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Review Article

Cotton versus climate change: the case of Greek cotton production

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Abstract

Through the last century, the increased greenhouse gases emissions altered the atmosphere's composition and resulted to the phenomenon known as climate change. Climate change threatens the sustainability of the agricultural sector in the Mediterranean region. Droughts and extreme heat waves will probably become more frequent in the next few decades, thus maintaining sufficient yields in heat and drought susceptible major crops will be challenging. In Greece, cotton is of paramount economic importance. Besides the fact that it is regarded as the most significant fiber crop, Greece is the main cotton producer of the European Union. The aim of the present review was to examine the environmental factors that might affect cotton production in Greece and assess whether (or not) climate change has the potential to limit the productivity of this crop in the near future. According to the existing literature, cotton can adapt to the changing climate. Climate change-induced elevated CO_2 levels and temperatures might even benefit cotton. The mitigation of the adverse effects of climate change is possible via the adaptation of site-specific agronomic practices. A simplistic framework, based on the literature and the goals of the European Union, that aims to the preservation of sufficient cotton yields in Greece is proposed in the present study.

Keywords: climate change; cotton; *Gossypium hirsutum*; Greece; greenhouse emissions

Introduction

Cotton is regarded as the most important fiber crop worldwide (Zaidi *et al.*, 2018). The origin of this crop is a complicated subject (Huckell, 1993), as the term "cotton" initially referred to four different species of the Malvaceae family (*Gossypium hirsutum*, *Gossypium barbadense*, *Gossypium arboreum*, and *Gossypium herbaceum*) (Smith and Cothren, 1999). These species were independently domesticated thousands of years ago in different parts of the world (Wendel and Cronn, 2003). Archeological evidence indicates that

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Gossypium barbadense was probably domesticated in the Americas 8.000 years ago (Splitstoser *et al.*, 2016). Similarly, *Gossypium herbaceum* was probably domesticated in the Nile Basin round 5.000 B.C. (Mokhtar, 1990). The first woven cotton record dates back to 3.000 B.C., in the Indus valley (Gulati and Turner, 1929). Presently, *Gossypium hirsutum* has prevailed as it consists 90% of the annual cotton production on a global scale (Wendel and Cronn, 2003). In 2019, the global cotton acreage was estimated to surpass 20 million ha, while the global cotton lint production was estimated approximately at 25 million tones (Figure 1) (OECD-FAO, 2020).

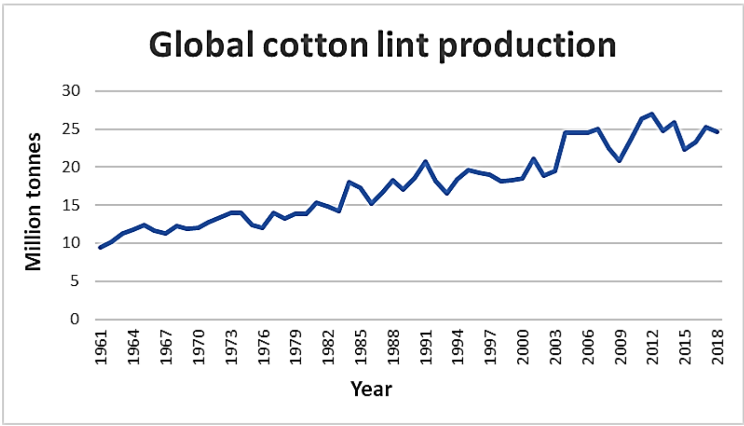

Figure 1. Global cotton lint production (million tones) from 1961 to 2018

Cotton had also been known to ancient Greeks. In 445 B.C., Herodotus mentioned that the Indian troops in Xerxes' army wore clothes made of cotton (Betts, 1994). However, it was not until the 2nd century A.D. that cotton was cultivated in Greece (Primentas, 1960). In fact, its cultivation in Greece was firstly reported by the ancient geographer Pausanias (120-180 A.D.), in the western part of the Peloponnese peninsula (Primentas, 1960). Nowadays, cotton is likely the most important arable crop on a national level, as it covers nearly 50% of the irrigated land (Gemtos *et al.*, 2004). Following the integration of Greece in the European Union (EU) cotton production was doubled within a decade, mainly due to the support from the Common Agricultural Policy (CAP) of EU (Figure 2) (Tzouvelekas *et al.*, 2001). Afterall, Greek cottonfields account for 80% of the total European cotton area. This constitutes Greece the main cotton producer of EU (EU Commission, 2006). Domestically, it has been estimated that cotton cultivation is the main source of income for more than 100,000 Greek households (Tzouvelekas *et al.*, 2001). Concurrently, the production of cotton-based textiles is included amongst the most important industrial sectors in terms of employment (Karagiannis *et al.*, 1997).

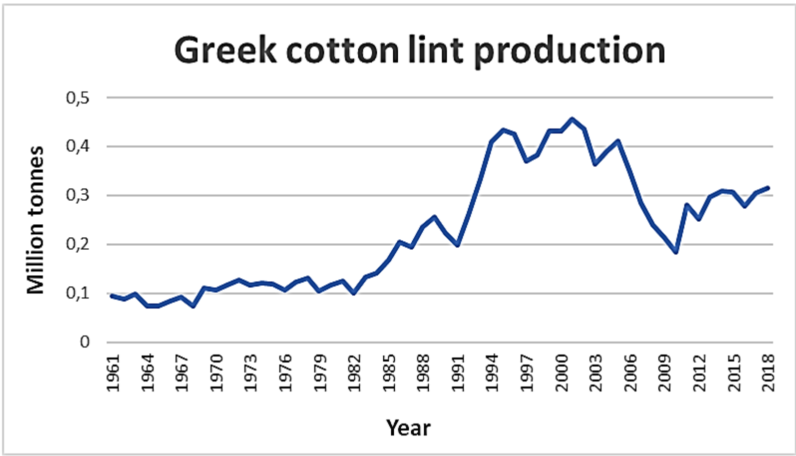

Figure 2. Greek cotton lint production (million tones) from 1961 to 2018

The cultivation of cotton

In Greece, cotton is sown from early March to mid-April. Depending on the variety and the environmental conditions, cotton is usually harvested 170-210 days after sowing (USDA, 2020). According to the literature, cotton development consists of 5 stages: (1) Germination and emergence, (2) seedling establishment, (3) leaf area and canopy development, (4) flowering and boll development and (5) maturation (Oosterhuis, 1990). Each growth stage is characterized by different physiological processes and nutrient needs (Basal *et al.*, 2019). Cotton thrives on warm climates as increased temperatures are vital for all the aforementioned growth stages (Burke and Wanjura, 2010). There is an optimal temperature range for the biochemical and metabolic activities of cotton known as the thermal kinetic window (TKW) (Burke *et al.*, 1988). Temperatures above or below the TKW stress the crop and affect negatively both plant growth and yield (Warner, 1993). The TKW for cotton ranges between 23.5 and 32 °C (Burke *et al.*, 1988). However, seed germination occurs at lower temperatures. In fact, the minimum temperature for seed germination has been estimated at 15 °C. At this temperature, germination occurs at a slow rate, while at 20-30 °C the germination rate gets doubled (Reddy *et al.*, 1991). Temperatures below 5 °C inhibit seed germination, and are detrimental for cotton seedlings (Christiansen, 1967; Christiansen 1968). During the stage of square development, temperatures exceeding 36 °C reduce the number of branches (Reddy *et al.*, 1995). In arid and semi-arid regions, irrigation is essential for cotton. Depending on the precipitations and the soil properties, cotton requires 6-7 million liters of water per ha (Roth *et al.*, 2013). Water scarcity may reduce the yield as it affects leaf physiology, flower bud formation, and metabolism of sucrose (Loka *et al.*, 2020). Crop establishment is favored by soils with a pH ranging from 5.2 to 8.0, adequate drainage and high-water capacity (Rehman, 2019). Fertilization is one of the main factors that enhances crop yields, crop growth and improves fiber quality (Sawan, 2014; Constable and Bange, 2015). The flowering and maturation stages are the most demanding stages in nutrient uptake (Oosterhuis, 2001). Apart from cultivar, tillage system, and irrigation regime, soil fertility influences fertilization management (Francisco and Hoogerheide, 2013; Marimuthu *et al.*, 2014; Kulvir *et al.*, 2015; Manjula and Chandrashekar, 2017), hence a soil analysis prior to seedbed preparation is recommended (Joham, 1951; Sabbe and Zelinski, 1990). Overall, the total N, P, K requirements of cotton range from 142-201 kg N ha^{-1}, 19-66 kg P ha^{-1}, and 89-254 kg K ha^{-1}, respectively (Bassett *et al.*, 1970; Halevy, 1976; Mullins and Burmester, 1990; Unruh and Silvertooth, 1996; Kadlag *et al.*, 2016).

A simple, yet efficient method to assess crop performance is the Growing Degree Days (GDD) (Hassan *et al.*, 2007). GDD represent the amount of heat required by the crop in a defined time period (Cleland *et al.*, 2007) and can be calculated based on equation 1 (Sharma *et al.*, 2021).

$$GDDs = \left(\frac{T_{max} + T_{min}}{2}\right) - T_{base} \quad (1)$$

Where Tmax is the highest daily temperature value, Tmin is the lowest daily temperature value, and Tbase is equal to 10°C. This index can be utilized in order to predict the number of days that it takes for the crop to go through each phenological stage (Miller *et al.*, 2001). On average, for a satisfactory cotton production, 1.800-2.200 °C-d are required (Supak, 1982). In Greece, GDD requirements range from 1600 in the northern areas to over 2900 °C-d in the southern regions (Matzarakis *et al.*, 2007; Tsiros *et al.*, 2009). The optimum environmental conditions for cotton production and its water, nutrient, and GDD requirements are summarized in Table 1.

Table 1. Optimum environmental conditions for cotton production and its water, nutrient, and °C-d requirements

Growth stage	Days (on average)	Optimal temperature range (°C)	Daily water needs (mm)	°C-d	Fertilization needs (Kg ha^{-1})	References
Germination and emergence	14	15-25	Well irrigated seedbed	31.33-86.65	N: 142-201 P: 19-66 K: 89-254	Bassett *et al.*, 1970; Halevy, 1976; Abdulmumin *et al.*, 1990; Mullins and Burmester, 1990; Unruh and Silvertooth, 1996; Hake *et al.*, 1996; Linker *et al.*, 2015; Kadlag *et al.*, 2016; Datta *et al.*, 2019; Tuttolomondo *et al.*, 2020
Seedling establishment	55		<2,5			
Leaf area and canopy development		18-27	2,5-5	550.91-786.35		
Flowering and boll development	75	27-32	5-7			
Maturation	65	18-32	-	1088.11-1360.25		

Climate change and cotton production

During the last century, the ever-rising emissions of greenhouse gases (GHGs) resulted in an increase of the mean temperature on a global scale, a phenomenon known as "Global warming" (Weart, 2008). Due to the increasing temperature droughts, wildfires, and soil degradation gradually became more frequent (Giannakopoulos *et al.*, 2011). These adverse effects of "Global warming" on the environment and/or the biota are now perceived as change in climatic conditions due to the alterations of the atmosphere's composition (UN, 1997), thus the adaptation of the term "Climate change". Although researchers had been expressing their concerns regarding climate change ever since the 1890s, it was not until the early 1970s that it was proven that anthropogenic pollutants, such as artificial chlorofluorocarbons (CFCs) and methane (CH_4), were depleting the ozone (O_3) layer, hence altering the Earth's climate (Şahin *et al.*, 2019). By the late 1970s climate change was regarded as the pivotal challenge of the 21st century (Şahin *et al.*, 2019).

The interplay between climate change and agricultural productivity is complicated since certain cultivation zones will be benefited, whereas others will be downgraded (Alcamo *et al.*, 2007). It should be noted that the production of agricultural commodities is believed to be responsible for at least 20% of the annual anthropogenic GHG emissions worldwide (Aydinalp and Cresser, 2008). Undoubtedly, climate change has significantly affected agriculture in the European continent (Olesen and Bindi, 2004), either positively or negatively. In the northern parts of Europe, the increasing temperatures are expected to promote the intensification of agriculture, encourage the introduction of new crops, and potentially increase yields (Audsley *et al.*, 2006; Olesen *et al.*, 2007; Bindi and Olesen, 2011). On the contrary, climate change has evolved to a major threat to agriculture in southern Europe, and especially in the Mediterranean Basin and in the south-west Balkans (Olesen and Bindi, 2002; Bindi and Olesen, 2011). The adverse effects of climate change (increasing temperatures, water scarcity) are expected to push the Mediterranean Basin to the limits of desertification (Jacobsen, 2014). In Greece, it has been predicted that by the mid-twenty-first century (2021-

2050) droughts will become more frequent, the minimum average temperature will increase, and the average precipitations will decrease (Giannakopoulos *et al.*, 2011). This could potentially be pernicious for the agricultural sector and the sustainability of the existing agricultural systems (Mimikou and Baltas, 2013; Gkiza *et al.*, 2021).

The effects of climate change on cotton production are crucial in Greece due to the aforementioned importance of this crop for the country's economy. As mentioned above, major cotton production areas of Greece include Aitoloakarnania, Fthiotida, Larissa, Serres and Pella. According to Giannakopoulos *et al.* (2011), droughts and temperatures exceeding 35 °C, will become more frequent in these areas. Water scarcity during the early vegetive stages and temperatures over 35 °C do not favor the canopy and root development in cotton (Reddy *et al.*, 1992; McMichael and Burke, 1994; Sadras and Milroy, 1996). Exposure to high temperatures (over 32 °C) has also been proven to reduce cotton boll retention, thus reduce the yield (Zafar *et al.*, 2018). It is worth mentioning though, that the severity of the yield losses due to heat stress depends not only on its intensity, but also on its duration (Zafar *et al.*, 2018). According to Singh *et al.* (2007), mean temperatures that exceed the optimal temperature range even by only 1 °C might reduce cotton yield by 110 kg ha^{-1}. Moreover, cotton produces irregularly sized bolls under heat stress (Ton, 2011). The quality of the fibers is also negatively affected by extreme temperatures, as they alter their micronair and strength values (Ton, 2011). If the heat stress is combined with droughts, the growth rate of cotton, as well as the yield, could be further reduced (Carmo-Silva *et al.*, 2012).

From the perspective of plant physiology, heat stress and water scarcity are known to interfere with plant functions and physiological processes such as photosynthesis, protein synthesis, stomatal movement, and nutrient uptake and translocation (Burke *et al.*, 1985; Bibi *et al.*, 2008; Pirasteh-Anosheh *et al.*, 2016; Shakoor *et al.*, 2017). In a cellular level, heat and water stress can damage the cell membrane (Mohamed and Abdel-Hamid, 2013), reduce the chlorophyll content (Hsiao *et al.*, 1976), and suppress the activity of Rubisco (Law *et al.*, 2001). As a response to this abiotic stress, cotton plants synthesize polypeptides known as Heat-Shock Proteins (HSPs) (De Ronde *et al.*, 1993) in order to recover and regulate their metabolic imbalances (Xiao and Mascarenhas, 1985; Mohamed and Abdel-Hamid, 2013). It should be noted that HSPs are correlated with stress tolerance (Zhang *et al.*, 2016), and their biosynthesis in cotton is to some extent cultivar dependent (De Ronde *et al.*, 1993). Perhaps HSPs could be determinant for the adaptation of cotton to climate change-induced heat stress (Ma *et al.*, 2016)

Although, based on the above, climate change seems to threaten cotton production in Greece, the literature provides contradictory results. For instance, the elevated atmospheric CO_2 concentration that has been reported during the 21st century might be beneficial for cotton, despite its contribution to the climate change. According to the findings of Radin *et al.* (1987), an increase of the atmospheric CO_2 concentration by a two-times-fold doubles the yield. Reddy *et al.* (1998) suggested that, under an irrigation regime that provides sufficient water, a similar increase of CO_2 concentration almost doubles the photosynthetic rate of cotton plants. Under water stress, the elevated CO_2 levels can partially compensate for the water scarcity (Chaves and Pereira, 1992; Kimball *et al.*, 1994), though others support that increased CO_2 levels benefit cotton only under optimal temperatures and soil moisture conditions (Broughton *et al.*, 2017). The enhanced performance of cotton in CO_2 enrichened environments could be attributed to the fact that cotton is a C3 plant. Several studies indicate that C3 plants are favored by elevated atmospheric CO_2 since it promotes photosynthesis and ammonium ($NH4^+$) utilization (Hamim, 2005; Wang *et al.*, 2020). Moreover, the observed heat and water stress-compensating effect of increased CO_2 concentrations is probably associated with stomatal movement. According to several studies, high CO_2 levels stimulate stomatal closure, thus reducing transpiration and increasing evapotranspiration efficiency (Mauney *et al.*, 1994; Hileman *et al.*, 1994; Ko and Piccinni, 2009).

Besides the adverse, heat stress-inducing extreme temperatures (>32 °C), the higher average temperatures could be beneficial for the cotton production in Greece. Occurrence of cold-stress events during the early growth stages of the crop might be significantly reduced (Giannakopoulos *et al.*, 2011). By 2050, the growing degree days per cultivation season in Greece are expected to increase at least by 150, depending on the area (Paparrizos and Matzarakis, 2016; Paparrizos and Matzarakis, 2017). According to Kukal and Irmak (2018), GDDs and yields are positively correlated, thus cotton yields might increase. Higher mean temperatures, within the optimal range for plant development, could increase their growth rate and, as a result, shorten the crop cycle (Reddy *et al.*, 1996). According to Voloudakis *et al.* (2015), this would also increase the yield significantly. In fact, several prediction models suggest that climate change might have a positive impact on cotton yields in Greece (Voloudakis *et al.*, 2015; Voloudakis *et al.*, 2018).

Future implications

An important aspect that should be regarded, in order to predict (at least to some extent) the future of cotton production in Greece, are the goals set by the EU and the United Nations (UN). The EU Green Deal, the Common Agricultural Policy of EU, as well as the Sustainable Development Goals (SDGs) of the UN, all aim to mitigate the adverse effects of climate change (Zhenmin and Espinosa, 2019; EU Commission, 2020a; EU Commission, 2021). For the implementation of these goals, a series of actions have been proposed in order to reduce GHGs emissions (Zhenmin and Espinosa, 2019; EU Commission, 2020a; EU Commission, 2021). Amongst these actions, the reduction of chemical inputs (fertilizers, pesticides) by at least 50% by 2030 was agreed (EU Commission, 2020b). As cotton production in Greece relies heavily on the application of chemical fertilizers (Setatou and Simonis, 1995), the yields could be negatively affected.

The need for a strategy regarding Greek cotton production in the "era of climate change" becomes evident. Such a strategy could be based on three axes: initially, the compliance with the goals of EU and UN is imperative. In the case of chemical fertilizers, their consumption in Greece has been indeed reduced by 25% during the last decade (Giannakopoulou *et al.*, 2020), however the literature regarding the potential reduction of applied fertilization in cotton is poor, if not non-existent. Provided that a further reduction of chemical fertilizers is required, replacing conventional fertilizers with slow-release ones (SRFs) is a potential solution. Slow-release fertilizers utilize urease or nitrification inhibitors and release their nutrients in a slower rate (Folina *et al.*, 2021). The application of SRFs has been found to increase cotton yield (Giannoulis *et al.*, 2020), and to be equally efficient compared to the application of conventional fertilization even at rates reduced by 40% (Oosterhuis and Howard, 2008).

Secondly, the increased mean temperature (within the optimal range for plant growth) and CO_2 levels could be regarded as short-term benefits of the climate change. Afterall, these two environmental parameters influence the photosynthetic rates of the plant and thus, they could positively affect plant canopy and yield (Reddy *et al.*, 1996). Moreover, it has been estimated that the elevated mean temperature will prolong growing seasons (Giannakopoulos *et al.*, 2011). Prolongation of the growing season even by one day could increase yields by 14-34 kg ha^{-1} (Bange and Milroy, 2004). Concurrently, the GDDs will rise in several parts of the country, facilitating its introduction to new areas (Paparrizos and Matzarakis, 2016; Paparrizos and Matzarakis, 2017).

Finally, the mitigation of the adverse effects of climate change, or rather the adaptation of cotton production under climate change, should be focused on agronomic practices and genetic engineering (Zafar *et al.*, 2018). Genetic engineering is a useful tool that can improve existing varieties via hybridization. For instance, breeding programs could utilize wild species with drought and heat resistance traits (Zafar *et al.*, 2018). However, such programs usually are too costly and time-consuming (Katageri *et al.*, 2020). On the contrary, the adoption of suitable, site-specific agronomic practices might be a more immediate alternative. Prolonged and intense droughts could be managed via deficit-irrigation regimes, or the application of zeolite (or synthetic super absorbent polymers), as these practices have been proven to improve water-use efficiency (Papastylianou and Argyrokastritis, 2014; Fallahi *et al.*, 2015). The latter has also been found to increase nutrient uptake and efficiency (Ahmed *et al.*, 2010). Alterations in row-spacing could also tackle water stress (Zafar *et al.*, 2018). Similarly, extremely high temperatures could be avoided by altering the sowing dates (Zafar *et al.*, 2018). Finally, the literature indicates that foliar application of organic compounds such as ascorbic acid, ascobine, and salicylic acid can alleviate heat stress in cotton (Omar *et al.*, 2018).

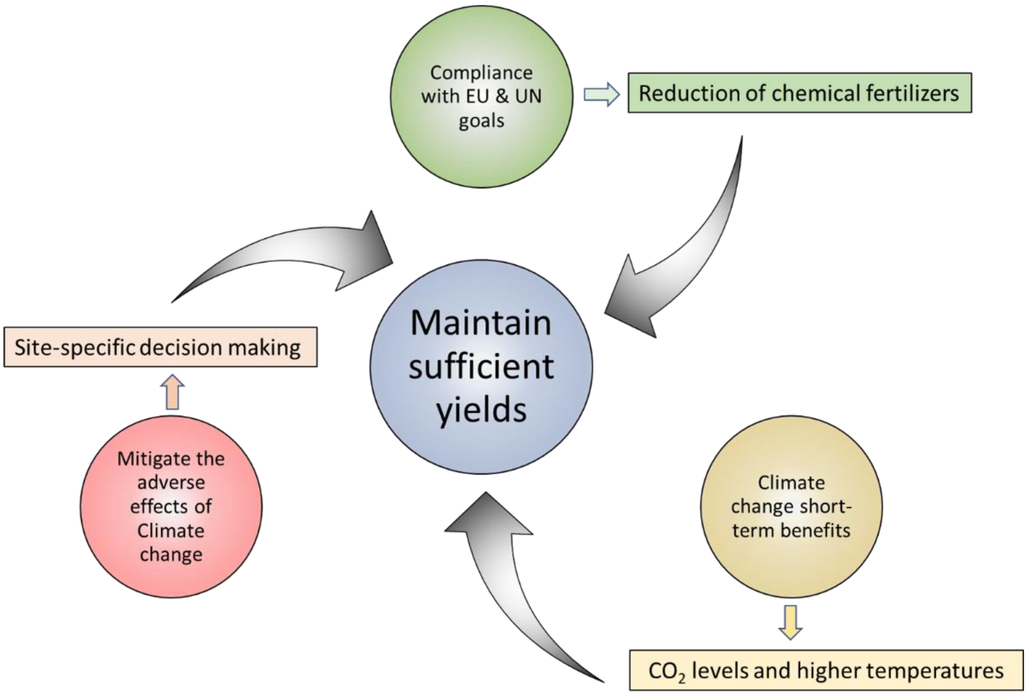

Figure 3. The three axes of modern Greek cotton production

Conclusions

Even though climate change threatens agriculture, the production of cotton in Greece will be probably unaffected by it. According to several prediction models, Greece will maintain or even increase its overall cotton production through the next decade. The elevated atmospheric CO_2 levels and the increased temperatures might have a positive impact on the yields. On the contrary, droughts and prolonged heat stress will negatively affect this crop. If necessary, climate change mitigation strategies can provide means to dilute the impact of heat and water stress on cotton production. Further research should be conducted in order to optimize these strategies.

Authors' Contributions

V.K., A.M., D.B. Conceived and designed the analysis; A.F., A.S. Collected the data; V.E., V.K., A.M., S.K., D.B. Contributed data or analysis tools; V.K., S.K., D.B. Performed the analysis; V.K., A.M., D.B. Wrote the paper. All authors read and approved the final manuscript.

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Conflict of Interests

The authors declare that there are no conflicts of interest related to this article.

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