of the database (2022), the average temperatures are 15,15 °C (59,27 °F) and 16,75 °C (62,15 °F) respectively.

The precipitation rate has not been reduced. Although the changes in precipitation are not stable due to specific factors, the increase of the temperature tends to cause increase evapotranspiration which eventually leads to more precipitation.

Since the temperature has been increased, the duration of each growing season is shorter, due to the fact that the desired temperature has been achieved earlier.

Increased temperature has an immediate effect on the increase of ETc and therefore at the crop coefficient factor, a fact that agrees to the aforementioned citations.

Key words: crop coefficient, precipitation, temperature, evapotranspiration, irrigation

ΕΠΙΡΡΟΗ ΤΗΣ ΚΛΙΜΑΤΙΚΗΣ ΑΛΛΑΓΗΣ ΣΕ ΚΑΛΛΙΕΡΓΕΙΕΣ ΒΑΜΒΑΚΙΟΥ ΚΑΙ ΣΙΤΑΡΙΟΥ ΣΤΗΝ ΕΛΛΑΔΑ ΤΗΝ ΤΕΛΕΥΤΑΙΑ ΔΕΚΑΠΕΝΤΑΕΤΙΑ

ΑΝΤΩΝΟΠΟΥΛΟΣ ΡΑΦΑΗΛ-ΙΩΑΝΝΗΣ
Τμήμα Γεωπονίας-Αγροτεχνολογίας, Πανεπιστήμιο Θεσσαλίας, 2023

Επιβλέπων Καθηγητής: Δρ. Βασίλειος Λιάκος,
Επίκουρος Καθηγητής Γεωργίας Ακριβείας

Περίληψη

Αναμφίβολα από τους τελευταίους τρεις αιώνες (18ος, 19ος και 20ος αντίστοιχα), η θερμοκρασία της Γης έχει αλλάξει. Παρόλο που μια μικρή αλλαγή στη θερμοκρασία μπορεί να φαίνεται να έχει ελάχιστη επίδραση σε εμάς ως ανθρώπινα όντα, έχει ωστόσο, τεράστιο αντίκτυπο στους φυτικούς οργανισμούς. Έχει αναφερθεί ότι, λόγω της κλιματικής αλλαγής, τα ήδη σπάνια είδη φυτών αντιμετωπίζουν ακόμη μεγαλύτερο κίνδυνο εξαφάνισης. Η κλιματική αλλαγή και ο αντίκτυπός της στη γεωργία και τους υδάτινους πόρους έχει γίνει παγκόσμια ανησυχία. Οι επιπτώσεις των ακραίων καιρικών φαινομένων στην παραγωγή τροφίμων και στη διαθεσιμότητα υδάτινων πόρων αρχίζουν να έχουν τόσο κοινωνικές, όσο και οικονομικές επιπτώσεις παγκοσμίως. Ωστόσο, παρά το γεγονός αυτό, πώς η κλιματική αλλαγή επηρεάζει τις κοινές καλλιέργειες, όπως το βαμβάκι και το σιτάρι;

Χρησιμοποιώντας και συγκρίνοντας τα δεδομένα της θερμοκρασίας του έτους 1978 και του τελευταίου έτους της βάσης δεδομένων (2022), οι μέσες θερμοκρασίες είναι 15,15 °C (59,27 °F) και 16,75 °C (62,15 °F) αντίστοιχα.

Ο ρυθμός βροχόπτωσης δεν έχει μειωθεί. Αν και οι αλλαγές στη βροχόπτωση δεν είναι σταθερές λόγω συγκεκριμένων παραγόντων, η αύξηση της θερμοκρασίας τείνει να προκαλεί την αύξηση της εξατμισοδιαπνοής που τελικά οδηγεί σε περισσότερες βροχοπτώσεις.

Δεδομένου ότι η θερμοκρασία έχει αυξηθεί, η διάρκεια κάθε καλλιεργητικής περιόδου είναι μικρότερη, λόγω του γεγονότος ότι η επιθυμητή θερμοκρασία έχει επιτευχθεί νωρίτερα.

Η αυξημένη θερμοκρασία έχει άμεση επίδραση στην αύξηση της ETc και επομένως στον καλλιεργητικό συντελεστή, γεγονός που συμφωνεί με τις προαναφερθείσες αναφορές.

Λέξεις-κλειδιά: καλλιεργητικός συντελεστής, βροχόπτωση, θερμοκρασία, εξατμισοδιαπνοή, άρδευση

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Chapter 1. INTRODUCTION

In the context of this research thesis, the data obtained from the Hellenic National Meteorological Service (HNMS) shall be fully utilized. In particular, the purpose of the research paper is to highlight the effects that climate change has brought to the crops of cotton and wheat since the year 2008, over a decade and a half (fifteen years), i.e. until the year 2022.

1.1 Definition and background of climate change

Climate change, essentially describes the increase of the temperature of our planet in global level. Climate change on a wider range, also includes changes (mostly long-term) in our planet's climate. The current increase in temperature is being accelerated than it used to be in the past decades and is mainly caused by ourselves, by the huge and constant use of fossil fuels [1] [2]. The use of fossil fuel, deforestation, and some specific agricultural and industrial activities conduce to greenhouse gases, especially CO_2 (carbon dioxide) and CH_4 (methane) [3]. Greenhouse gases absorb some of the heat that the Earth emits after being heated by sunlight. Greater amounts of these gases trap more heat in Earth's lower atmosphere, causing global warming.

The World Health Organization (WHO) refers to climate change as the most notable threat to international health in the current century [4]. Societies and ecosystems shall encounter more dreadful risks without the possibility of taking measures in order to limit warming [5]. Adjusting to climate change via efforts like flood restraint measures or the creation of drought-resistant varieties for crops, reduces climate change risks up to a point, although some limits to adjustment have already been achieved [6].

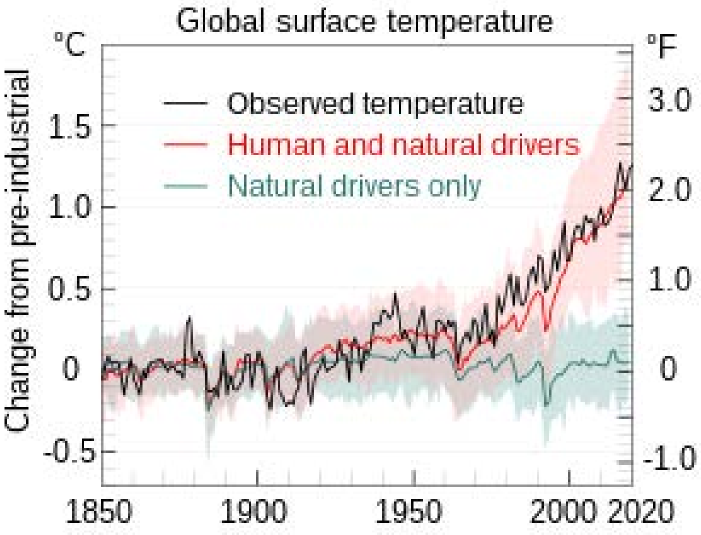


Figure 1. Change in average surface air temperature since the Industrial Revolution, plus drivers for that change. Human activity has caused increased temperatures, with natural forces adding some variability (Source: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., et al., 2021).

Many climate change impacts are already felt at the current 1.2 °C (34.2 °F) level of warming. Under the 2015 Paris Agreement, nations collectively agreed to keep warming "well under 2 °C (35.6 °F)". However, with pledges made under the Agreement, global warming would still reach about 2.7 °C (36.9 °F) by the end of the century [7]. Limiting warming to 1.5 °C (34.7 °F) will require halving emissions by 2030 and achieving net-zero emissions by 2050 [8].

The contribution of this thesis is that, based on the data from the HNMS, from the year 2008 onwards, we will obtain equations for the irrigation difference per year in a depth of a decade and a half. In this way, we shall be able to understand how climate change affects cotton and wheat crops in depth.

1.2 Cotton and wheat crop needs

1.2.1 Cotton crop needs

The classification of cotton is presented at Table 1. According to it, there are four (4) different subspecies and each one is cultivated at different regions.

Table 1. *Taxonomic hierarchy of cotton* (Source: https://www.itis.gov/servlet/SingleRpt/SingleRpt?search_topic=TSN&search_value=21709#null).

Domain	Eukarya
Kingdom	Plantae
Subkingdom	Viridiplantae
Infrakingdom	Streptophyta
Superdivision	Embryophyta
Division	Tracheophyla
Subdivision	Spermatophytina
Class	Magnoliopsida
Superorder	Rosanae
Order	Malvales
Family	Malvaceae
Genus	Gossypium L.
Species	Gossypium L.
Subspecies	Gossypium hirsutum L.
Subspecies	Gossypium barbadense L.
Subspecies	Gossypium arboretum L.
Subspecies	Gossypium herbaceum L.

Cotton is known for its soft and shaggy fiber that grows in a pericarp, around the seeds of the cotton plants of the Gossypium genus in the Malvaceae family. Cotton’s fiber is almost pure cellulose, and may contain minor percentages of other substances such as waxes, fats, pectins, and H_2O (water). Under natural conditions, the pericarp of the cotton will increase the dispersal of the seeds. The plant is a bush and it is native to tropical and subtropical regions around the globe, including the continents of America, Africa and Asia. The greatest diversity of cotton subspecies in the wild, is found in South America, followed by the continents of Australia and Africa [9]. Cotton was independently domesticated in the Old and New Worlds [10].

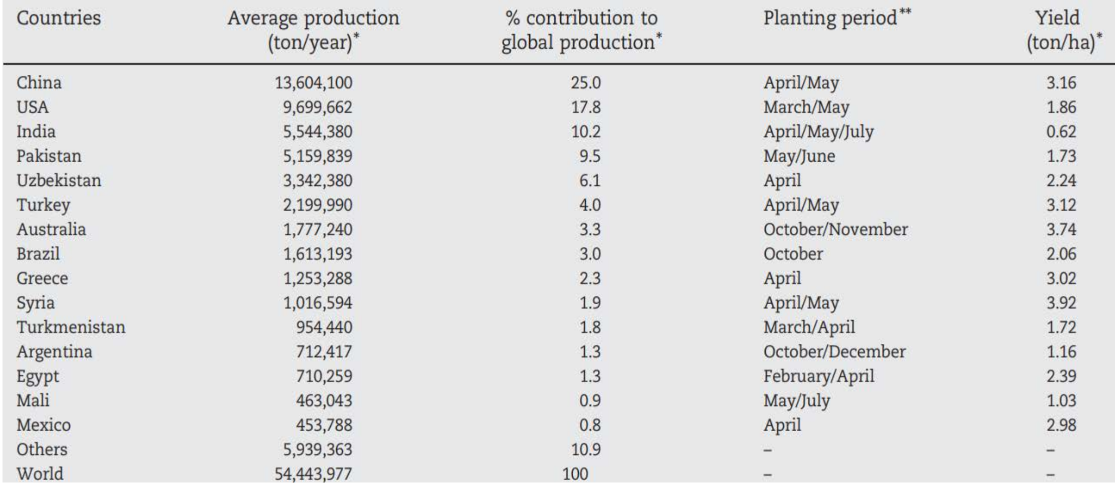
The fiber is most often spun into a thread and it’s used to make a squashy, breathable, and enduring textile. The fabric use of cotton, is quite known since antiquity. Moreover, fragments of cotton fabric dated to the fifth (5th) millennium B.C and have been found in the continent of Asia with Indus Valley civilization, as well as fabric remnants in South America are dated back to 4200 B.C in Peru. Although cultivated since ancient times, it was the invention of the cotton gin that reduced the cost of production that led to its global use, and it's the most commonly used crude fiber cloth in the clothing industry nowadays. Current estimates for world production are about 25 million tons or 110 million bales annually, accounting for 2.5% of the world's arable land. Although Asia is the world's largest producer of cotton, the North America has been the largest exporter for decades [11].

Cultivation:

Cultivation should start just before cotton appears or just immediately after cotton is up to a good stand. Cotton should be cultivated to a depth of 1 to 3 inches (2.54 to 7.62 cm) with one or two row cultivators with sweeps. Cultivation should be continued throughout the plant's normal growing season as often as is necessary to control weeds and grass. Cotton should be chopped when it is up to a stand and after the permanent leaves are present. Chopping should allow a spacing of 12 to 18 inches (30.48 to 45.72 cm) between hills with two to three stalks per hill. Hoeing may be necessary if grass and weeds cannot be controlled by cultivation [12].

Water footprint:

Although the environment, soil types, and other factors must be considered across a diverse Cotton Belt, the one common denominator is that a cotton crop needs ample moisture throughout the growing season. This can come from rainfall, supplemental irrigation, or full irrigation. Avoidance of water-deficit stress beginning at first square is critical in establishing adequate plant structure to facilitate yield goals, especially with early-maturing varieties grown in northern locations with a limited growing season. Begin early bloom at or near field capacity and maintain adequate water supplies at least through cutout by constantly monitoring crop water use and soil moisture conditions, and by irrigating before the crop stresses [13].



Countries	Average production (ton/year)*	% contribution to global production*	Planting period**	Yield (ton/ha)*
China	13,604,100	25.0	April/May	3.16
USA	9,699,662	17.8	March/May	1.86
India	5,544,380	10.2	April/May/July	0.62
Pakistan	5,159,839	9.5	May/June	1.73
Uzbekistan	3,342,380	6.1	April	2.24
Turkey	2,199,990	4.0	April/May	3.12
Australia	1,777,240	3.3	October/November	3.74
Brazil	1,613,193	3.0	October	2.06
Greece	1,253,288	2.3	April	3.02
Syria	1,016,594	1.9	April/May	3.92
Turkmenistan	954,440	1.8	March/April	1.72
Argentina	712,417	1.3	October/December	1.16
Egypt	710,259	1.3	February/April	2.39
Mali	463,043	0.9	May/July	1.03
Mexico	453,788	0.8	April	2.98
Others	5,939,363	10.9	–	–
World	54,443,977	100	–	–

Figure 2. The top-15 of seed cotton producing countries for the period of years 1997-2001. *Source: FAOSTAT 2004. **Sources: UNCTAD (2005a), FAO (2005), Cotton Australia (2005) (Source: Chapagain et al. 2005, published at Elsevier).

1.2.2 Wheat crop needs

The classification of wheat is presented at Table 2. According to it, there is one (1) subspecies.

Table 2. *Taxonomic hierarchy of wheat* (Source: https://www.itis.gov/servlet/SingleRpt/SingleRpt?search_topic=TSN&search_value=42236#null).

Domain	Eukarya
Kingdom	Plantae
Subkingdom	Viridiplantae
Infrakingdom	Streptophyta
Superdivision	Embryophyta
Division	Tracheophyla
Subdivision	Spermatophytina
Class	Magnoliopsida
Superorder	Lilianae
Order	Poales
Family	Poaceae
Genus	Triticum L.
Species	Triticum L.
Subspecies	Triticum aestivum L.

Common wheat (Triticum aestivum), also known as bread wheat, is a cultivated wheat species [14] [15].

Wheat is one of the very first plants that human domesticated and cultivated. According to archeobotanical finds, wheat cultivates is estimated between 10.000-15.000 B.C and supported the establishment of human communities and the raise of population [16]. In Mediterranean and in Greece, wheat's cultivation begins at Neolithic Age around 7.000 B.C [17]. While domesticating it, the wheat lost its ability to spread the seeds (brittle spine) and lethargy and as a result, the cultivation and the conservation of the varieties that have been created, to be dependent exclusively by humans. The wide adaptability of the plant as well as the large number of improved varieties that have been created characterize the plant as the most widespread on the planet compared to the rest of the cultivated species. The creation and introduction into cultivation of varieties with the characteristic of low height spectacularly improves wheat yields by allowing increased fertilization without the risk of tilting. Wheat grows mainly in the temperate zone between 30-60° North latitude and between 25-40° Southern latitude and from coastal areas to the highlands at 3000 meters (~9842 ft.) altitude. In temperate regions with mild winters and in Mediterranean climate it is sown in autumn, while in continental climates and high latitudes it is sown in spring.

Cultivation:

In Greece, 1.5 million acres of soft wheat are cultivated every year with a production of 450 to 550 thousand tons. In the period 1961-1985 the cultivated area of soft wheat prevailed over that of hard, while from 1986 until today the opposite is observed due to the increased demand and higher prices of the product. The average acre yields, are ranged between 280-320 and 260-300 kgr/acre (573.2 – 661.3 lb/acre) for durum and common wheat respectively (Table 3). The cultivation of wheat (soft and hard) in Greece interests more than 300,000 farms.

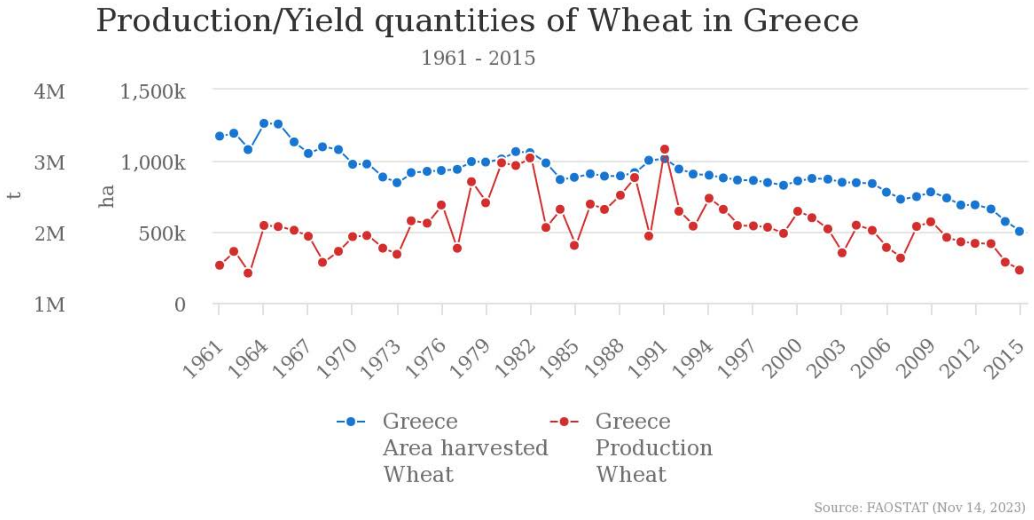
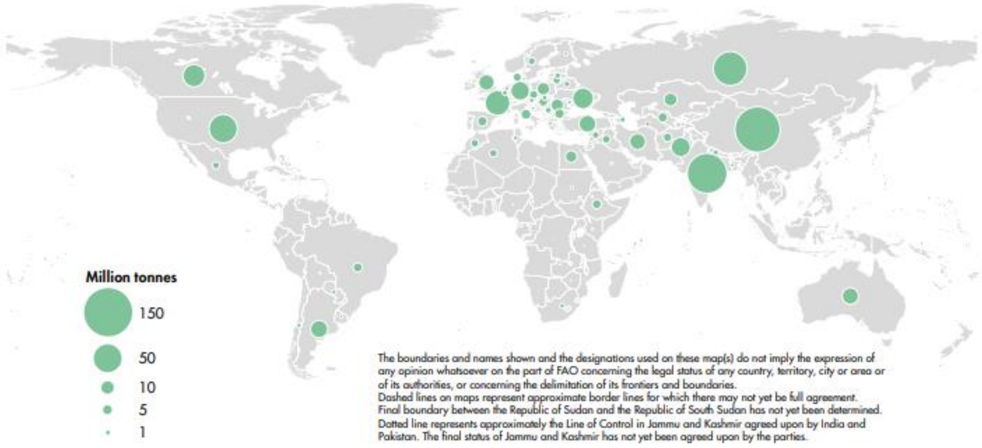


Figure 3. Production and yield quantities of wheat in Greece in the period 1961-2015 (Source: FAOSTAT).

Table 3. *Thirty (30) most important crops for human nutrition* (Source: Acquaah G., 2002. Principles of crop production: theory, techniques, and technology. Prentice Hall, New Jersey. pp 460.).

1. Wheat	11. Sorghum	21. Apples
2. Rice	12. Sugar cane	22. Yam
3. Corn	13. Millet	23. Peanut
4. Potato	14. Banana	24. Watermelon

5. Barley	15. Tomato	25. Cabbage
6. Cassava	16. Sugar beet	26. Onion
7. Sweet potato	17. Rye	27. Beans
8. Grapes	18. Oranges	28. Pea
9. Soy	19. Coconut	29. Sunflower
10. Oat	20. Cotton seed	30. Mango



The boundaries and names shown and the designations used on these map(s) do not imply the expression of any opinion whatsoever on the part of FAO concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers and boundaries.
Dashed lines on maps represent approximate border lines for which there may not yet be full agreement.
Final boundary between the Republic of Sudan and the Republic of South Sudan has not yet been determined.
Dotted line represents approximately the Line of Control in Jammu and Kashmir agreed upon by India and Pakistan. The final status of Jammu and Kashmir has not yet been agreed upon by the parties.

Figure 4. Production of wheat of the year 2019 (Source: FAOSTAT https://doi.org/10.4060/cb4477en-map12).

1.3 Hypothesis/Research questions

1) The climate change has changed the climate in Greece
    i) The temperature has risen
    ii) The precipitation has been reduced
2) The factors affect the plants’ growth have changed
    i) GDDs
    ii) Kc

1.4 Organization of thesis

The rest of this thesis is divided into four sections, which are Chapters 2 - 5, respectively. More specifically:

Chapter 2 analyzes the impacts of climate change on irrigation, on cotton crops and on wheat crops.

Chapter 3 analyzes the meteorological data.

Chapter 4 analyzes the impact of climate change on cotton irrigation and there is a comparison for each year, starting from the year 2008, until the year 2022 (2008-2010, 2011-2013, 2014-2016, 2017-2019, 2020-2022).

Chapter 5 analyzes the impact of climate change on wheat irrigation and there is a comparison each year, starting from the year 2008, until the year 2022 (2008-2010, 2011-2013, 2014-2016, 2017-2019, 2020-2022).

In Chapter 6 there is the discussion part.

Chapter 2. Irrigation

Irrigation is the technique of the application of controlled amounts of water, in order to assist crops to grow, landscape plants, and lawns. Irrigation has been quite an essential part of agriculture for over 5 millennia and has been developed by many civilizations around the globe through history. The technique of irrigation aids the growth of various crops, the maintenance of landscapes, and the cure and the restoration of disturbed soils in withered areas and during times of the lack of precipitation. In addition to these uses, irrigation is also employed to preserve crops from extreme low temperatures [18], keep under control the growth of weeds in grain fields, and impede the unification of the soil. It is also used to cool livestock, lower dust amounts, dispose of effluent, and support mining operations. Drainage, which involves the removal of surface and sub-surface water from a given location, is often studied in conjunction with irrigation.

There are several methods of irrigation that differ in how water is supplied to plants. Surface irrigation, also known as gravity irrigation, is the oldest form of irrigation and has been in use for thousands of years. In sprinkler irrigation, water is piped to one or more central locations within the field and distributed by overhead high-pressure water devices. Micro-irrigation is a system that distributes water under low pressure through a piped network and applies it as a small discharge to each plant. Micro-irrigation uses less pressure and water flow than sprinkler irrigation. Drip irrigation delivers water directly to the root zone of plants. Sub-irrigation has been used in field crops in areas with high water tables for many years. It involves artificially raising the water table to moisten the soil below the root zone of plants. Irrigation water can come from groundwater (extracted from springs or by using wells), from surface water (withdrawn from rivers, lakes or reservoirs) or from non-conventional sources like treated wastewater, desalinated water, drainage water, or fog collection. Irrigation can be supplementary to rainfall, which is common in many parts of the world as rain fed agriculture, or it can be full irrigation, where crops rarely rely on any contribution from rainfall. Full irrigation is less common and only occurs in arid landscapes with very low rainfall or when crops are grown in semi-arid areas outside of rainy seasons.

The environmental effects of irrigation relate to the changes in quantity and quality of soil and water as a result of irrigation and the subsequent effects on natural and social conditions in river basins and downstream of an irrigation scheme. The effects stem from the altered hydrological conditions caused by the installation and operation of the irrigation scheme. Amongst some of these problems is depletion of underground aquifers through over drafting.

Soil can be over-irrigated due to poor distribution uniformity or management wastes water, chemicals, and may lead to water pollution. Over-irrigation can cause deep drainage from rising water tables that can lead to problems of irrigation salinity requiring water table control by some form of subsurface land drainage.

2.1 Impact of climate change on irrigation

Climate change and global warming have become the main concern of studies in the field of water resources, agriculture, ecology, and other disciplines [19]. Global warming promoted shifts in the climatic zones of various parts of the world, causing expansion in arid zones and reduction of glacial areas—consequently resulting in changes in the abundance and seasonal activities of various plant and animal species. Climate change also caused changes in rainfall intensity, drought frequency and severity, wind speed, and rise in sea level [20]. Irrigated agriculture depends on freshwater from rivers, lakes, and aquifers and it consumes about 70% of the total renewable water resources [21].

Agriculture is directly affected by climatic conditions and changes, and it is essential to understand the impact of climate change on agricultural water resources for sustainable agriculture and to minimize the negative effects caused by such changes [19]. According to [21], lack of rainfall, soil moisture, and persistent above-normal temperatures are found to be the important factors in cases of severe loss in rice productivity in Bihar state, India. Furthermore, food security has been affected by climate change due to warming, changing precipitation patterns, and increasing frequency of extreme events [20]. Therefore, careful planning of water use by crops is of strategic importance from farm to the global level [23]. Remote sensing data have been excessively used in mapping the agriculture area and detecting their change as well as mapping water resources and their changes, which is vital for evaluating water availability and usability. Furthermore, the capability of GIS to analyze and visualize spatial information can be very important in water resources management. Considering their data collection and analysis capability, they are viewed as efficient and effective tools for irrigation water management. For instance, remote sensing can be used in improving agricultural irrigation water accounting, both independently and in combination with in situ monitoring [24]. An integrated approach of remote sensing, GIS, and CROPWAT model was used to determine the irrigation requirements of rice crops on different soils [25]. Satellite data were used to estimate the rice and fallow lands, and climate and soil data were integrated into the GIS platform.

2.2 Impact of climate change on cotton crops

According to the IPCC 2014 report, it is projected that by the end of the 21st century, there will be a 0.3 °C (32.5 °F) increase in global temperature, along with an increase in extreme precipitation events. Increase in the concentrations of greenhouse gases is responsible for global warming, which is responsible for warmer temperature, uncertain precipitation, and more adverse climatic conditions.

Climate change has both negative and positive impact on cotton productivity. An overall decrease of 9% in the cotton yield has been predicted, due to the negative effect of projected climate change for the Mississippi cotton zone and the same study also observed an increase of 10% in the cotton yield when CO_2 increased to 540 ppm [26] [27]. It has been indicated that an increase of 3.56 - 4.55 °C (38.4 – 40.2 °F) in temperature, has resulted in decrease of 6.5% of yield in RCP8.5 a scenario for 2061-2080 in Northwest China [28]. It has been observed that the increase in CO_2 from 493 ppm (in 2040) to 635 ppm (in 2070) has increased the cotton yield by 14-29% in Texas High Plan region [29]. It has been assessed that future climate change scenarios have shown increase in cotton yields and evapotranspiration by shortening the growing season [30].

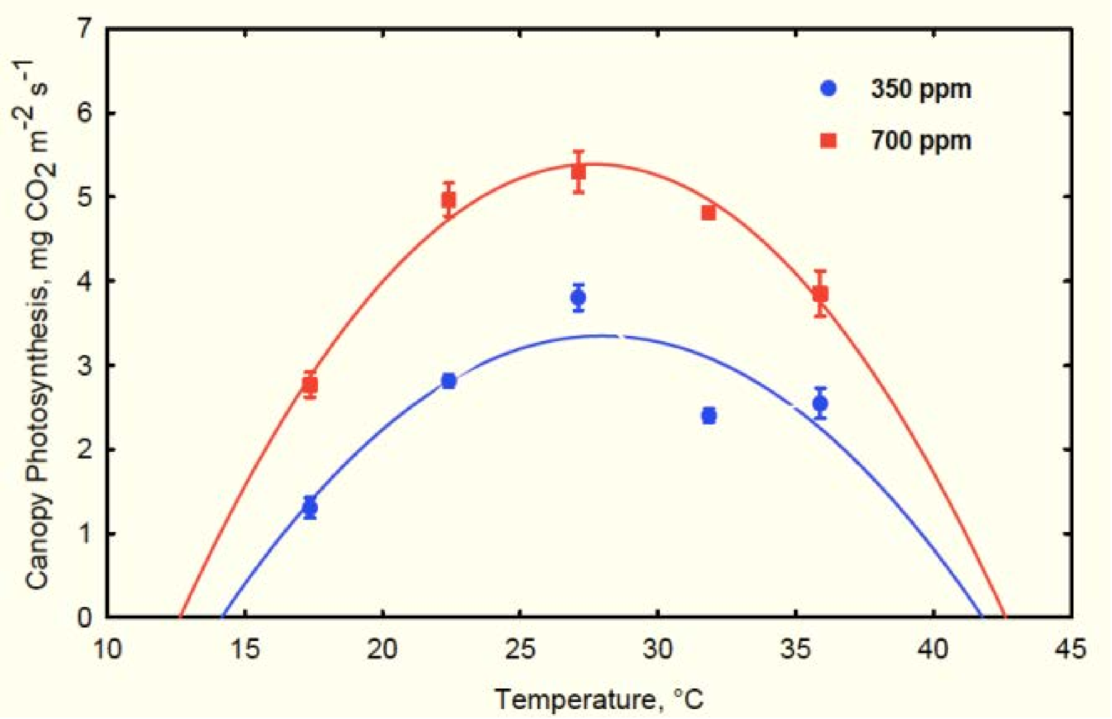


Figure 5. Higher CO_2 levels benefit cotton, but high temperatures can lower cotton yields (Source: Raja Reddy, 2020, Cotton and Climate Change https://www.wto.org/english/tratop_e/agric_e/item_3_icac_climate_change__cotton_final.pdf).

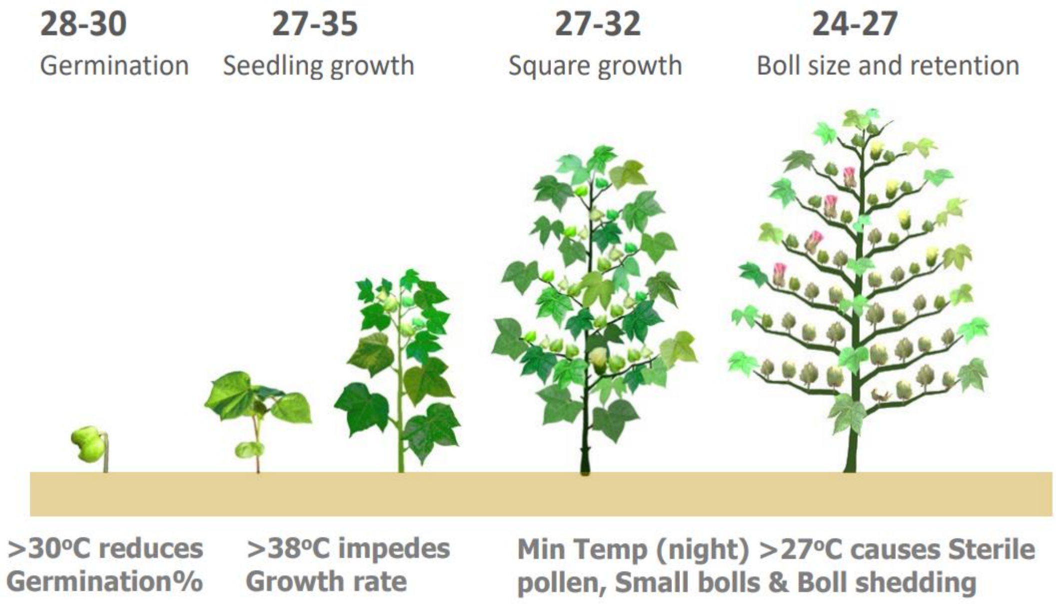


Figure 6. Optimum temperature (°C) of cotton (Source: Raja Reddy, 2020, Cotton and Climate Change https://www.wto.org/english/tratop_e/agric_e/item_3_icac_climate_change__cotton_final.pdf).

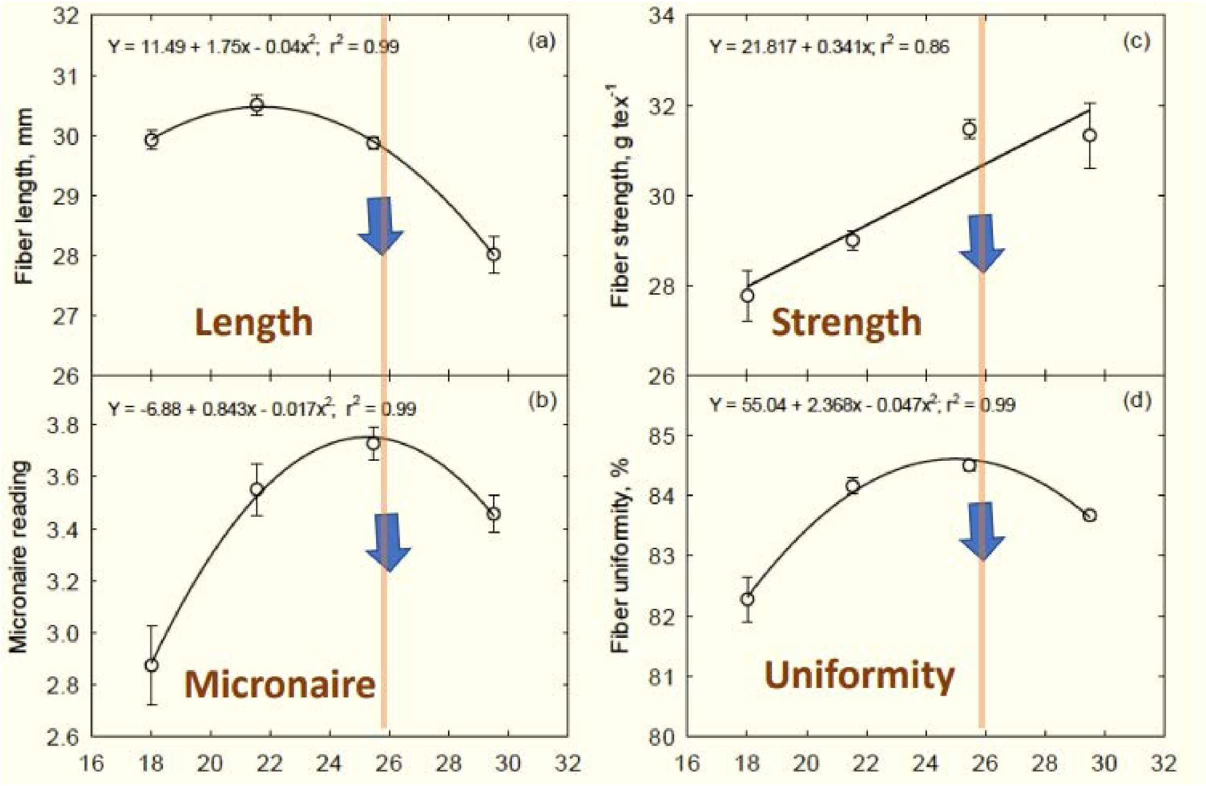


Figure 7. Higher temperatures (°C) affect fiber qualities (Source: Raja Reddy, 2020, Cotton and Climate Change https://www.wto.org/english/tratop_e/agric_e/item_3_icac_climate_change__cotton_final.pdf).

2.3 Impact of climate change on wheat crops

Wheat, ranking first in total harvested area worldwide (about 216 Mha in 2019) [31], is the most important grain crop for humans. In general, a climate change related increase in temperature will have negative effects on wheat yield on a global scale according to a number of recent studies [32] [33] [34] [35]. Although effects on yields show regional and seasonal variations, without considering fertilization effects of carbon dioxide, effective adaptation, and genetic improvement, a 1 °C (33.8 °F) increase in global mean temperature could reduce global wheat yields by 6.0% [32]. However, average yields have increased across Europe since the 1960s due to lengthening of the growing season due to rising temperatures [36]. Also, expansion of the cultivatable area is projected to occur in northern Europe and Asia [36], while in most developing countries, located at lower latitudes, the cultivatable area is projected to decrease.

The physiological mechanisms of yield and quality reduction by climate change have been explored in many studies. An increase in atmospheric CO_2 concentration has a beneficial effect on wheat since it is a precursor in photosynthesis. An elevated atmospheric CO_2 concentration can increase photosynthetic rate, promote growth, and consequently change yield levels [37]. However, an increase in temperature can impact all physiological processes of wheat, also negatively affecting yield. Wheat benefits from a mild (10 – 24 °C) (50.0 – 75.2 ° F) temperature for growth and development [38]. The suitable range of temperature varies for different developmental stages from germination and seedling growth to heading and flowering [37]. Wheat can stop forming new seeds when the temperature rises above the suitable range of temperature for these processes [38]. Porter and Gawith [39] summarized the temperature ranges for different phenological phases of wheat plants. Recent studies showed that wheat, as a C_3 plant (with a Calvin-Benson cycle), has a considerable ability to adjust its photosynthetic capacity to respond to rising temperatures [40]. Nevertheless, high temperatures can still limit the growth and development of wheat through changing metabolic processes [40]. Several studies and reviews examined the effects of climate change on wheat quality [41] [42]. An ongoing increase in CO_2 concentration and temperature will have negative impacts on wheat quality. For example, the protein content of wheat flour has been shown to decrease significantly with increasing CO_2 concentrations [43]. In addition, grain yield, grain weight, protein yield, globulin content and total starch accumulation have been shown to decline under temperature stress [42].

The relationship of drought footprints with crop productivity is less studied and rarely reported leaving a research gap for detailed investigation. In this way, crop models are essential in modeling crop yield. AquaCrop, is a well-known crop simulation model developed by the Food and Agriculture Organization (FAO), United Nations [44]. The model was widely used by researchers to model the biomass and yield all over the globe under different climatic and management conditions [45]. Hence, this model is considered, in various studies, to generate future crop yields based on climate change.

The AquaCrop model has been utilized to examine adjusting sowing dates and rates for wheat in North China Plain under future climate change. Wheat yields decreased by 5.45% to 11.05% (RCP4.5) and 9.35% to 16.84% (RCP8.5) in 2022–2100 using current practices. Adapted strategies countered losses, ensuring food security in the NCP amid future climate change [46].

2.4 Crop coefficient factor (Kc) for cotton and wheat crops for Thessaly in Greece

The determination of the actual crop evapotranspiration (ETc) during the growing season, has a potential advantage to attain proper irrigation scheduling. Crop coefficient factor (Kc) is widely used to estimate crop water use and scheduled irrigations. [47] introduced the concept of Kc and other researchers [48] furtherly developed the method. The methodology was developed to provide growers with a simple ETc prediction tool for guiding irrigation management decisions. The use of on-site microclimatological data and crop coefficient factors, enables the determination of crop water use and dissemination of such information to growers in a reliable, usable, and affordable format. Kc is defined as the following equation (Eq. 1) [49]:

$$\mathrm{Kc} = \frac{ETc}{ETo} \tag{1}$$

This approach to ETc estimation is governed by empirically developed Kc ratios of measured ETc and reference evapotranspiration (ETo) which is based on either grass or alfalfa evapotranspiration. Values of Kc for most agricultural crops increase from a minimum value at planting until a maximum Kc is reached at about full canopy cover. The Kc tends to decline at a point after a full cover is reached in the crop season. The declination extent primarily depends on the particular crop growth characteristics [50] and the irrigation management during the late season [49]. A Kc curve is the seasonal distribution of Kc, often expressed as a smooth continuous function. ETo has been standardized for grass or alfalfa [50] and for a hypothetical short crop [49], and more recently developed for both a short crop (ETos) and a taller crop (ETrs) [51]. ETo is able to be measured directly from a reference crop such as a perennial grass [52] [53] or computed from meteorological data using (a) temperature models [52] [54], (b) radiation models [52] [55], and (c) combination models [49].

The Penman–Monteith (P–M) equation is adopted and recommended by FAO-56 [49] [56]. The P–M can be applied to a variety of vegetation conditions, including systems having varying leaf area and varying height. It is possible to standardize parameters in the P–M equation including aerodynamic resistance for application to grass reference ETo [49] [50] [56] [57] [58]. ASCE adopted a standardized reference evapotranspiration equation to simplify and standardize the calculation [56]. A key purpose of the ASCE/EWRI standardized ET equations is to utilize similar reproducible ETo values with routine meteorological data [51]. Weighing lysimeters are employed to measure ETo and ETc directly by detecting changes in the weight of the soil/crop unit [59] [60] [61]. Meteorological data are used to compute ETo via equations such as the ASCE Penman–Monteith [56]. By utilizing the following equation:

$$\mathrm{ETc} = \mathrm{Kc} \times \mathrm{ETo} \quad (2)$$

where all that is needed to provide growers with real time irrigation recommendations (ETc) are local weather stations to provide data to determine ETo. According to [49], crop type, variety, and developmental stage affect ETc.

Thessaly, is consisted of Larissa (capital), Magnesia, Karditsa, Trikala and Sporades and is located 39.6°N 22.2°E while Larissa is located 39°38.5′N 22°25′E.

Crop	1st SG	Kc	2nd SG	Kc	3rd SG	Kc	4th SG	Kc	sum	date of seeding	date of harvest
cotton	35	0,35	65	0,35~1,15	50	1,15	35	1,15~0,60	185	20/4	22/10
sugar beets	30	0,35	45	0,35~1,20	90	1,20	50	1,20~0,70	215	1/3	2/10
maize	25	0,30	40	0,30~1,20	60	1,20	30	1,20~0,35	155	15/4	17/9
vines	30	0,30	60	0,30~0,75	40	0,75	80	0,75~0,45	210	17/2	15/9
trees	25	0,55	80	0,55~0,85	85	0,85	70	0,85~0,70	260	28/1	15/10
cucumber family	25	0,50	35	0,50~1,00	40	1,00	20	1,00~0,75	120	5/4	3/8
vegetables	25	0,60	35	0,60~1,15	40	1,15	20	1,15~0,70	120	24/4	22/8
cereals	20	0,30	120	0,30~1,15	50	1,15	20	1,15~0,25	210	20/11	18/6
tobacco	15	0,50	25	0,50~1,15	55	1,15	20	1,15~0,80	115	5/5	28/8
alfalfa 1st cut	10	0,40	30	0,40~1,20	25	1,20	10	1,20~1,15	75	18/2	4/5
alfalfa 2nd cut	5	>>	16	>>	11	>>	5	>>	37	4/5	10/6
alfalfa 3rd cut	5	>>	10	>>	10	>>	5	>>	30	10/6	10/7
alfalfa 4th cut	5	>>	11	>>	10	>>	5	>>	31	10/7	10/8
alfalfa 5th cut	5	>>	15	>>	11	>>	5	>>	36	10/8	15/9
alfalfa 6th cut	5	>>	15	>>	10	>>	5	>>	35	15/9	20/10

Figure 8. Crop coefficients at stage of growth (SG), Kc, for crops that develop in semi humid climate, for use with the combined FAO Penman-Monteith method, as they are given by Allen et al. (1996) (Source: https://www.ewra.net/ew/pdf/EW_2006_13-14_01.pdf).

Crop	1st SG	Kc	2nd SG	Kc	3rd SG	Kc	4th SG	Kc	sum	date of seeding	date of harvest
cotton	35	0,45	65	0,45~1,05	50	1,05	35	1,05~0,60	185	20/4	22/10
sugar beets	30	0,45	45	0,45~1,00	90	1,00	50	1,00~0,50	215	1/3	2/10
maize	25	0,50	40	0,50~1,05	60	1,05	30	1,05~0,60	155	15/4	17/9
vines	90	0,40	45	0,40~0,60	60	0,60	15	0,60~0,45	210	17/2	15/9
trees	25	0,55	80	0,55~0,85	85	0,85	70	0,85~0,70	260	28/1	15/10

Figure 9. Crop coefficients at stage of growth (SG), Kc, adapted in the climatic conditions of Greece, as they were defined by Papazafeiriou (1999) for use with the combined FAO Penman-Monteith method (Source: https://www.ewra.net/ew/pdf/EW_2006_13-14_01.pdf).

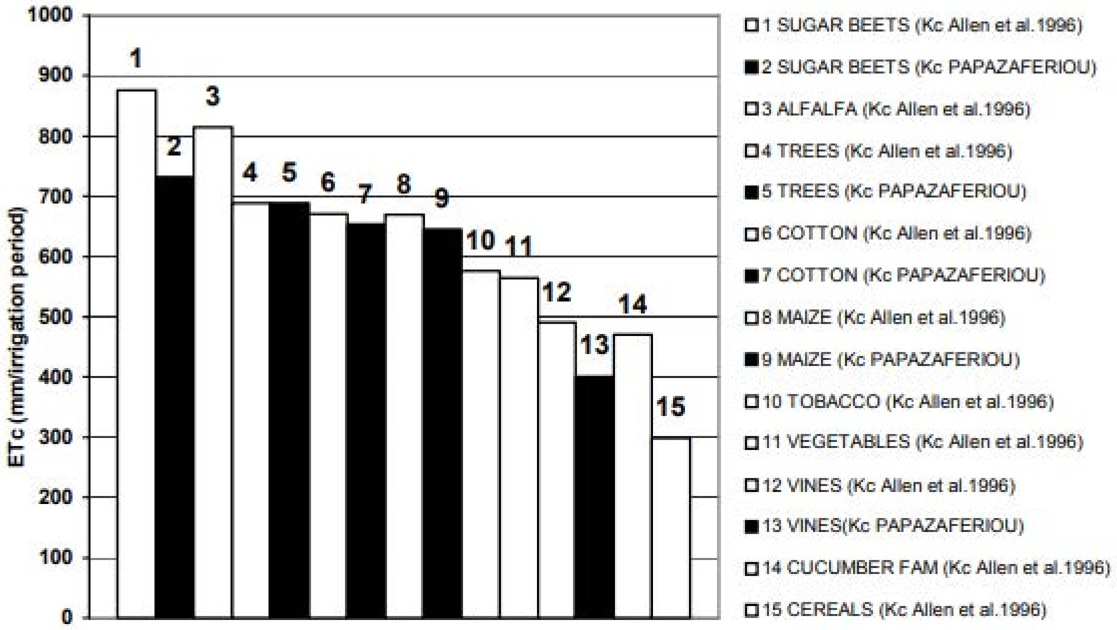
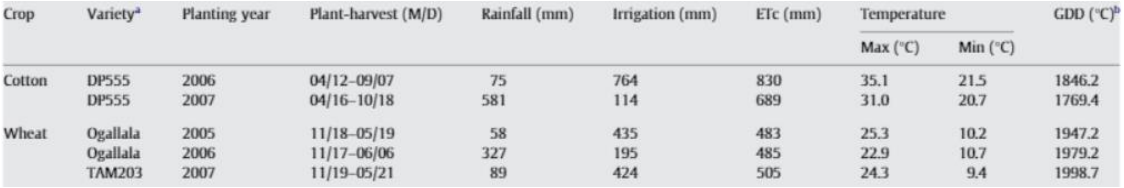


Figure 10. Crop evapotranspiration ETc (mm/period) for each crop for the Prefectures of Larissa and Magnesia, $I_{n\ tot}$ (m^3) (Source: https://www.ewra.net/ew/pdf/EW_2006_13-14_01.pdf).



Crop	Variety[a]	Planting year	Plant-harvest (M/D)	Rainfall (mm)	Irrigation (mm)	ETc (mm)	Temperature		GDD (°C)[b]
							Max (°C)	Min (°C)	
Cotton	DP555	2006	04/12–09/07	75	764	830	35.1	21.5	1846.2
	DP555	2007	04/16–10/18	581	114	689	31.0	20.7	1769.4
Wheat	Ogallala	2005	11/18–05/19	58	435	483	25.3	10.2	1947.2
	Ogallala	2006	11/17–06/06	327	195	485	22.9	10.7	1979.2
	TAM203	2007	11/19–05/21	89	424	505	24.3	9.4	1998.7

Figure 11. Crops grown at the Texas AgriLife Research—Uvalde for determination of crop coefficient and associated seasonal data.

[a] DP555 from Delta and Pine Land Co. (Scott, MS), Ogallala from AgriPro COKER (Berthoud, CO), and TAM203 from Texas A&M Univ. (College Station, TX, USA).

[b] GDD, growing degree days, was determined using a base temperature of 15.6 °C (~60.1 °F) for cotton and 0.0 °C (32 °F) for wheat

(Source: https://www.researchgate.net/publication/222697427_Determination_of_growth-stage-specific_crop_coefficients_Kc_of_cotton_and_wheat).

2.5 Growing Degree Days for cotton and for wheat (GDD)

Growing Degree Days (GDDs), also known as Growing Degree Units (GDUs), are a probing way of determination in phenology. GDDs are the measure of the aggregation of the heat used by horticulturists, in order to predict plant development rates, like the date that a flower will bloom, a crop will reach maturity, etc. In 1735, Reaumur was the first inductor of the term “GDD” [62].

GDD, or heat units, are used to estimate the growth and development of certain crops and pests during the growing season. They can be used retrospectively to calculate the current growth stage of a crop, or to help forecast the date that a crop will reach a predetermined growth stage. Corn growth, for example, closely follows the accumulation of average daily temperatures during its lifetime. The accumulation of average daily temperatures is calculated as 'growing degree days (GDD)' and includes a minimum development threshold that must be exceeded for growth to occur. This is called minimum development threshold a base temperature. Alfalfa for example, is adapted to relatively cool weather and has a base temperature of 41 °F (5 °C).

In contrast, field corn, sweet corn, sorghum, and soybeans have a base temperature of ~50 °F (~10 °C). There is little growth occurring below a crop or pests' base temperature. In order to calculate GDDs, the mean temperature need to be first recorded, this can be done by adding together the high and low temperature for the day and dividing that value by two (Eq. 3). If the mean temperature is at or below the base temperature for a crop or pest of interest, then the GDD value is zero (Eq. 4). If the mean temperature is above the base temperature, then the GDD equals the value of the mean temperature minus the base temperature. If the low temperature of the day is below your crop or pests' base value, use the base temperature during your calculations.

Producers often utilize a calendar in order to predict plant and insect development for management decisions. However, calendar days are often misleading, especially during early growth stages. Research has shown that utilizing GDD provides a more accurate physiological estimate of crop development than calendar days alone. Slight deviations in development can be expected if the crop or pest becomes limited by mechanisms other than heat, such as moisture or fertility [63].

$$GDD = \int (T(t)-T_{base}) = dt \text{ (where integration is over the time period with } T(t) > T_{base}\text{). (3)}$$

A simpler, approximately tantamount formulation utilizes the average of the daily maximum (T_{max}) and minimum (T_{min}) temperatures compared to a base temperature (T_{base}), in order to calculate degree-days for any given day

$$GDD = \frac{Tmax+Tmin}{2} - T_{base}$$

If and only if the minimum temperature (T_{min}) is below the base temperature (T_{base}) then, there exist two variations:

i) Variation A: Keep abiding the minimum temperature (T_{min}). If only $\frac{(Tmax+Tmin)}{2} < T_{base}$, set $\frac{(Tmax+Tmin)}{2} = T_{base}$. The resulting GDD is 0.

(4)

This can also be written more concisely as: $GDD = \max\left(\frac{Tmax+Tmin}{2} - T_{base}, 0\right)$

ii) Variation B: Change $T_{min} < T_{base}$ to $T_{min} = T_{base}$

2.5.1 Growing degree days for cotton (GDD cotton)

The cotton plant has perhaps the most complex structure of all major field crops. Its indeterminate growth habit and extreme sensitivity to adverse environmental conditions is unique. The growth of the cotton plant is very predictable under favorable moisture and temperature conditions. Growth, follows a well-defined and consistent pattern expressed in days. Another useful and more precise way to assess crop development relies on using daily temperatures during the season to monitor progress (Table 4). The heat unit concept utilizes accumulated hours above a critical temperature rather than calendar days in describing growth and development. For cotton, the threshold temperature is 60°F (15.55 °C), therefore, the GDD are referred to as “DD60’s”. The basic formula for calculating heat units involves averaging the maximum and minimum temperatures for each day and subtracting the threshold temperature. Calculation of the accumulated heat units and knowledge of the heat unit requirement for any particular growth stage can be used to explain and predict the occurrence of events or duration of stages in crop development [64] [65] [66].

Table 4. *The average number of days and heat units required for various growth stages of cotton in the Mid-South* (Source: https://www.cotton.org/tech/ace/growth-and-development.cfm).

Growth Stage	Days	Heat Units – DD60s

Planting to emerge	4 to 9	50 to 60
Emerge to First Square	27 to 38	425 to 475
Square to Flower	20 to 25	300 to 350
Planting to First Flower	60 to 70	775 to 850
Flower to Open Bool	45 to 65	850 to 950
Planting to Harvest Ready	130 to 160	2200 to 2600

Table 5. *Timing of various events during square development relative to the flowering date of an individual fruiting structure* (Source: https://www.cotton.org/tech/ace/growth-and-development.cfm).

Days Before Flower	**Size of Bud**	**Comments**
40	Microscopic	Square initiation can occur as early as 2nd true leaf expansion. Hot weather induces four-bract squares, cool weather delays square initiation
32	Microscopic	Lock numbers determined. Carbohydrate stress decreases number from 5 to 4
23	2mm PHS	Ovule number determined. Carbohydrate stress decreases potential seed number
22	2mm PHS	Pollen cells divide
19	3mm PHS	Pollen viability reduced by high nighttime temperatures

5	13mm	Square start expanding rapidly
3	17mm	Fibers begin to form
0	Flower opens White Flower	Pollen shreds and fibers start to elongate. Extremes of humidity or water disrupts pollen function

Table 6. *Timing of various events during boll development relative to flowering and primary factors influencing the event* (Source: https://www.cotton.org/tech/ace/growth-and-development.cfm).

Days After Flower	**Event**	**Primary Factors Influencing the Event**
2 to 12	Fiber density on seed surface	Temperature and carbohydrate status
0	Pollen shred	Temperature and relative humidity
0 to 3	Rate of fiber initiation	Temperature and potassium status
0 to 3	Pollen tube growth and seed fertilization	Temperature and relative humidity
1 to 14	Boll abscission	Plant water and carbohydrate status
3 to 25	Fiber length and seed number	Temperature and potassium status
15 to 45	Fiber cellulose (fiber thickening)	Temperature

25 to 50	Protein and oil accumulation	Temperature, plant water, nitrogen and potassium status
49 to 50	Boil opening	Temperature and relative humidity

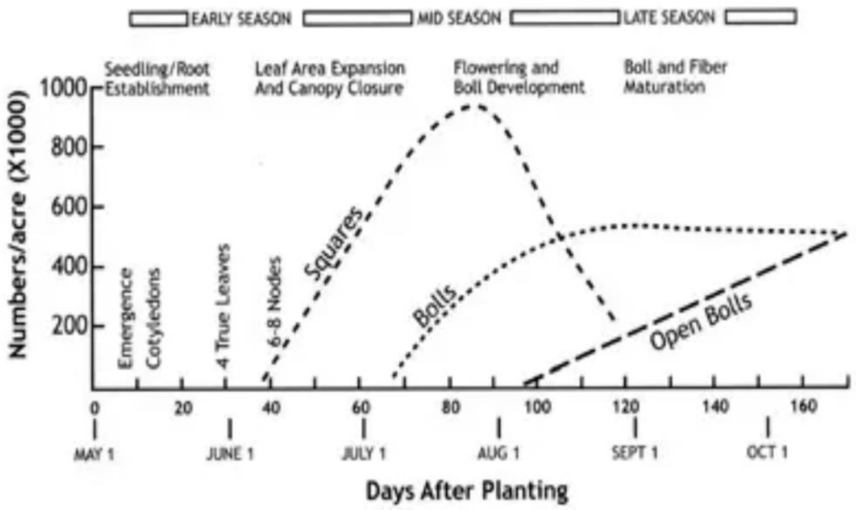


Figure 12. Seasonal development of cotton in the Mid-South with a May 1 planting date, showing typical production patterns of squares, bolls and open bolls (Oosterhuis, 1990, with permission ASA) (Source: https://www.cotton.org/tech/ace/growth-and-development.cfm).

2.5.2 Growing degree days for wheat (GDD wheat)

As [68] has cited, a common base temperature for wheat is 32 °F (0 °C). Although, other references like [69] have a different T_{base}, in this thesis and paper that temperature has been selected.

Generally, it takes about 100 GDD for each leaf on a cereal plant to grow out. It is being said that the phyllochron for wheat is 100 GDD. Thus, if it is known when the plant emerged, it is possible to calculate about how many leaves it should have on it, after a certain period of time if it is known what the temperature has been. For instance, if it is known that the crop began to emerge on November 1 and it is also known that there have been 275 GDD from November 1 to the present. Then is will being expected that the crop would be getting its third leaf since it should be at about the 2.75 leaf stage. The actual number of GDD per leaf required by a crop is not exactly 100, but ranges from about 80 to 120. The most important factor in setting the phyllochron is the environment at, or near planting time and it is unknown yet exactly what the triggering factor is. Generally, wheat planted early in the fall will have a longer GDD requirement than that planted later in the fall. There is very little varietal difference in the phyllochron for different cultivars of wheat planted at the same time, but there is a tendency for spring wheats to have shorter phyllochrons than winter wheats.

When planted at 1.5″ (3.81 cm) depth in a bare (no surface residue) moist soil, it takes an accumulation of about 180 GDD (°F) beginning with the day after planting until emergence occurs. Emergence by these criteria means plants are visible in the row (the rows can be seen), and the first leaf is equal to about one half of its eventual full length. By this criteria emergence is defined as Haun stage 0.5.

Following emergence (stage 0.5) standard 8 leaf wheat varieties require the accumulation of 143 GDD (°F) for each growth stage through stage 12.0. Growth from stage 0.5 to stage 1.0 requires 72.5 additional GDD (°F), or a total of 252 GDD (°F) after planting. Then, 143 additional GDD are required to reach stage 2.0. This continues through stage 12.0. Growing degree day requirements for stages above 12.0 do not follow a pattern, because they are usually defined by seed water content, and are subject to considerable variation. Accumulated GDD threshold values are shown through stage 12.0 in the Table 7.

The Haun growth stage scale [67], is far more precise than other commonly used scales. The Haun scale assigns consecutive numbers to main stem leaves in the order in which they appear. When the first leaf is fully developed, the plant is at stage 1, and so on through stage 8. Each leaf, is fully developed when the next leaf is visible in the rolled part of the leaf. For example, leaf 2 is fully developed when the third leaf is visible in the rolled par of leaf 1. The number assigned to each stage can be further subdivided into fractional sub-stages to provide more information.

Fractional leaf stages are determined by comparing the length of the developing leaf to the preceding leaf. For example, if leaf 3 is one-third (⅓) as long as leaf 2, then the Haun growth stage is 2.3, and if leaf 3 is one-half (½) as long as leaf 2 it is designated stage 2.5. The same type of system is also used to designate sub-stages in the growth units following stage 8.

Table 7. *Estimated Haun stage on wheat. All growth stages are defined by conditions on the main stem* (Source: https://ndawn.ndsu.nodak.edu/help-wheat-growing-degree-days.html).

Stage	**Name**	**Description**	**GDD Required**	**GDD Accumulated**

-	Planting date	Date crop was planted	0	0
0.5	Emergence Date	Emergence is defined here as the date leaf 1 reaches half of its length (Stage 0.5). The GDD required from planting until emergence depends on planting depth, soil water, soil temperature, surface residue, and soil type. Predicting emergence is the most uncertain part of this model	180	180
1.0	Leaf 1 fully extended	Leaf 1 is fully developed when the second leaf is visible in the rolled part of leaf 1	72	252
2.0	Leaf 2 fully extended	Leaf 2 is fully developed when the third leaf is visible in the rolled part of	143	395

		leaf 2. This is the same concept for leaves 2 through 7		
3.0	Leaf 3 (Tillers begin to emerge)	Tillering begins at a Haun stage of 2.0 to 2.5, but tillers are not visible until Haun stage of 3.0-3.5	143	538
4.0	Leaf 4	Leaf 4 fully extended	143	681
5.0	Leaf 5 (Tillering ends)	Cool, moist weather, and abundant N fertilizer will extend tillering period	143	824
6.0	Leaf 6 (Tillering ends)	Cool, moist weather, and abundant N fertilizer will extend tillering period	143	967
7.0	Leaf 5 fully extended	Severe drought stessed plants may pass directly to stage 9	143	1110
7.5	Flag leaf visible	-	71	1181

8.0	Flag leaf visible	The flag leaf (Leaf 8) is fully developed when the flag leaf collar is visible	72	1255
9.0	Boot swelling begins	Flag leaf stem elongates elevating the flag leaf above the previous leaf. This usually ends with the first signs of boot swelling	143	1396
10.0	Boot completed	Complete when awns become visible at the flag leaf collar	143	1539
10.2	Heading begins	Heading begins when the head begins to emerge through the flag leaf collar	28	1567
11.0	Headed (head extension begins)	Heading begins when the head begins to emerge through the flag leaf collar Heading is complete when the head	115	1682

		has completely cleared the collar and head extension begins. Head extension refers to continued growth of the stem which raises the head about the flag leaf. Head extension is usually complete when flowering begins		
11.4	Flowering begins	Flowering or anthesis begins about in the middle of the head, and simultaneously progresses toward the top and the bottom of the head	57	1739
11.6	Flowering completed	Most tillers (T0, T1, T2 tillers) flower within a few days of the main stem. Later-emerging	29	1768

		tillers flower later, and are the most common source of green "nuisance" heads at swathing time		
12.0	Kernel watery ripe	During watery ripe stage the kernel length and width are established, but little dry matter is accumulated	57	1825
13.0	Early milk	A white, milk-like fluid can be squeezed from the kernel	-	-
14.0	Early dough	During the dough stages, kernel water content continues to decrease as more and more dry matter is accumulated	-	-
14.5	Soft dough	-	-	-
15.0	Hard dough	By the end of the hard dough stage, the kernel reaches	-	-

		physological maturity. Reductions in yield after this stage result from harvest losses and/or environmental injuries such as sprouting and hail		
15.4	Swathing can begin	-	-	-
15.6	Physiology maturity	The kernel is hard, but can still be dented with a thumbnail. The plant is completely yellow. Swathing is still necessary	-	-
16.0	Ripe (kernel hard)	Kernel is dry, brittle, and hard. It can no longer be dented with thumbnail and, if crushed, it splits into pieces	-	-
16.4	Direct combining	Water content is low enough for	-	-

		direct (straight) combining		

Table 8. *Phenology calculations using 0 °C and 32 °F base temperatures are combined with the Universal Growth Staging Scale (UGSS) descriptive terms for crops grown in Montana* (Source: https://landresources.montana.edu/soilfertility/documents/PDF/pub/GDDPlantStagesMT200103AG.pdf).

-	-	**Stage**	**GDD °C**	**GDD °F**
Emergence	Leaf tip just emerging from above-ground coleoptile	1.0	125-160	257-320
Leaf development	Two leaves unfolded	1.1	169-208	336-406
Tillering	First tiller visible (tillering of cereals may occur as early as stage 1.3, in this case continue with 2.1)	2.1	369-421	696-789
Stem elongation	First node detectable	3.1	592-659	1097-1218
Anthesis	Flowering commences, first anthers of cereals are visible	6.1	807-901	1484-1653
Seed fill	Seed fill begins. Caryopsis of cereals watery ripe (first grains have reached	7.1	1068-1174	1954-2145

	half of their final size)			
Dough stage	Soft dough stage, grain contents soft but dry, fingernail impression does not hold	8.5	1434-1556	2613-2832
Maturity complete	Grain is fully mature and drydown begins. Ready for harvest when dry	8.9	1538-1665	2800-3029

Chapter 3. Meteorological data

Greece is located 37° 58′ 0″ N, 23° 43′ 0″ E, whereas and as aforementioned in Chapter 2.4, Thessaly is located 39.6°N 22.2°E and Larissa, where this thesis and paper is conducted is located 39°38.5′N 22°25′E.

In the region of Thessaly, Greece, HNMS has a total of 4 observation stations. More specifically, these stations are:

i) Agchialos, with a Longitude (Lon): 22.79, a Latitude (Lat): 39.22 and an Altitude (Alt): 19 m
ii) Kranea, with a Longitude (Lon): 20.747, a Latitude (Lat): 39.246 and an Altitude (Alt): None m
iii) Larissa, with a Longitude (Lon): 22.46, a Latitude (Lat): 39.65 and an Altitude (Alt): 74 m
iv) Sofades, with a Longitude (Lon): 22.09, a Latitude (Lat): 39.336 and an Altitude (Alt): None m

Of the aforementioned observation stations in Thessaly, the data that will be used in Chapter 4 and Chapter 5 were obtained by the station of Larissa.

In the region of Central Macedonia, Greece, which is located 40.7°N 23.0°E, HNMS has a total of 4 observation stations. More specifically, these stations are:

i) Edessa, with a Longitude (Lon): 22.05, a Latitude (Lat): 40.8 and an Altitude (Alt): 314 m
ii) Polykastro, with a Longitude (Lon): 23.567, a Latitude (Lat): 40.9 and an Altitude (Alt): None m
iii) Serres, with a Longitude (Lon): 23.53, a Latitude (Lat): 41.08 and an Altitude (Alt): 32 m
iv) Thessaloniki, with a Longitude (Lon): 22.97, a Latitude (Lat): 40.53 and an Altitude (Alt): 2 m

Of the aforementioned observation stations in Central Macedonia, the data that will be used in Chapter 4 and Chapter 5 were obtained by the stations of Serres and Thessaloniki.

Chapter 4. COTTON (GOSSYPIUM L.)

The rest of Chapter 4 is organized as follows.

In Section 4.1, the graphs of the precipitation of cotton from the years 2008-2010 are presented.

In Section 4.2, the graphs of the precipitation of cotton from the years 2011-2013 are presented.

In Section 4.3, the graphs of the precipitation of cotton from the years 2014-2016 are presented.

In Section 4.4, the graphs of the precipitation of cotton from the years 2017-2019 are presented.

In Section 4.5, the graphs of the precipitation of cotton from the years 2020-2022 are presented.

In Section 4.6, the final chart of the precipitation of cotton, from the years 2008-2022 are presented.

All the following charts are for the period of months from 1st of May to 31st of October.

4.1 Data charts of precipitation of the years 2008-2010

Figure 13. Data chart of the precipitation of cotton in Larissa of the years 2008-2010

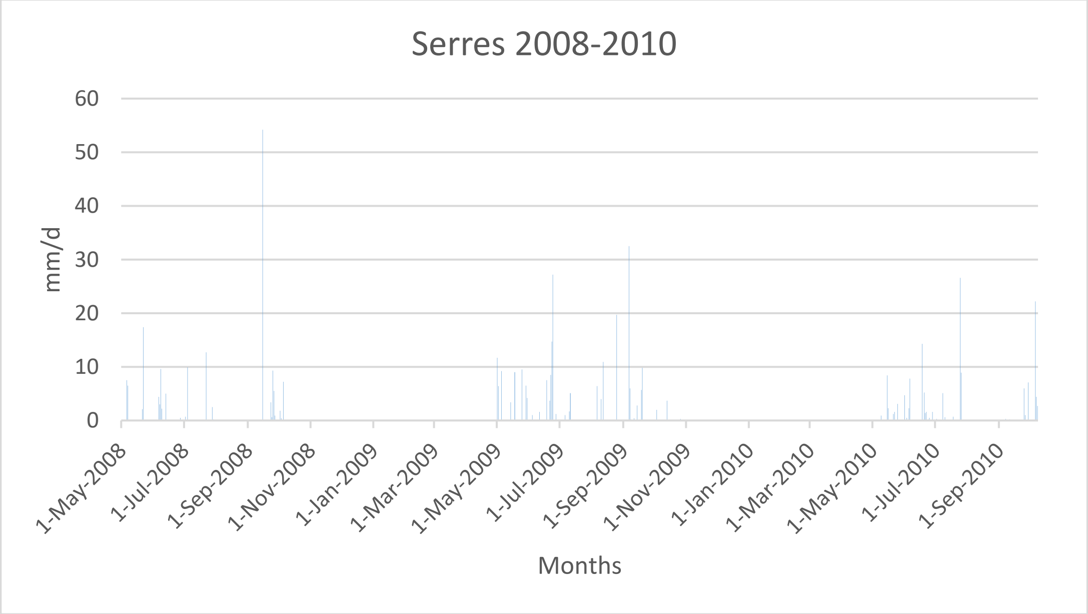


Figure 14. Data chart of the precipitation of cotton in Serres of the years 2008-2010

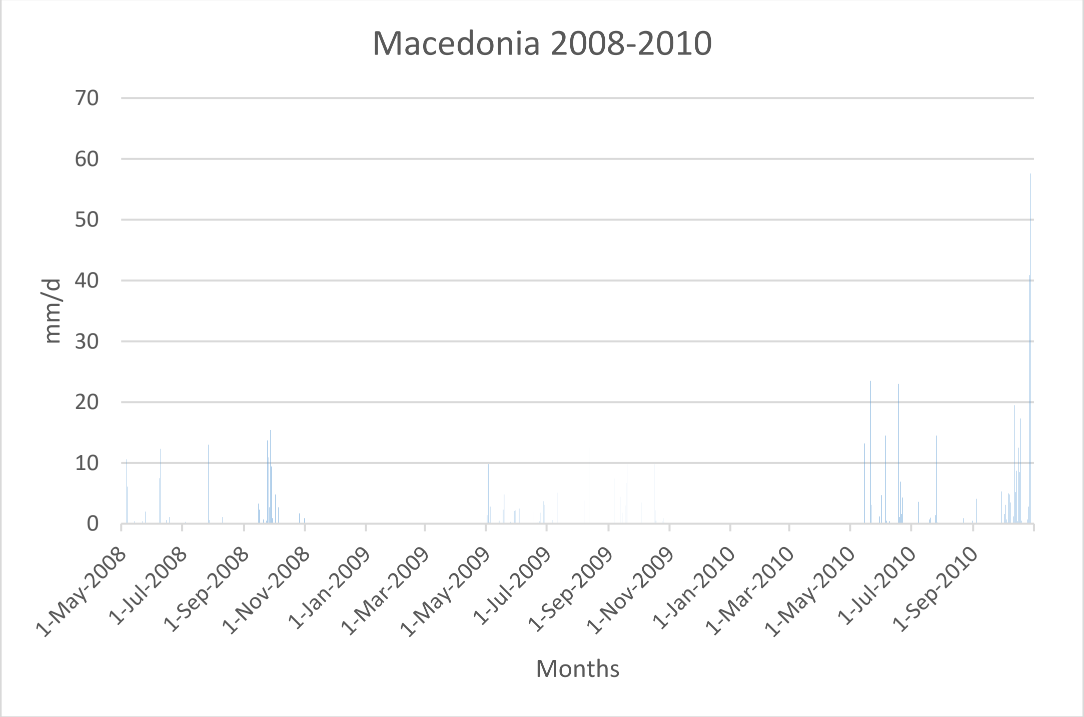


Figure 15. Data chart of the precipitation of cotton in Macedonia of the years 2008-2010

4.2 Data charts of precipitation of the years 2011-2013

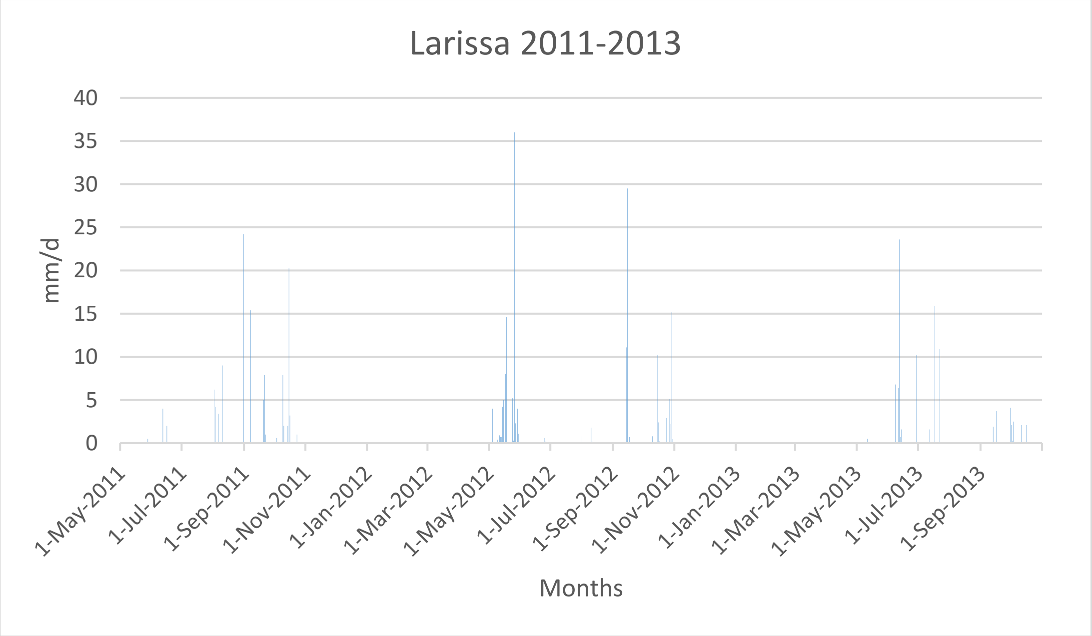


Figure 16. Data chart of the precipitation of cotton in Larissa of the years 2011-2013

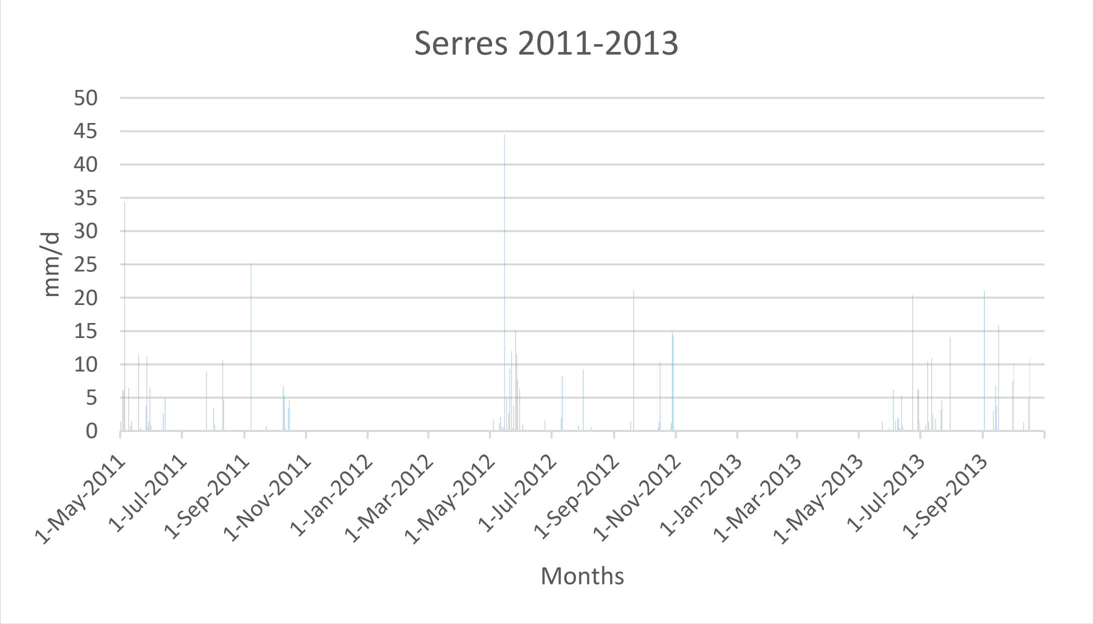


Figure 17. Data chart of the precipitation of cotton in Serres of the years 2011-2013

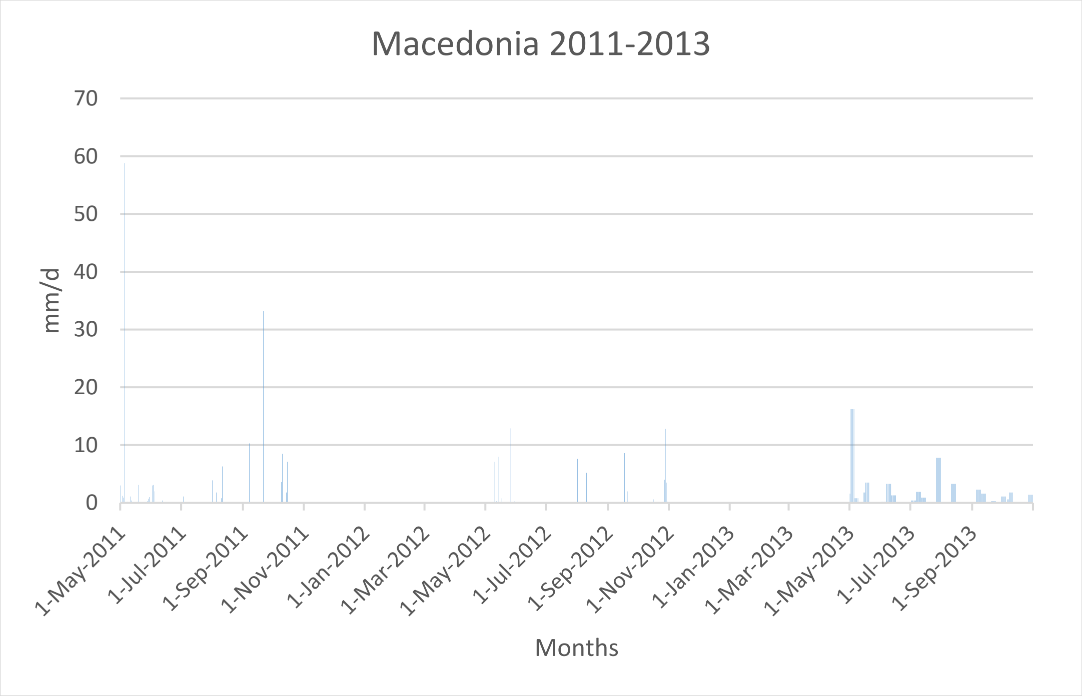


Figure 18. Data chart of the precipitation of cotton in Macedonia of the years 2011-2013

4.3 Data charts of precipitation of the years 2014-2016

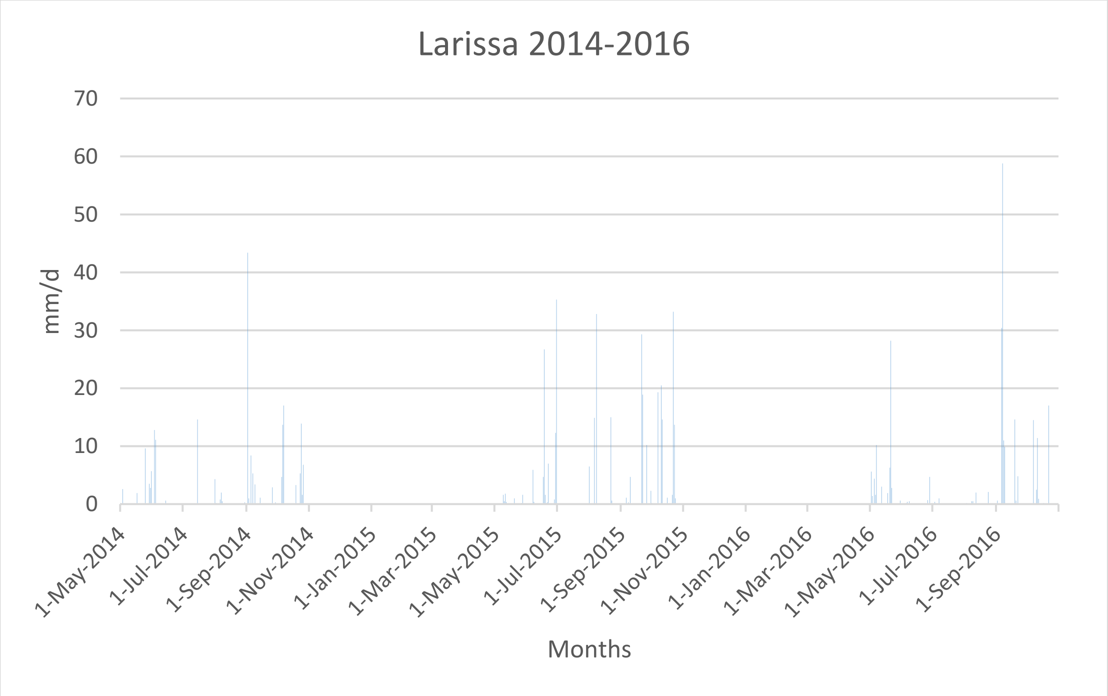


Figure 19. Data chart of the precipitation of cotton in Larissa of the years 2014-2016

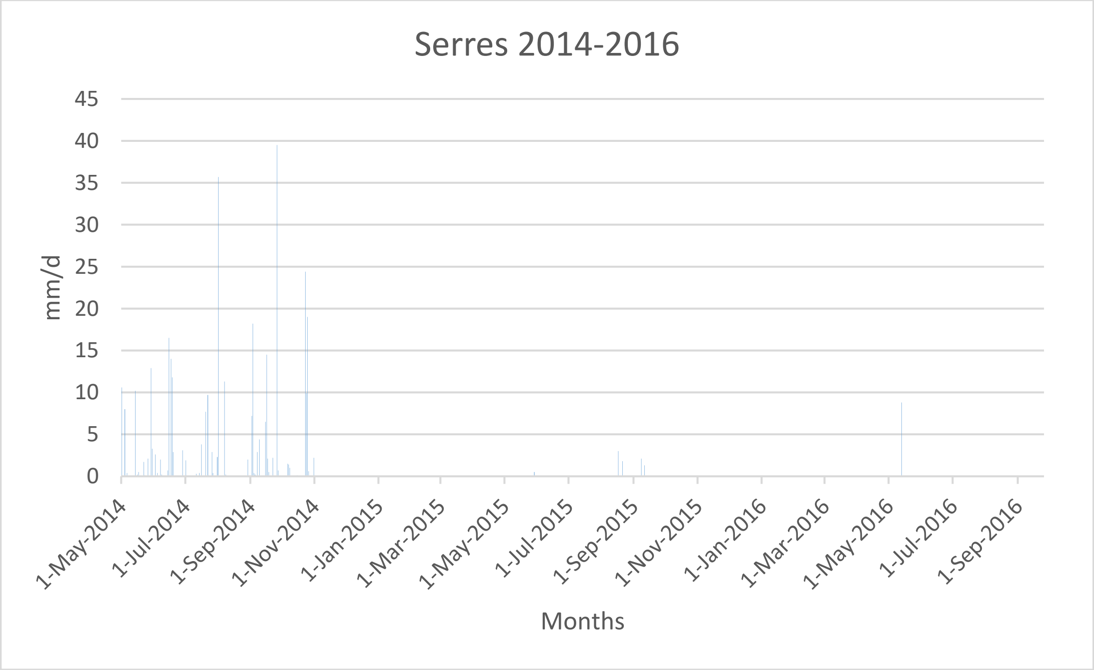


Figure 20. Data chart of the precipitation of cotton in Serres of the years 2014-2016

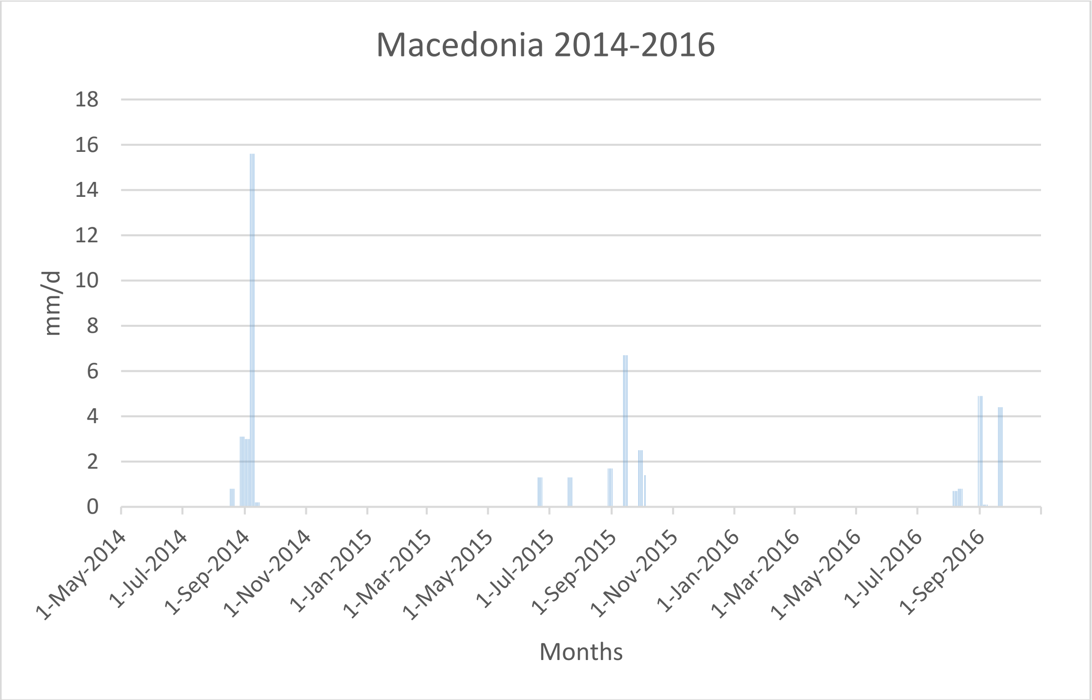


Figure 21. Data chart of the precipitation of cotton in Macedonia of the years 2014-2016

4.4 Data charts of precipitation of the years 2017-2019

Figure 22. Data chart of the precipitation of cotton in Larissa of the years 2017-2019

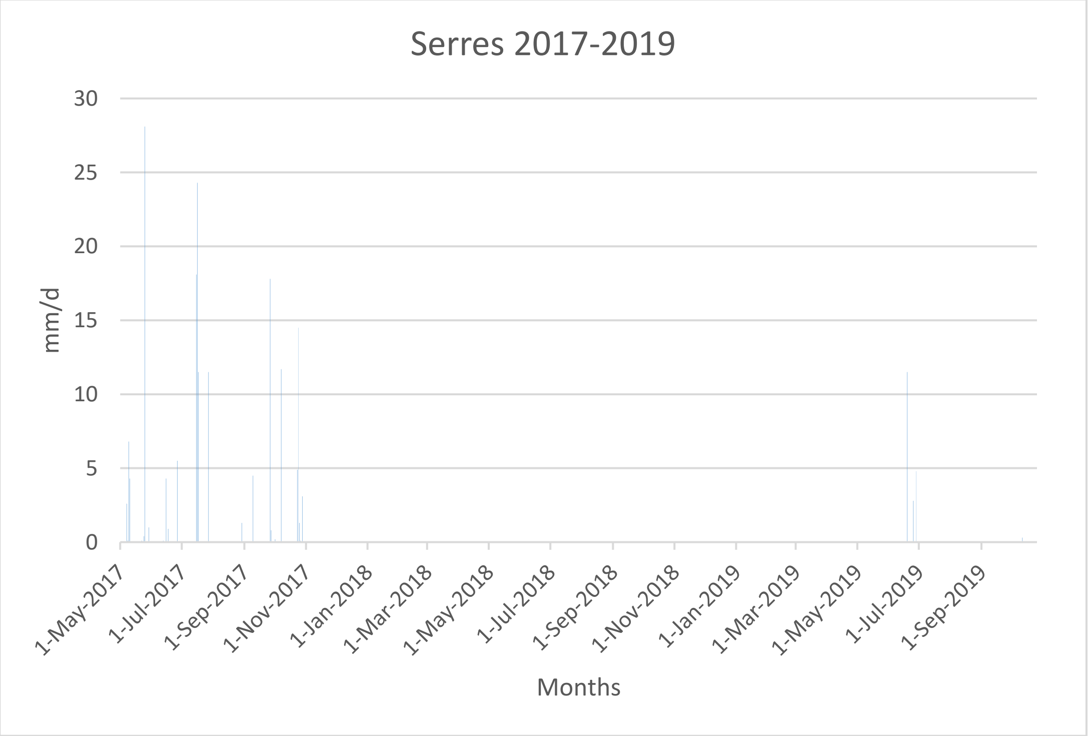


Figure 23. Data chart of the precipitation of cotton in Serres of the years 2017-2019

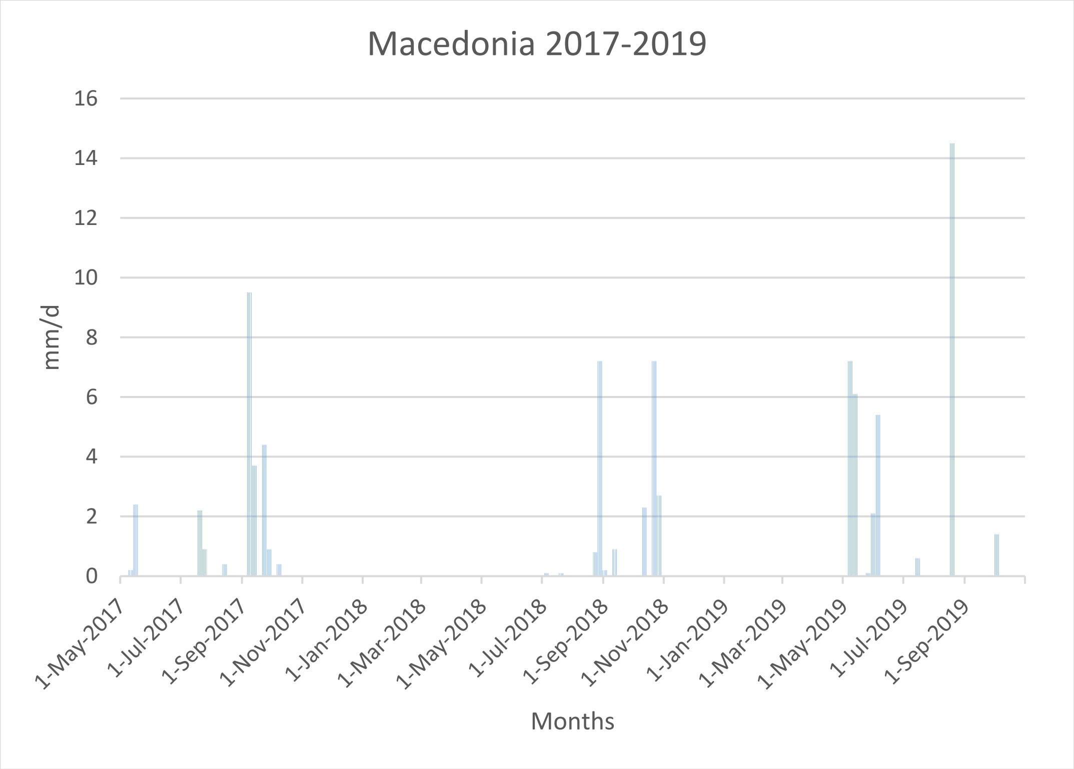


Figure 24. Data chart of the precipitation of cotton in Macedonia of the years 2017-2019

4.5 Data charts of precipitation of the years 2020-2022

Figure 25. Data chart of the precipitation of cotton in Larissa of the years 2020-2022

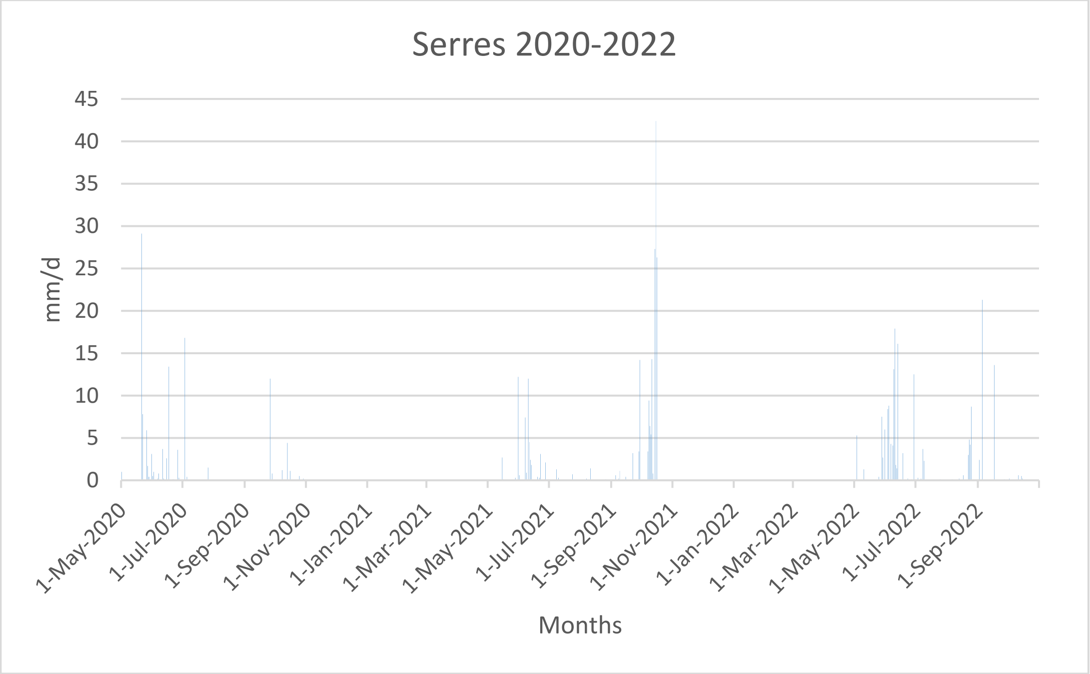


Figure 26. Data chart of the precipitation of cotton in Serres of the years 2020-2022

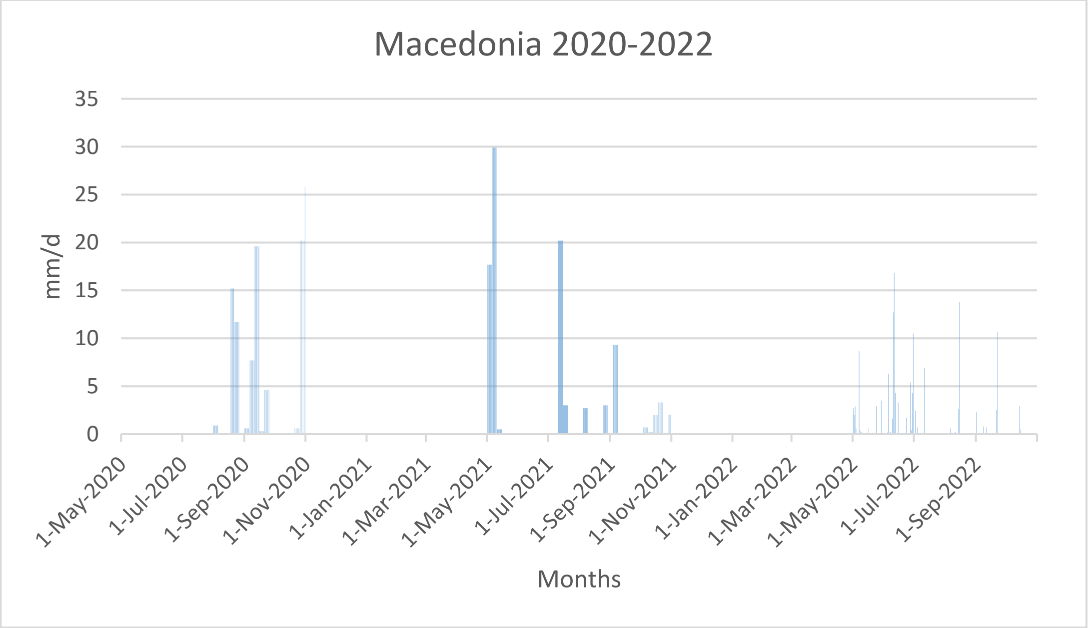


Figure 27. Data chart of the precipitation of cotton in Macedonia of the years 2020-2022

4.6 Final charts of precipitation of totals

Figure 28. Data chart of the precipitation of cotton in Larissa of the years 2008-2022

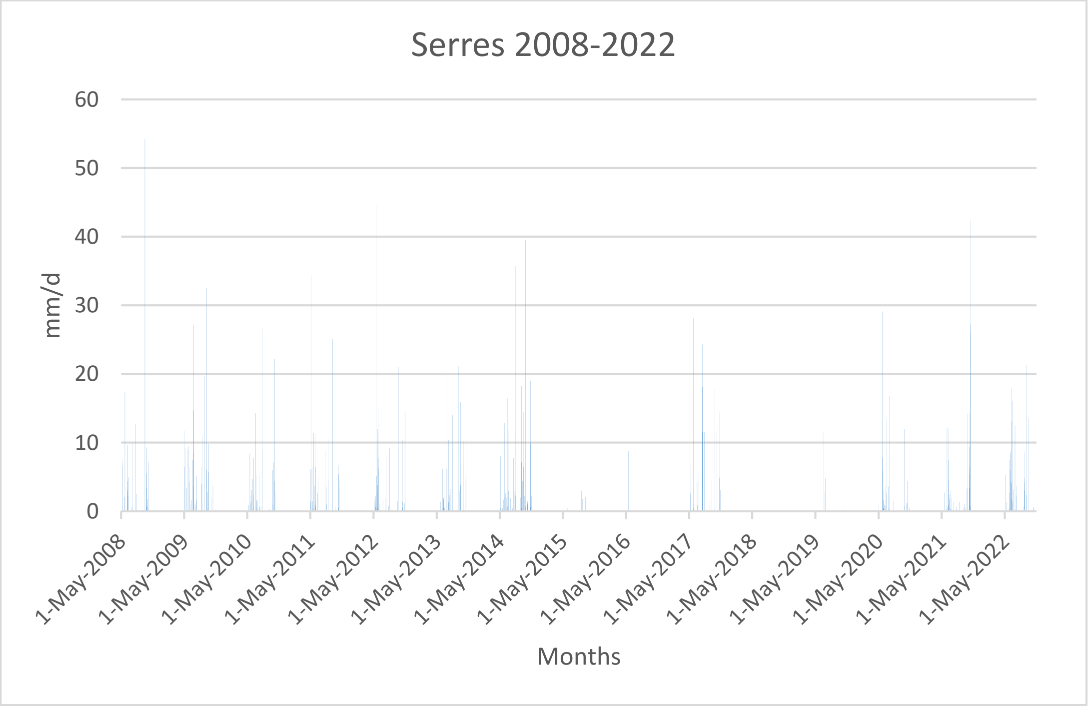


Figure 29. Data chart of the precipitation of cotton in Serres of the years 2008-2022

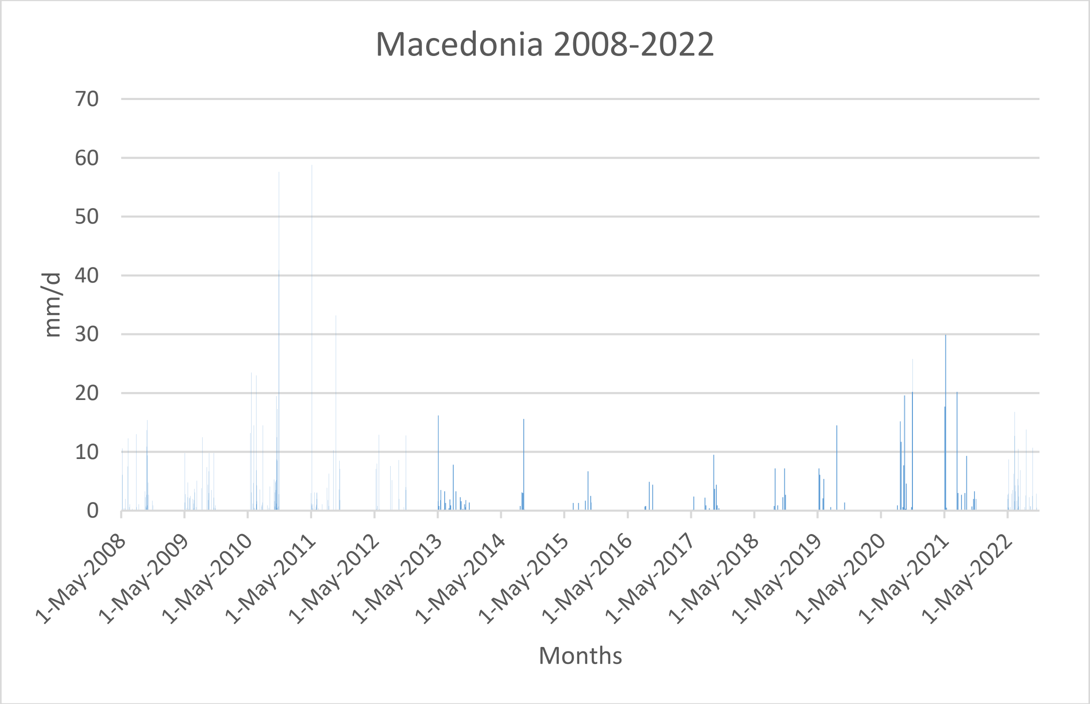


Figure 30. Data chart of the precipitation of cotton in Macedonia of the years 2020-2022

Chapter 5. WHEAT (TRITICUM L.)

The rest of Chapter 5 is organized as follows.

In Section 5.1, the graphs of the precipitation of wheat from the years 2008-2010 are presented.

In Section 5.2, the graphs of the precipitation of wheat from the years 2011-2013 are presented.

In Section 5.3, the graphs of the precipitation of wheat from the years 2014-2016 are presented.

In Section 5.4, the graphs of the precipitation of wheat from the years 2017-2019 are presented.

In Section 5.5, the graphs of the precipitation of wheat from the years 2020-2022 are presented.

In Section 5.6, the final chart of the precipitation of wheat, from the years 2008-2022 are presented.

All the following charts are of the period of months from 1st of November to 30th of June.

5.1 Data charts of precipitation of the years 2008-2010

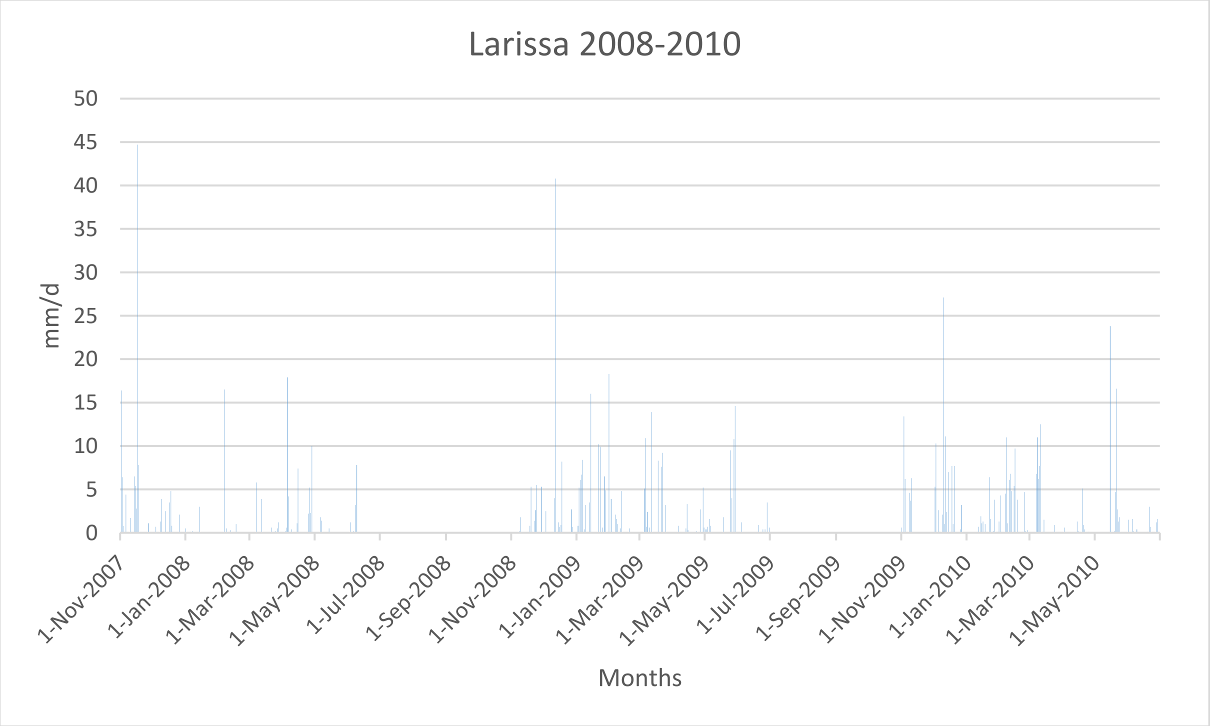


Figure 31. Data chart of the precipitation of wheat in Larissa of the years 2008-2010

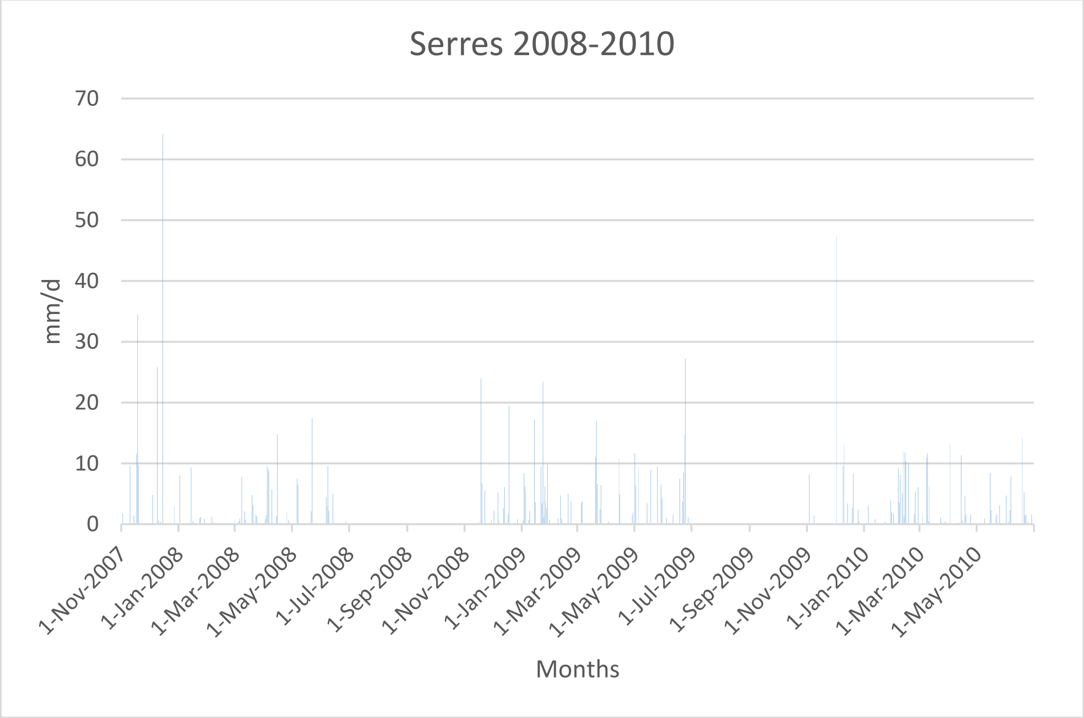


Figure 32. Data chart of the precipitation of wheat in Serres of the years 2008-2010

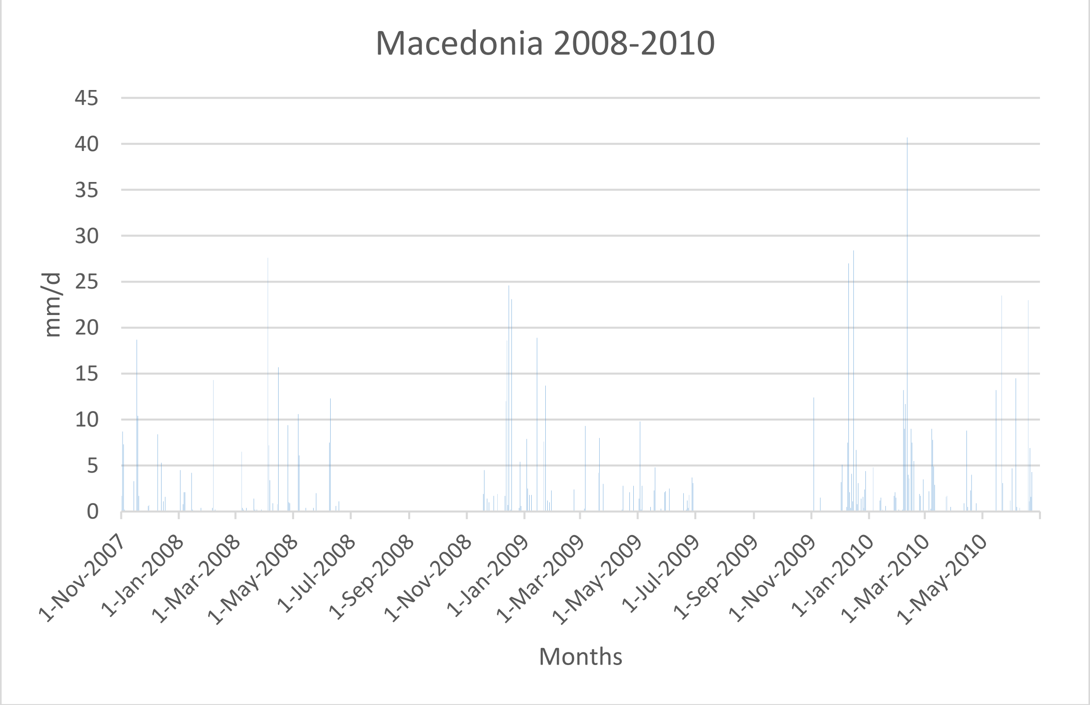


Figure 33. Data chart of the precipitation of wheat in Macedonia of the years 2008-2010

5.2 Data charts of precipitation of the years 2011-2013

Figure 34. Data chart of the precipitation of wheat in Larissa of the years 2011-2013

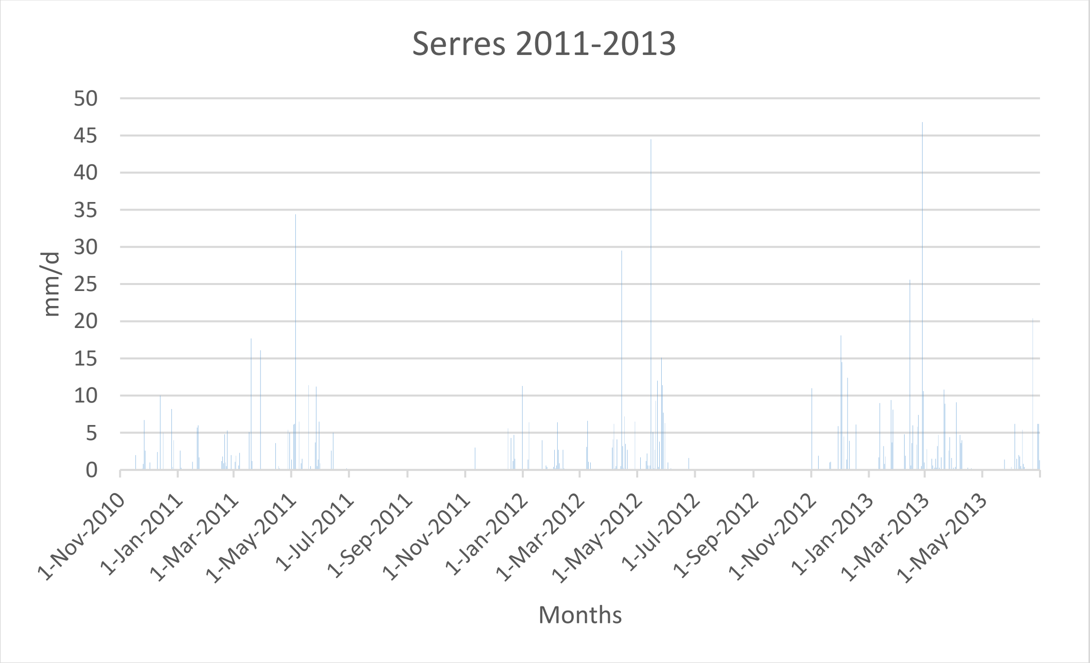


Figure 35. Data chart of the precipitation of wheat in Serres of the years 2011-2013

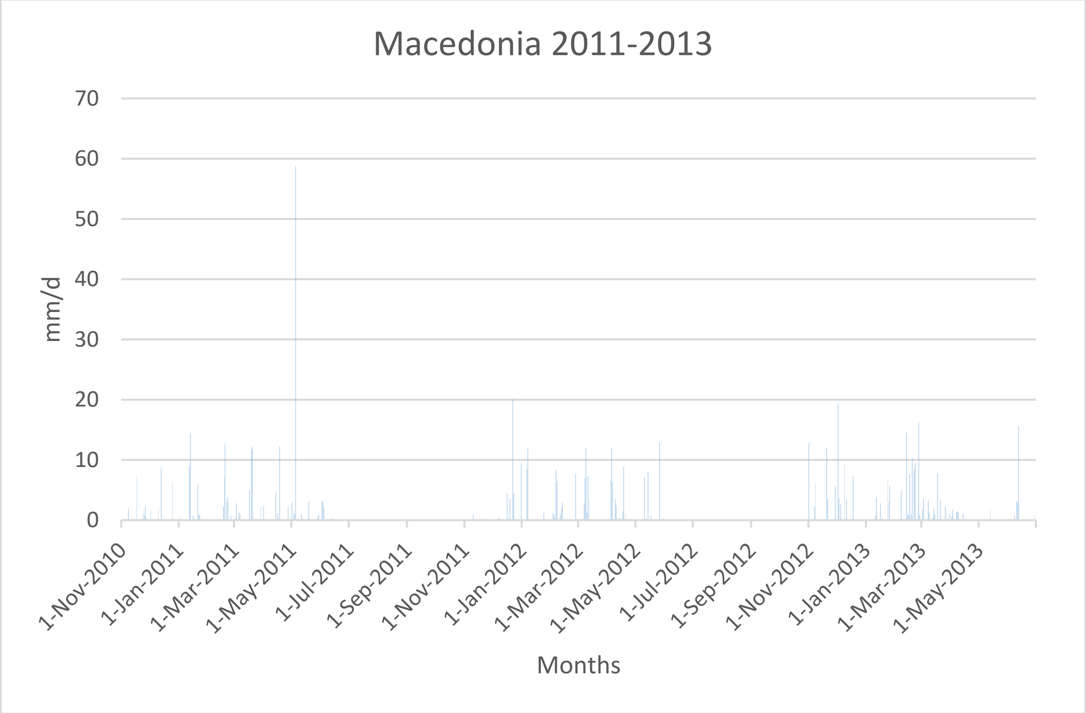


Figure 36. Data chart of the precipitation of wheat in Macedonia of the years 2011-2013

5.3 Data charts of precipitation of the years 2014-2016

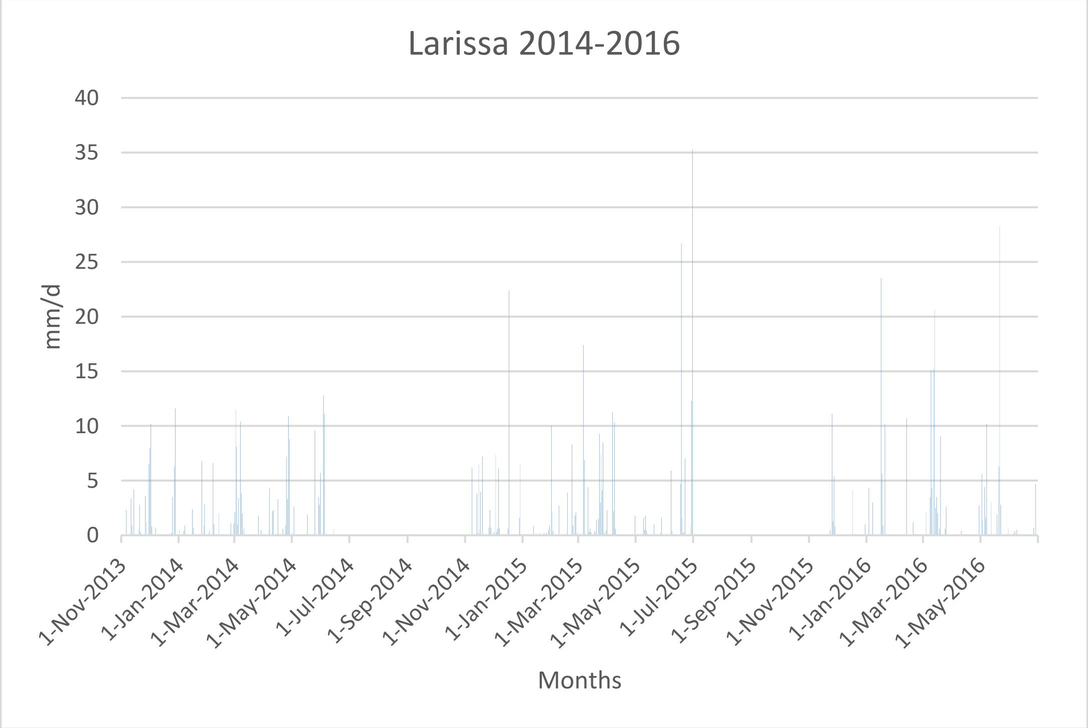


Figure 37. Data chart of the precipitation of wheat in Larissa of the years 2014-2016

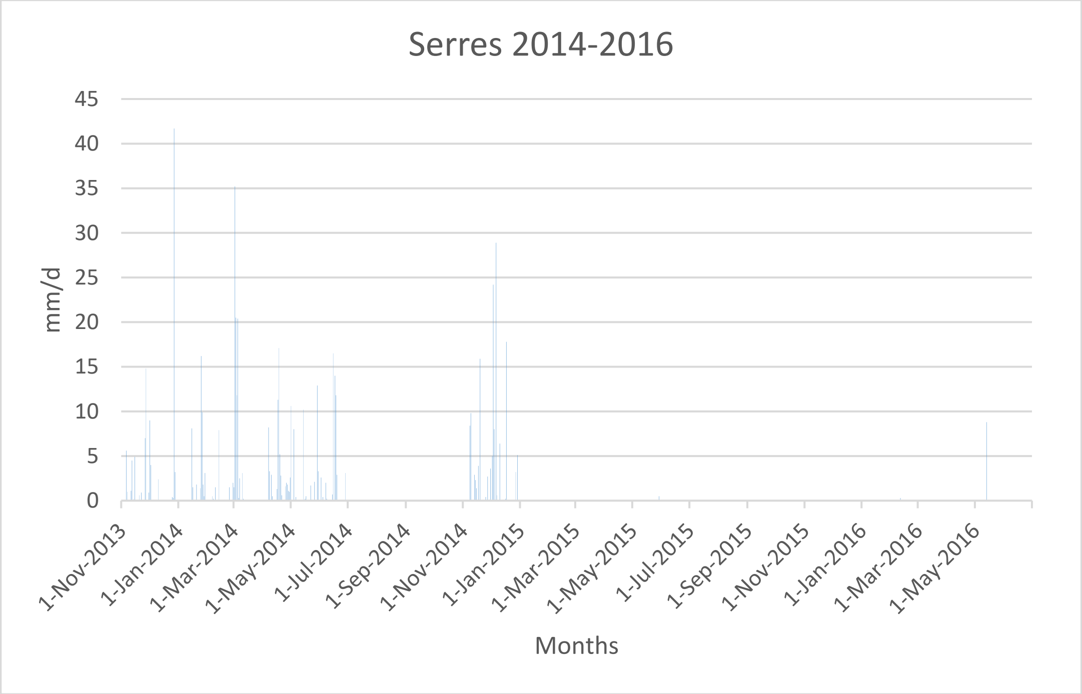


Figure 38. Data chart of the precipitation of wheat in Serres of the years 2014-2016

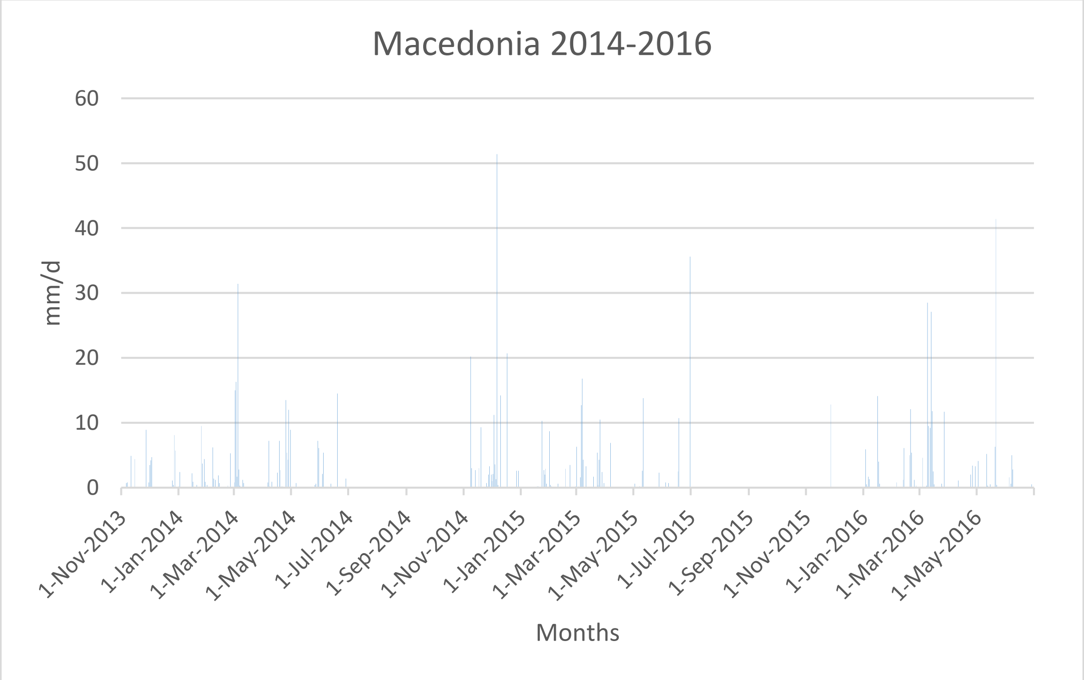


Figure 39. Data chart of the precipitation of wheat in Macedonia of the years 2014-2016

5.4 Data charts of precipitation of the years 2017-2019

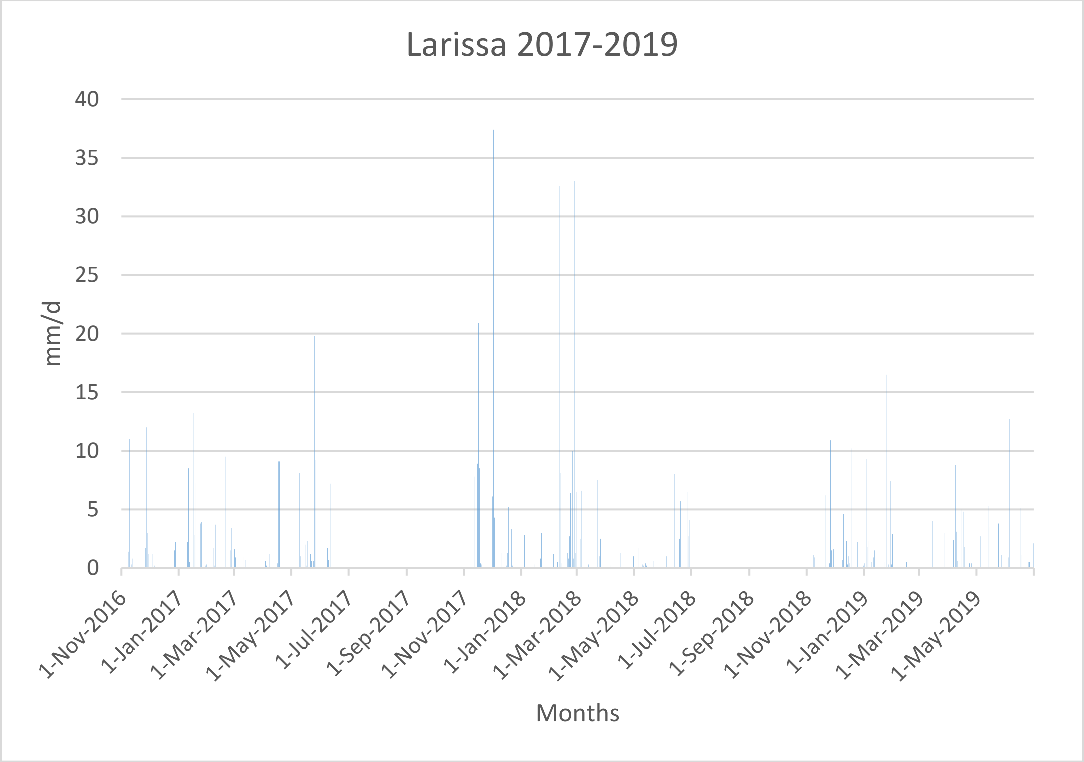


Figure 40. Data chart of the precipitation of wheat in Larissa of the years 2017-2019

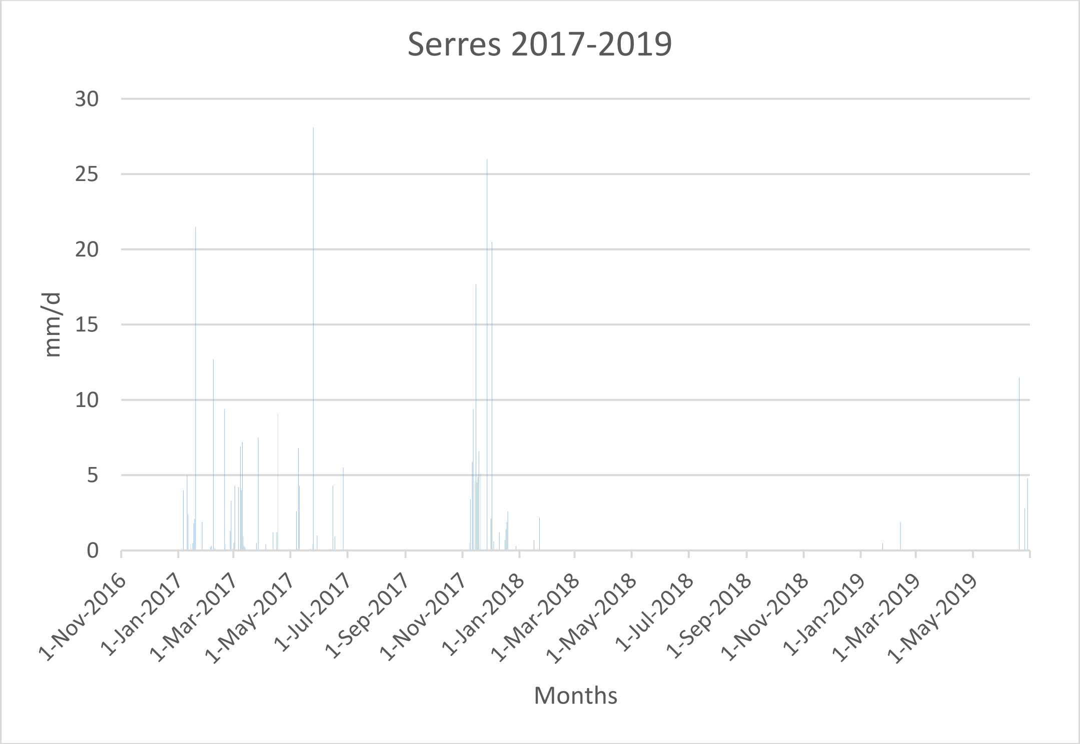


Figure 41. Data chart of the precipitation of wheat in Serres of the years 2017-2019

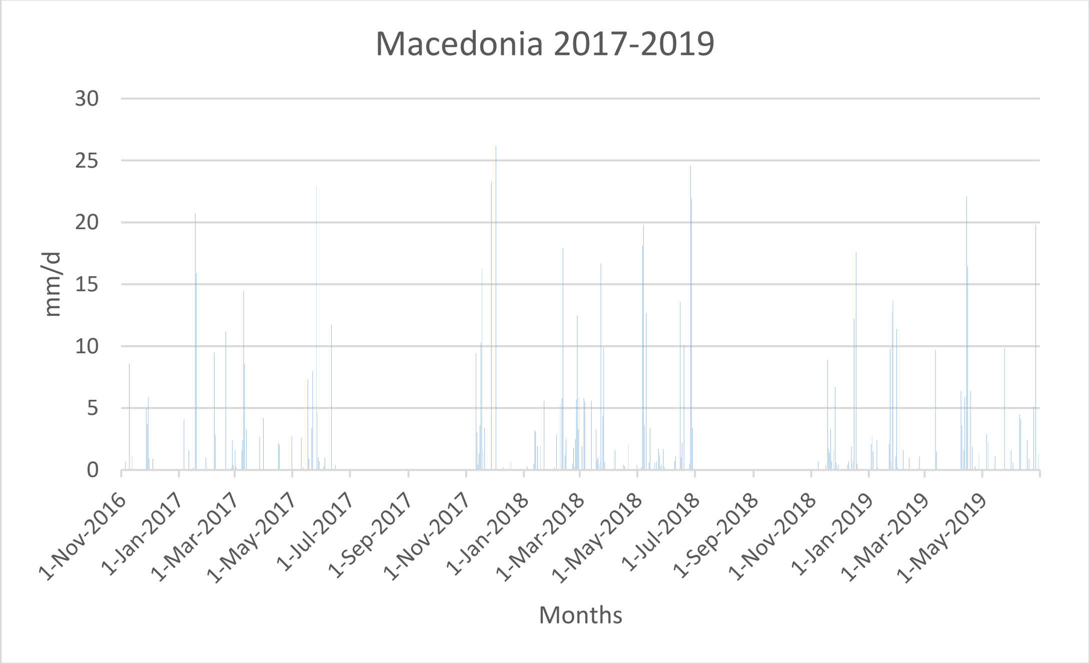


Figure 42. Data chart of the precipitation of wheat in Macedonia of the years 2017-2019

5.5 Data charts of precipitation of the years 2020-2022

Figure 43. Data chart of the precipitation of wheat in Larissa of the years 2020-2022

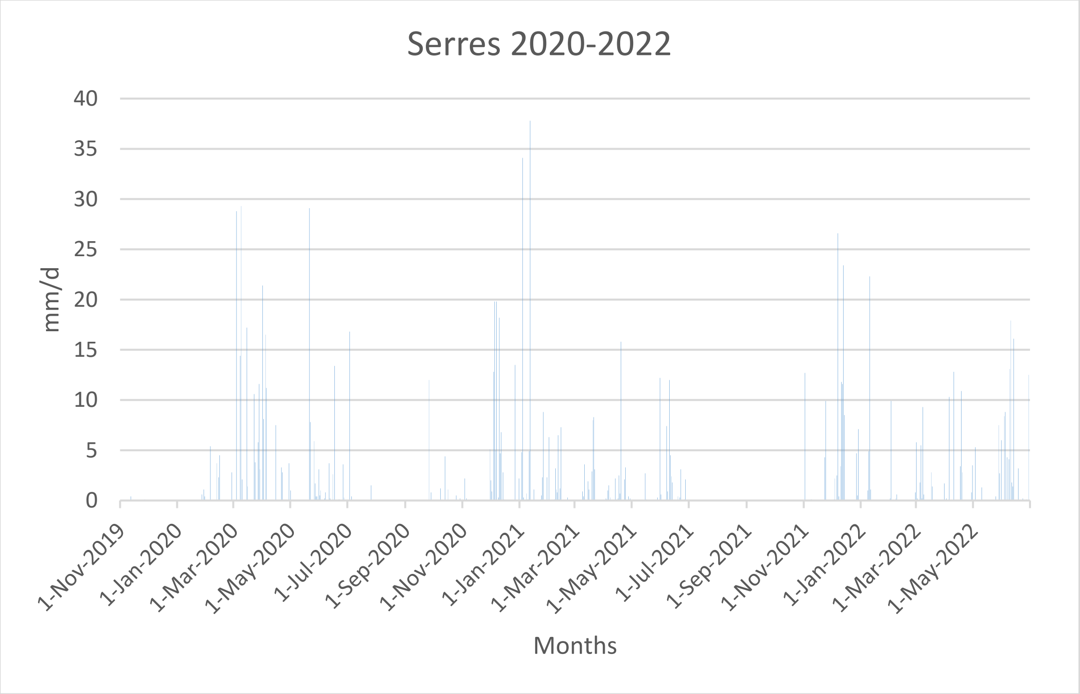


Figure 44. Data chart of the precipitation of wheat in Serres of the years 2020-2022

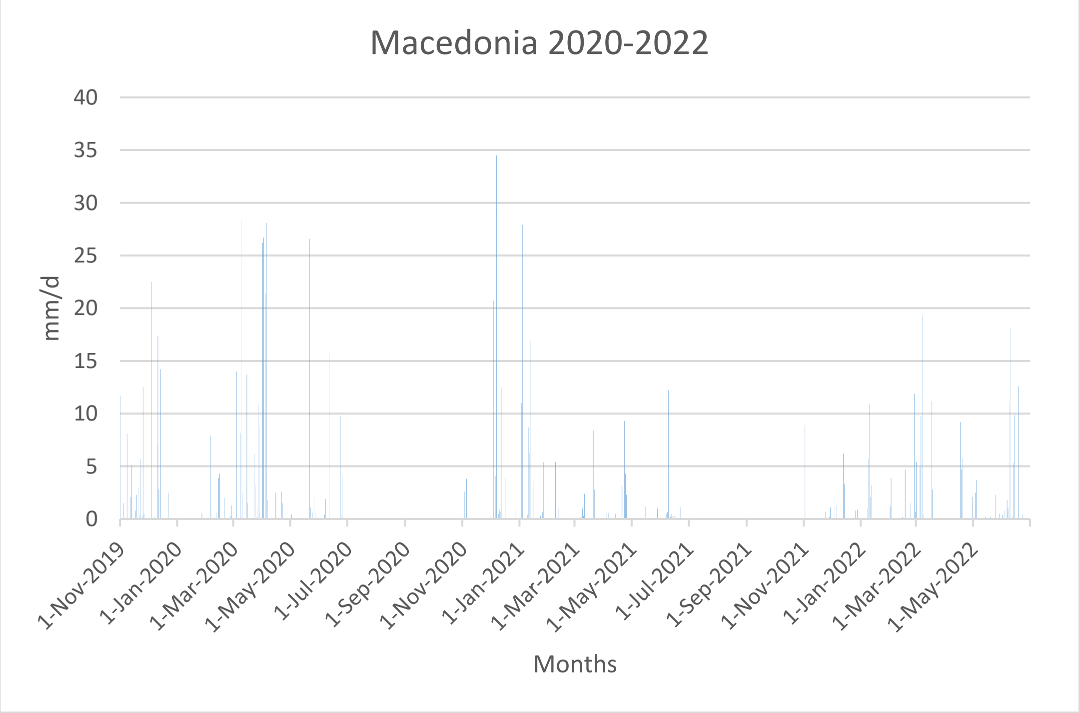


Figure 45. Data chart of the precipitation of wheat in Macedonia of the years 2020-2022

5.6 Final charts of precipitation of totals

Figure 46. Data chart of the precipitation of wheat in Larissa of the years 2008-2022

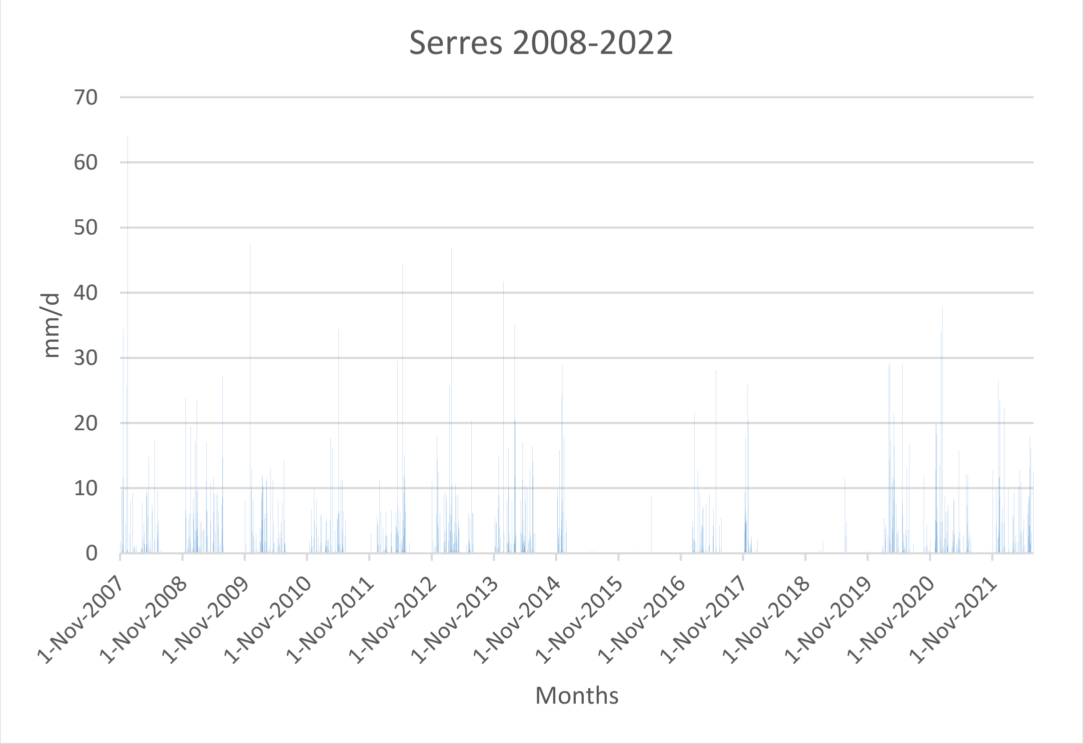


Figure 47. Data chart of the precipitation of wheat in Serres of the years 2008-2022

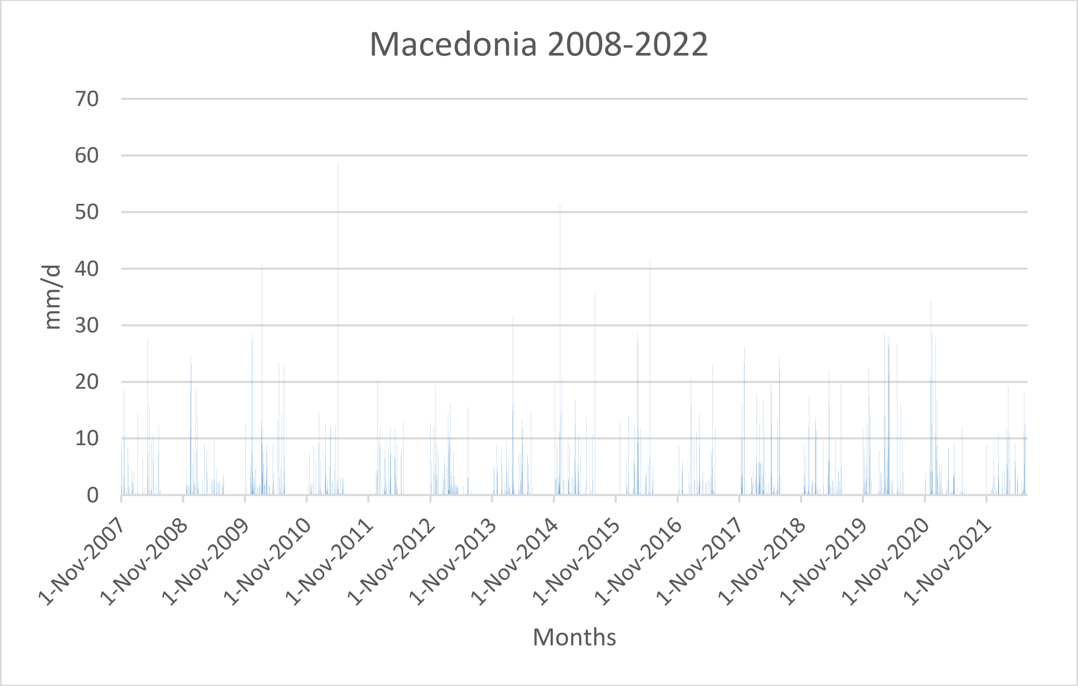


Figure 48. Data chart of the precipitation of wheat in Macedonia of the years 2008-2022

Chapter 6. DISCUSSION

In this thesis it was studied if and how the climate change has affected cotton and wheat crops the last fifteen (15) years. As aforementioned, in Chapter 1.5, a couple of scientific questions have been asked.

Beginning with the questions about the hypothesis if the climate change has changed the climate in Greece, as mentioned in Chapter 1 and more specific on Chapter 1.1, a rise of 1.2 °C (34.2 °F) in temperature has been observed in global level [7]. Moreover, according to World Data Info, between 1978 and 2023 the temperature in Greece has been increased by 1.6 °C (34.8 °F), which justifies the temperature raise in global level. By utilizing and comparing the data of the temperature of the year 1978 and the latest year of the database (2022), the average temperatures are 15,15 °C (59,27 °F) and 16,75 °C (62,15 °F) respectively. Also, by adding the mean temperature of each year (2008, 2009, …, 2022) of each area (Larissa, Serres and Macedonia) combined, we observe that indeed the temperature has risen.

Figure 49. Diagram of the mean temperature of each year (1st of January – 31st of December) for the years 2008-2022 of the areas of Larissa, Serres and Macedonia combined.

Hence, the rise of the temperature has changed the climate in Greece.

Additionally, with the questions about the hypothesis if the climate change has changed the climate in Greece, the precipitation rate has not been reduced. Although the changes in precipitation are not stable due to specific factors, the increase of the temperature [7] tends to cause increase evapotranspiration which eventually leads to more precipitation.

Thereinafter, with the questions about the hypothesis regarding if the factors affecting the plants’ growth have changed, the GDDs depend upon the daily temperature. Since the temperature has been increased, the duration of each growing season is shorter, due to the fact that the desired temperature has been achieved earlier. By calculating the sum of the GDDs (both on °C and °F) and by taking the average temperature of each growing period (1st of May to 31st of October of cotton and 1st of November to 31st of June of wheat) of each year, from 2008 to 2022, the following conclusions have been reached:

i) GDDs (°C/°F) of cotton of Larissa: Tends to decrease

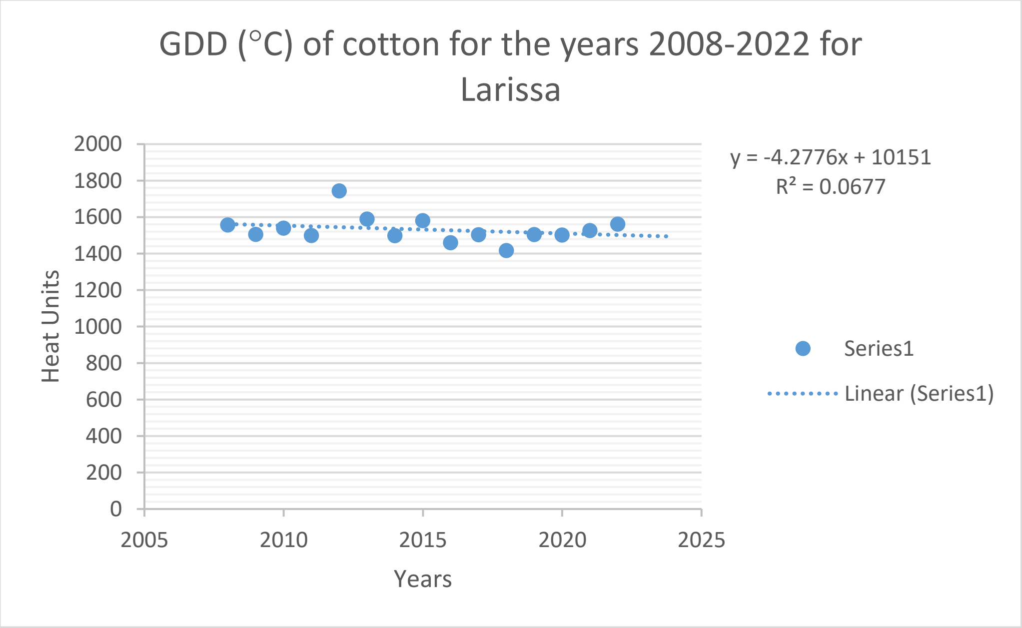


Figure 50. Linear prediction of the GDDs of cotton for Larissa for the years 2008-2022 and for the future.

ii) GDDs (°C/°F) of cotton of Serres: Tends to decrease

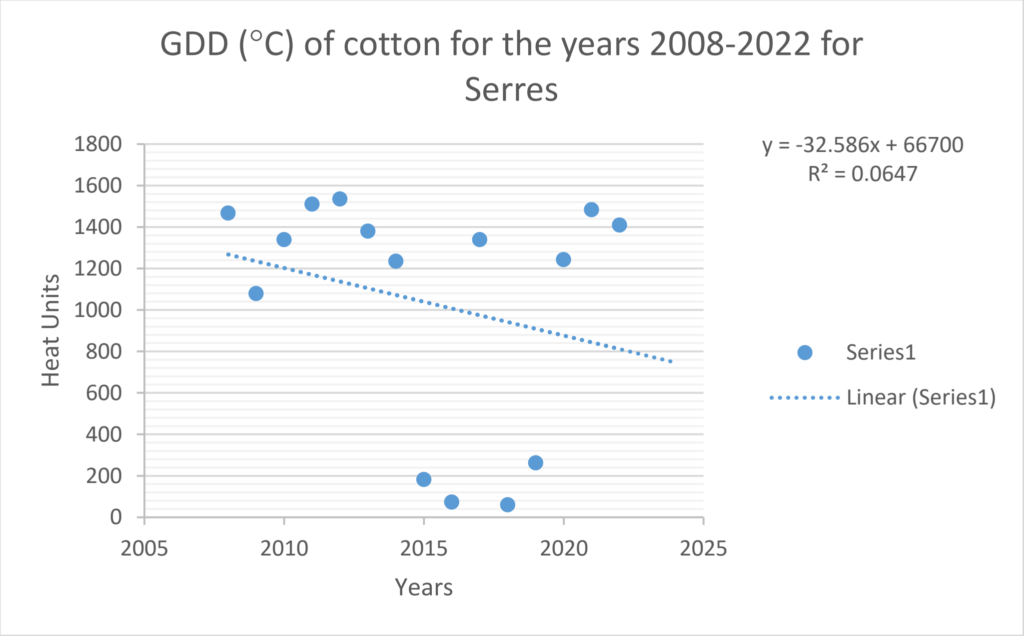


Figure 51. Linear prediction of the GDDs of cotton for Serres for the years 2008-2022 and for the future.

iii) GDDs (°C/°F) of cotton of Macedonia: Tends to increase

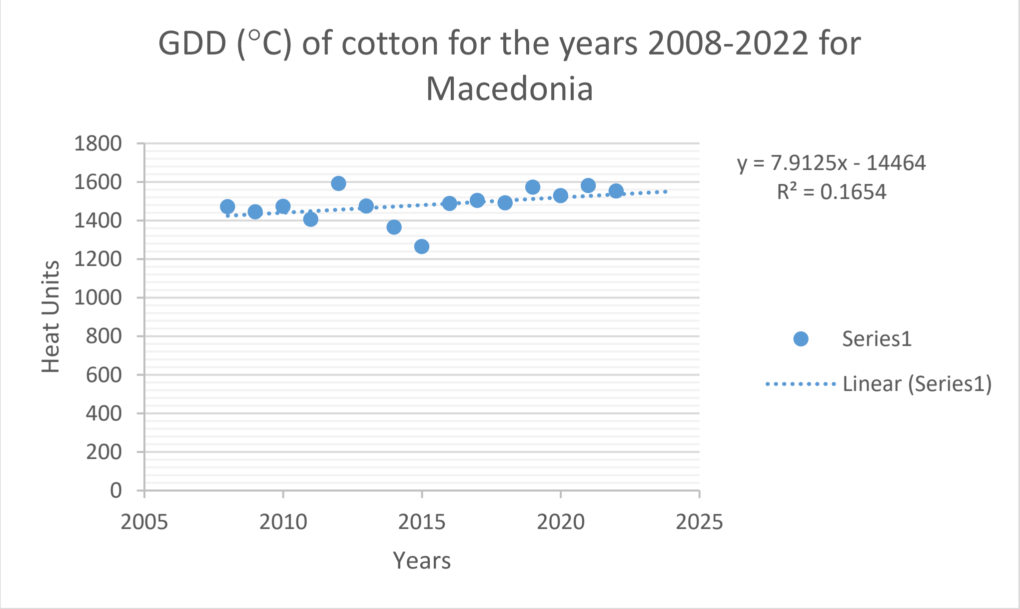


Figure 52. Linear prediction of the GDDs of cotton for Macedonia for the years 2008-2022 and for the future.

iv) GDDs (°C/°F) of wheat of Larissa: Tends to decrease

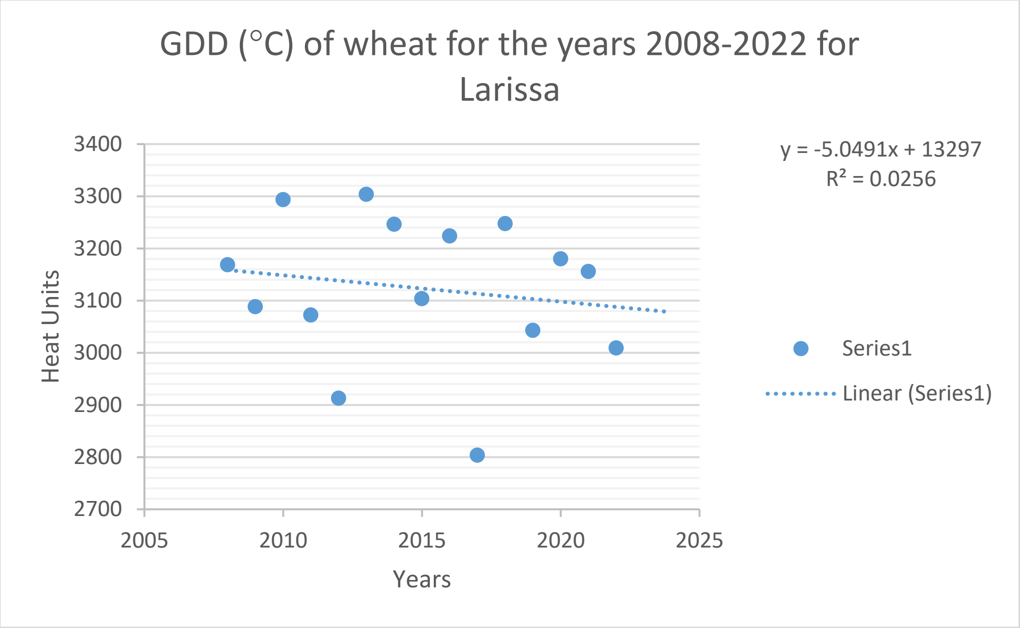


Figure 53. Linear prediction of the GDDs of wheat for Larissa for the years 2008-2022 and for the future.

v) GDDs (°C/°F) of wheat of Serres: Tends to decrease

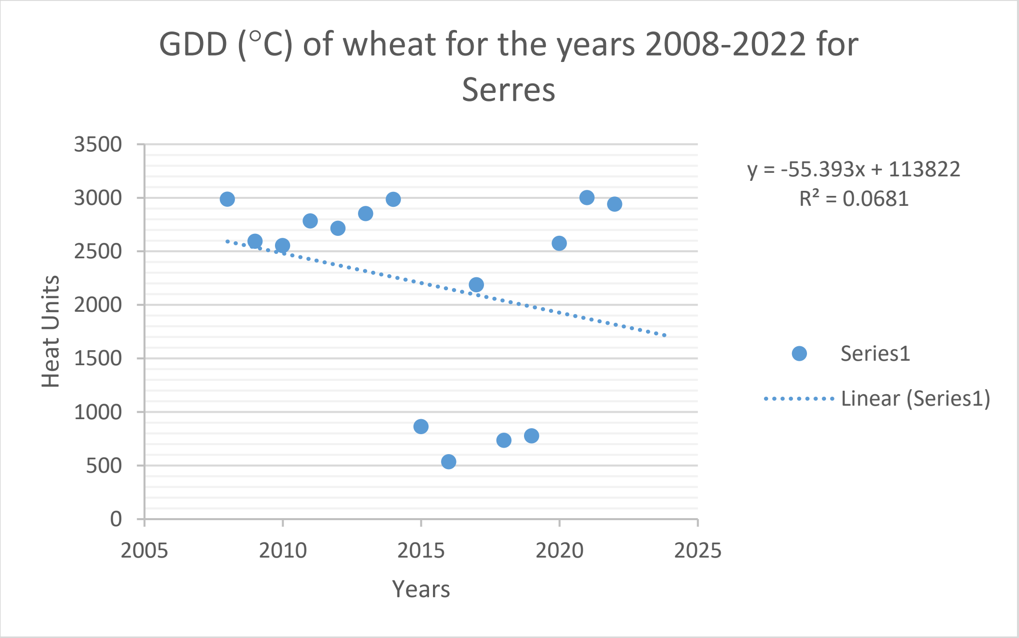


Figure 54. Linear prediction of the GDDs of wheat for Serres for the years 2008-2022 and for the future.

vi) GDDs (°C/°F) of wheat of Macedonia: Tends to increase

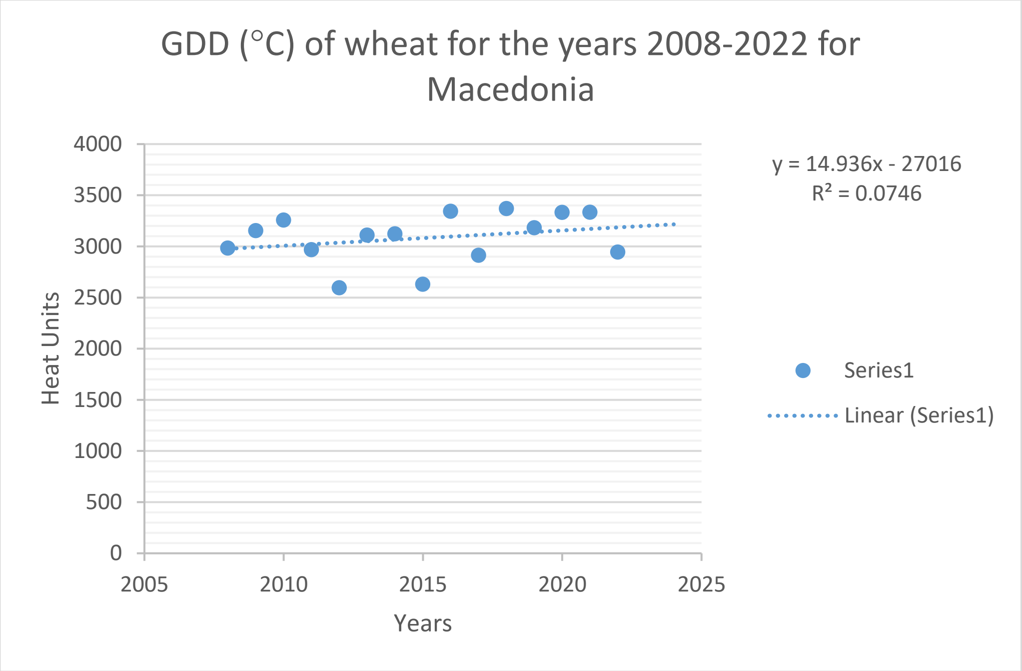


Figure 55. Linear prediction of the GDDs of wheat for Macedonia for the years 2008-2022 and for the future.

Due to this conclusion, the need of the creation of new hybrids and/or varieties that can last at higher temperature and maintain their GDDs as the original plants is quite necessary.

In conclusion, the last question about the hypothesis regarding if the factors affecting the plants' growth have changed, Kc has been affected as well. Particularly, Kc depends on the evapotranspiration of crop (ETc) which depends on solar radiation, the velocity of air, the temperature and the humidity [50] [57]. Increased temperature has an immediate effect on the increase of ETc and therefore at the crop coefficient factor, a fact that agrees to the aforementioned citations.

Some of the questions that remain unanswered and perhaps could be the object of study of future and farther work are how does climate effect will affect the temperature, the precipitation and the GDDs of various crops in the next decade.

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