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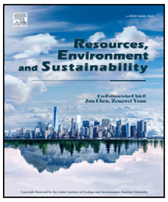

Review article

Durum wheat productivity today and tomorrow: A review of influencing factors and climate change effects

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ABSTRACT

Durum wheat is a crucial staple crop in many arid and semi-arid regions around the world, significantly contributing to local food security. This review paper aims to explore the current status of durum wheat productivity and the potential impacts of future climatic conditions on its cultivation. Various drivers and constraints affecting durum wheat yield are examined, including biotic and abiotic stressors, CO_2 concentrations and agronomic practices. Drought and heat stress were identified as the primary yield limiting factors. Furthermore, the influence of climate change on durum wheat is evaluated, focusing on altered precipitation patterns, temperature extremes, and increased atmospheric CO_2 levels. Most prominent quantification methods for climate change impact on yields are explored. The paper provides a summary of the current state of research, which reveals some contradictory results for future durum wheat yields. On the one hand, significant increases in productivity due to the fertilization effect of higher CO_2 levels are predicted. On the other hand, the crop failures are foreseen as consequence of elevated heat and drought stress as part of climate change. Overall, this paper underlines the importance of understanding the complex interactions between climate change and durum wheat productivity and highlights the urgency to explore sustainable adaptation strategies to ensure future food security.

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1. Introduction

Durum Wheat (*Triticum turgidum* L. ssp. *Durum*) is a minor cereal crop on global scale, though it is concentrated in specific geographical regions where it serves as primary cereal crop, playing a crucial role in food production and agricultural income (Martínez-Moreno et al., 2022; Tedone et al., 2018). Originating from eastern Mediterranean, where is has been cultivated for the last 12,000 years, it is considered one of the oldest winter wheat cultivars in the world (Habash et al., 2009; Constantinidou et al., 2016). Nowadays the Mediterranean basins, along with North America (in particular Canada), continue to be recognized as the main growing areas (De Vita and Taranto, 2019). In general, durum wheat is considered a favourable crop for semi-arid environments due to its exceptional adaptation to climatic stresses such as high temperatures and droughts (Sall et al., 2019; Martínez-Moreno et al., 2022). In the warmer, drier regions, like the Mediterranean basin, it is cultivated as winter wheat, whereas in the northern areas, which are characterized by cold and long winters, sowing is usually performed in spring and harvesting in early autumn (Bassu et al., 2009; Sieber et al., 2014). Durum wheat, which is known for its high-protein content, golden colour and firm texture, serves as an important food source in certain regions (De Santis et al., 2021; Liu et al., 2019) with a nutritional composition of 70% carbohydrates, 12%–18% protein, 1.9% fat, 1.6% minerals, and 1.6% fibre (Monneveux et al., 2012; Saini et al., 2022). The wheat's milling produces a granular product called semolina, whose further processing varies depending on the region (Sissons, 2008). In North Africa and West Asia regional foods derived from durum wheat mainly include couscous, bulgur and freekeh whereas in Italy durum wheat is predominantly used for the preparation of pasta in numerous forms and different bakery products (Martínez-Moreno et al., 2022; Li et al., 2013). It was reported that about 75% of the worldwide durum wheat production is used by the pasta industry (Beleggia et al., 2018). With 3.36 million tons of pasta produced annually, Italy is the largest producer worldwide (Altamore et al., 2019). To ensure high quality, Italy, together with France and Greece, has decreed that only durum wheat to be used to produce dried pasta and any undeclared use of other cereal is considered fraud (Sissons, 2008).

A wide variety of durum wheat cultivars has evolved over time to meet specific environmental and agronomic requirements. Finding and developing cultivars with improved grain yields has been the main agenda of many durum wheat breeding programmes worldwide (Khayatnezhad and Gholamin, 2020), which are expected to play a crucial role in climate change adaption (De Vita and Taranto, 2019). As durum wheat growth is highly influenced by climatic factors, such as temperature and water availability, changing conditions may accordingly affect its cultivation. Even in present days, changes in weather extremes and average temperatures are perceptible with the average global surface temperature between 2011–2020 being 1.1 °C above the 1850–1900 level (IPCC, 2023). The mean temperature increases in recent decades were shown to already exert adverse effects on wheat yields around the world (De Vita and Taranto, 2019) and are projected to intensify in forthcoming years. Further, the frequency and intensity of extreme heat waves, heavy precipitation, and, in some regions, ecological and agricultural droughts will increase according to the Intergovernmental Panel on Climate Change (IPCC), with the potential to significantly decrease crop production (D'Odorico et al., 2018). Concomitantly world population is expected to rise in the next decades, resulting in increasing food demands and pressure on agricultural production (Goicoechea et al., 2016; Rulli et al., 2013). To address this in the frame of climate change scenarios it is crucial to understand the response of crop yield to the changing environment. This review aims to give an overview of the main influencing factors of durum wheat yields and to show how changing climatic conditions in the future might alter their effects and therefore the worldwide durum wheat productivity. Scientific literature was accessed through the Scopus database by Elsevier and Google Scholar based on search requests with combinations of different keywords, such as *durum wheat, climate change, crop yield, drought, heat, CO_2-fertilization, crop model*. The most relevant papers have been selected for further investigation.

The review is structured as follows. Section 2 introduces the actual state of the durum wheat yield in terms of global distribution and fluxes. The main drivers and constraints of durum wheat crop yield, such as temperature, water availability and CO_2 concentration, are discussed in Section 3. Furthermore, in Section 4 climate change impacts on durum wheat are analysed investigating the combined effects of changing climatic factors. A conclusive discussion is presented in Section 5, where the potential changes in future yields are put into context and the need of further research on the topic is emphasized.

2. Present state of durum wheat yield

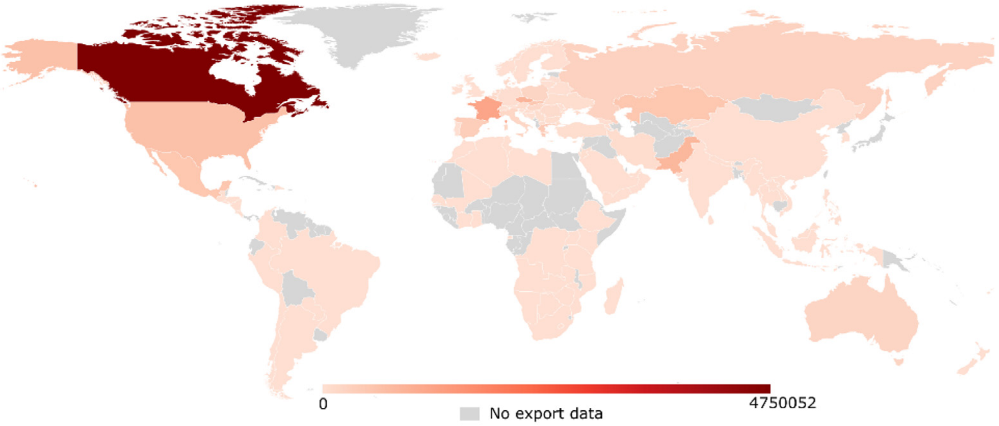
2.1. Global yield

Durum wheat is the 10th most cultivated cereal in the world in terms of production (Broccanello et al., 2023), while in the wheat sector, it is second only to bread wheat (Marti and Slafer, 2014). The global annual durum wheat production ranges from 35 to 40 million tons (De Vita and Taranto, 2019; Xynias et al., 2020), accounting for about 7% of the total wheat production (Broccanello et al., 2023). This percentage has steadily decreased since the 19th century, when durum wheat represented about 14%–16% of all wheat globally (Martínez-Moreno et al., 2022). Currently, Canada is the leading producer of durum wheat, cultivating an annual total of 5.2 million tons, with Italy and Turkey following closely behind, yielding 4.3 and 3.7 million tons respectively (Xynias et al., 2020; Sabella et al., 2020). In terms of cultivated area, durum wheat occupies around 18 million hectares worldwide, which is approximately 8%–10% of all the global wheat cultivation area (De Vita and Taranto, 2019). The main growing regions are concentrated in the Mediterranean Basin and the North American Great Plains as well as in West and Central Asia. The countries with the largest durum wheat acreage are Canada, Kazakhstan, Algeria, Italy, and Turkey (Ceglar et al., 2021; Martínez-Moreno et al., 2022). Further, some smaller cultivation areas can be found in Mexico and Australia (Mccallum et al., 2019; De Vita and Taranto, 2019). In sub-Saharan Africa, Ethiopia is the country with the largest durum wheat production (Sall et al., 2019). At present, the geographic distribution has already commenced to undergo alterations due to climate change and expanded to selected areas in Central and Eastern Europe, such as Poland (Bozek et al., 2021).

When looking at the different agronomic characteristics, the focus is primarily on the amount of harvested wheat per area. The average yield varies considerably at country level, largely attributed to geographic location and climate (Sabella et al., 2020). Within the last ten years, Italy and Turkey, the biggest European producers, have had average annual yields in the range of 3.1 and 3.8 ton/ha and 2.6 and 3.2 ton/ha, respectively. Other European countries, that contribute significantly less to the total annual durum wheat production, are characterized by higher productivity. In fact, Germany, France, Croatia, and Slovakia mostly reached values around 5 ton/ha in the same time span (Eurostat, 2023a). In Canada, the annual durum wheat yield varied between 2.3 and 3.3 ton/ha (Agriculture and Agri-Food Canada, 2023). Lower productivity can be found in the northern African countries, such as Morocco and Algeria, with average yield around 2 ton/ha or below (Boussakouran et al., 2021; Merouche et al., 2014).

Further, the largest producers of durum wheat do only partly coincide with the main consumers. The Mediterranean countries, such as Italy, Algeria, Tunisia and Turkey, remain the primary consumers (Sabella et al., 2020), highly appreciating durum wheat as an essential food source, providing dietary proteins, carbohydrates, calcium, fibre, zinc, and fats (Pour-Aboughadareh et al., 2020; De Santis et al., 2021). Additionally, it is known for its intense yellow colour, grain hardness and unique nutty flavour as well as the relatively high protein content

(a) Durum wheat export in tons per country



(b) Durum wheat import in tons per country

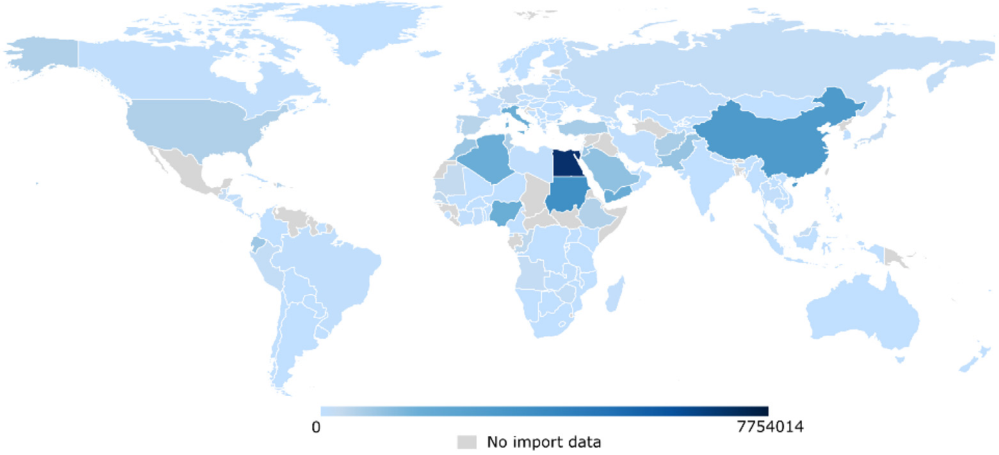


Fig. 1. (a) Average Annual Durum Wheat Export Quantity and (b) Average Annual Durum Wheat Import Quantity in tons per country (2017–2021) based on WITS Da Silva et al. (2022), created with QGIS.

compared to bread wheat, reaching up to 18% of the grain weight (Monneveux et al., 2012; Sissons, 2008). To over 1 billion people worldwide living in poverty, durum wheat serves as the primary food source, providing between 20 and 50 % of calories and 20 % of protein daily (Broccanello et al., 2023).

2.2. Global fluxes of durum wheat

Looking at the larger consumers and producers of durum wheat, as described in Section 2.1, it is evident that most of the countries rely on an import/export mechanism. Fig. 1 illustrates the average annual durum wheat import and export quantity per country using data from the World Integrated Trade Solution (WITS, 2023). If we consider more in detail the durum fluxes among countries, Canada is the largest durum wheat exporter in the world (Fig. 1a), with an average quantity of 4.75 million tons and trade value of 1.29 billion USD per year from 2017 to 2021 (WITS, 2023; Martínez-Moreno et al., 2022). In 2021, the main destinations from Canadian durum wheat exports were Algeria, Italy, and Morocco (OEC observatory of economic complexity). France and the Czech Republic were the second and third largest exporters over the same five-year period. In 2021, Greece surpassed the two with a trade value of 415 million USD, making it second biggest exporter after Canada (WITS, 2023).

In general, African countries constitute the major durum wheat importers as presented in Fig. 1b. Per year, Africa as a whole imports over 5.31 billion USD of durum wheat (Sall et al., 2019). On a country-level Egypt, Nigeria, and Sudan were the leading importers between 2017 and 2021. Egypt imports durum wheat with an average annual value of 2.72 billion USD (WITS, 2023), mainly coming from Russia, Romania, and Ukraine. In 2021 Nigeria was the largest importer, primarily purchasing durum wheat from the Ukraine, Lithuania, and Russia (OEC observatory of economic complexity).

Moving to Europe, Italy, renowned as the global leader in pasta production, is also the largest importer of durum. The wheat is mostly imported from Canada, the United States, France, and Greece with an average annual import value of 740 million USD from 2017 to 2021 (WITS, 2023; Eurostat, 2023b; OEC observatory of economic complexity, 2023). In 2022 the total import value increased significantly (Eurostat, 2023b).

Fig. 2. Most important factors influencing the productivity of durum wheat.

3. Main drivers and constraints of durum wheat yield

Durum wheat cultivation is subject to several influencing factors, that can have different effects depending on the growth stage of the wheat. Among these factors, temperature, water availability (including precipitation and soil water content), CO_2 concentration, and agricultural practices play vital roles. The climatic factors tend to be correlated, such as precipitation reducing maximum temperature and solar radiation, or high temperatures frequently being accompanied by a lack of rainfall (Yu et al., 2014). Furthermore, some influencing factors can both contribute to yield formation and act as stressors (Bozek et al., 2021). A certain range of temperature, for instance, is beneficial for durum wheat growth whereas temperatures over a particular threshold are potentially harmful. Stresses constraining the durum wheat yields can be divided into abiotic and biotic ones. The former includes threats originating from the surrounding environment such as droughts, heat and frost damage, whereas the latter refers to stresses coming from living organisms like weed, insect pests, and disease (Beres et al., 2020; Khayatnezhad and Gholamin, 2020). Further, the susceptibility of durum wheat for stressors is highly determined by the growth stage in which they occur. In general, the phenological development of cereals contains germination, seeding growth, tillering, stem elongation, booting, inflorescence emergence, anthesis, milk development, dough development, and ripening (Zadoks et al., 1974), which show varying responses to external influences such as high temperatures and water deficit as described in detail in the subsequent section. In the following both types of stresses, with a focus on abiotic stress factors, are being reviewed, as well as the main drivers of durum wheat yield, taking into consideration the temporal variation of their effect. Fig. 2 illustrates the most important factors influencing the productivity durum wheat. Further, the most important findings for each influencing factor available in literature are summarized in Table 1 with indication of the according main references.

3.1. Temperature

Temperature is one of the most influencing factors for durum wheat cultivation. Its effect on the crop's characteristics and yields is versatile, depending not only on the temperature degree, but also on its temporal distribution with regards to the different growth stages (Yu et al., 2014). Each phenological stage requires the accumulation of a certain amount of heat and is limited by different maximum and minimum temperatures (Cetin et al., 2022; Bozek et al., 2021). Temperature requirements for wheat are increasing for the successive phenological stages: 2–3 °C are sufficient for germination and tillering, 10 °C for rising, 15 °C for flowering and 20 °C for ripening. Since the numerous durum wheat genotypes worldwide are adapted to different regional climatic conditions, including temperature ranges (Broccanello et al., 2023; Chaparro-Encinas et al., 2021), these values might not be valid comprehensibly. In general, durum wheat requires colder temperatures in the earlier stages for sufficient vernalization (Motzo and Giunta, 2007), whereas warmer temperatures are prerequisite in grain filling. However, towards the end of the growing cycle higher temperatures constrain durum wheat yields and grain quality (Rharrabti et al., 2003).

Numerous studies stated that high temperatures are a major limiting factor for durum wheat growth with a decreasing effect on wheat yields (Cetin et al., 2022; De Vita and Taranto, 2019; Bozek et al., 2021; Chaparro-Encinas et al., 2021; Cosentino et al., 2018) as they were

Table 1
Summary of the effects of the main influencing factors for durum wheat productivity.

Influencing factor	Key findings	Main references
 Temperature	• The effect on the durum wheat plant depends on temperature **level, duration** of exposure and **plant growth stage** • Required temperatures and heat tolerance increase over **plant lifecycle** • **High temperatures** are a main constraint leading to shortened growing cycle and reduction in yield • **Vegetative stage and grain filling** are mostly sensitive to heat stress. • **Frost** constraints yields by inducing sterility	Cetin et al. (2022), Bozek et al. (2021), Chaparro-Encinas et al. (2021), Robertson et al. (2013), Beres et al. (2020), Cosentino et al. (2018), Diaz et al. (2019)
 Water availability	• **Water demand increases** with progressing growth stages, peaking during anthesis • Higher yields can be obtained with irrigation, still most durum wheat is grown under rainfed conditions • Durum wheat offers relatively **high adaptability** to water related stresses compared to other crops • **Droughts** affect physiological, biochemical, and agronomic parameters • Vulnerability to drought increases over lifecycle, with **heading, anthesis, and grain filling** as critical stages • Drought resistance involves dehydration avoidance, tolerance, and escape strategies	De Santis et al. (2021), Khadka et al. (2020), Habash et al. (2009), Ben-Amar et al. (2020), Liu et al. (2015), Pour-Aboughadareh et al. (2020), Liu et al. (2019), Cossani et al. (2012)
 CO_2 concentration	• Currently durum wheat is not photosynthetically saturated, and increasing CO_2 levels can increase photosynthetic capacity • Increased CO_2 concentrations can lead to **greater biomass production** in durum wheat but can also **deteriorate grain quality** in terms of nutrient concentration and protein content	Goicoechea et al. (2016), Kaddour and Fuller (2004), Vicente et al. (2015), Sabella et al. (2020), Fares et al. (2016), Beleggia et al. (2018)
 Agricultural practices	• The impact varies depending on cultivar, location, climate and intensity of practice • Soil conditions can be optimized through conventional and conservation **tillage** • **Crop rotation** supplies nitrogen and improves soil structure • **Nitrogen fertilization** can increase yield and improve grain quality, but also poses environmental risks • Adjustment of **sowing date** can help durum wheat plants to avoid or benefit from climatic changes	Mancinelli et al. (2023), Seddaiu et al. (2016), Grahmann et al. (2014), Morari et al. (2017), Ercoli et al. (2017), Wozniak (2013), Bassu et al. (2009), Moriondo et al. (2021, 2010a)
 Additional stress factors	• Fungal diseases, weeds, and insect pests are the main **biotic stresses** • **Salt stress** can inhibit seed germination, affect nutrient accumulation, and damage plant cells • **Soil contamination** with potentially toxic elements has negative effects on crop yields and food safety • **Fires** events are potentially leading to pollution and health hazards	De Santis et al. (2021), De Vita and Taranto (2019), Rascio et al. (2023), Beres et al. (2020), Trematerra and Throne (2012), Abraham et al. (2017)

found to accelerate crop development, leading to a shortened growing cycle and a decreased timeframe for biomass accumulation (Ferrise et al., 2011; Valizadeh et al., 2014). Cetin et al. (2022), for example, predict that an increase of 1 °C in the daily mean temperature might result in a 2,5% decline of durum grain yield.

Other papers, that focus on wheat in general, expect higher grain yield reduction of around 6% per rise of 1 °C in global mean temperature (Liu et al., 2016; Zhao et al., 2017) or yield declines between 4% and 7% for a 1 °C increase in seasonal temperature (Hatfield et al., 2011). Overall, cooler temperatures seem to delay the development for durum wheat, while warmer temperatures, within a certain range, appear to accelerate the growth stages (STATISTA, 2023; Cetin et al., 2022). According to Uprety and Reddy (2016) a temperature increase of 1 °C would cause a 21-day reduction in the duration of crop and 8-day reduction in the reproductive period.

When discussing the effect of prolonged high temperature, two cases can be distinguished: heat stress and heat shock. The first refers to moderately high maximum temperatures in the range of 20 °C to 30 °C occurring for a longer period of time while the later describes scenarios where for a short duration of about 3 to 5 days sudden and extremely high temperatures over 32 °C occur (Li et al., 2013). The effect that prolonged high temperature has on wheat yield strongly depends on the phenological stage of the crop in which it occurs and its duration (Balla et al., 2019). In terms of growth stages both heat stress and heat shock can result in a yield penalty when occurring during grain fill and sensitive reproductive growth stages (Beres et al., 2020). Chaparro-Encinas et al. (2021) state that for durum wheat the development stages most affected by heat stress are the vegetative period, which includes leaf and stem development, as well as anthesis since the two stages determine the nutrient acquisition and the grain filling. This is consistent with Robertson, Jeffrey et al.'s (2013) research on critical maximum temperature at which yields decline. The study revealed that the heat tolerance of crops increases through the course of the growing season. For durum wheat grown in the Canadian prairie region, where it is typically sown as spring wheat, the average critical maximum temperature for the growing season was found to be 29 °C. This threshold temperature gradually increases throughout the season, starting at 19–24 °C initially and eventually reaching 38 °C in August. Critical minimum temperatures could only be detected for April, May and July, ranging from 3 °C in July to 15 °C in May. Further, the effect of heat stress on yield-related traits, such as number, weight, and biomass of different plant components, is becoming stronger with increasing heat duration for all growth stages. Balla et al. (2019) showed that five days of increased temperature already significantly decreased most yield traits, while higher yield decline could be observed with increasing duration. Next to the yield limiting effects, heat stress may also enhance grain protein content and increase the flour yellowness (Li et al., 2013).

Frost is another temperature related, abiotic stress that causes yield loss. The plant growth of durum wheat is greatly affected by extreme low temperatures. The tolerance to frost varies along durum wheat varieties and development stages (Diaz et al., 2019). According to Sieber et al. (2014) most varieties provide rather low winter hardiness caused by their frost susceptibility. In growing regions with severe winters, like North America or Central Europe, durum wheat is typically grown as spring wheat to avoid the local winter conditions. For durum wheat varieties grown in winter the occurrence of late frosts offers a severe risk of damage as the plant is more vulnerable to lower temperatures in the reproductive stage (Diaz et al., 2019). Overall, yield losses due to frost can be attributed to sterility, which directly reduces the number of grains. It results from the combined effects of desiccation, cold and frost damage on floral organs and developing grains (Beres et al., 2020).

3.2. *Water availability*

The availability of water assumes, next to temperature, a pivotal role in durum wheat cultivation. Water is a crucial resource for the plant's growth and development, and its availability greatly influences the productivity of the crop (Zhang and Oweis, 1999). Adequate supply is necessary for various physiological processes in plants, including nutrient and water uptake, photosynthesis, and transpiration (Allahverdiyev, 2015; De Santis et al., 2021; Liu et al., 2019; Saghouri El Idrissi et al., 2023). The specific water requirements of a crop refer to the quantity of water needed to provide the equivalent of maximum evapotranspiration. This ultimately determines the potential yield of the crop in a particular climate (Fellah et al., 2018). Both the total water availability throughout the growing season as well as the availability during individual growth stages influence the productivity of durum wheat (Zhang and Oweis, 1999). The water demand progressively increases with the advancing growth stages of wheat, peaking during the anthesis phase (Khadka et al., 2020). In the early stages the plant root system and the canopy are not yet developed properly and therefore less water is needed (Cetin et al., 2022). Further, surplus water can also have disadvantageous effects on wheat as excessive precipitation may cause waterlogging. At the same time, high precipitation was often found to be negatively correlated with solar radiation and maximum temperature thus creating unfavourable conditions (Yu et al., 2014). The quantification of wheat's total water requirements varies between 450 mm and 650 mm, depending on the climatic conditions and duration of the growing season (FAO, 2023). Only few studies exist, that have examined the water requirements for durum wheat in specific regions. For crops grown in the High Plains of Sétif in Algeria water requirements were estimated approximately 672 mm for a crop cycle that extends from November to May (Houria, 2012), whereas in Bourbiaa, Tunisia the cumulative water consumption of durum wheat varied between 381 mm and 443 mm (M'hamed et al., 2015).

The water availability is determined by the combination of soil water, precipitation, and eventually irrigation (Cossani et al., 2012). Limited rainfall during the growing season frequently necessitates irrigation treatment to cover the crops water requirements. Even though higher yields can be obtained under irrigated conditions (Houria, 2012; Cossani et al., 2012; Rulli et al., 2013), durum wheat is mostly grown under rainfed conditions (De Santis et al., 2021; Liu et al., 2019). Depending on the geographical location sustainable water extraction for irrigation might not be feasible as it competes with other water uses or strains the capacity of local water sources (Zhang and Oweis, 1999; Casolani et al., 2016; Rosa et al., 2019). Various types of irrigation methods can be employed to fill the gap between precipitation and plant water requirements such as surface irrigation, sprinkler irrigation and drip irrigation. They vary in water source, water use efficiency, scope and cost of installation and maintenance among other factors and might be selected depending on factors such as crop characteristics, climate, water resource availability, economic considerations, and desired efficiency (D'Odorico et al., 2020; Sauer et al., 2010).

In general, a deficiency in water availability can trigger a range of physiological changes, such as in evapotranspiration, photosynthetic efficiency, nutrient metabolism, and transport, which limits the yield potential of the crop (Liu et al., 2019; De Santis et al., 2021; Liu et al., 2015). Durum wheat offers a relatively high adaptability to water related stresses compared to other crops, which makes it a favourable crop in semi-arid environments such as the Mediterranean region (Monneveux et al., 2012; Martínez-Moreno et al., 2022). However, despite being considered one of the most drought-tolerant cereal crops, durum wheat can experience severe negative impacts as a result of water stress (De Vita and Taranto, 2019; Kaddour and Fuller, 2004). In general water stress may occur either due to an excessive amount of water or a deficit of water. Drought stress, the deficit of water, is the more common water stress (Oliveira et al., 2014). Further, it is defined based on its occurrence timing in relation to critical physiological stages of crop growth, its level of intensity, and the presence of other abiotic stresses like extreme temperatures (Habash et al., 2009). There is a consensus among scientists that droughts pose the greatest risk as an abiotic stress factor for durum wheat (Pour-Aboughadareh et al., 2020; Saghouri El Idrissi et al., 2023; Khayatnezhad and Gholamin, 2020; Ben-Amar et al., 2020).

Overall, the total effect of drought on durum wheat is determined by the crop's growth stage, the drought duration and intensity (Khayatnezhad and Gholamin, 2020) as well as the durum wheat genotype (Pour-Aboughadareh et al., 2020). Drought has been found to significantly affect morpho-physiological, biochemical, and agronomic parameters in durum wheat, as evidenced by multiple studies (Liu et al., 2019, 2015; Saghouri El Idrissi et al., 2023; Habash et al., 2009; Pour-Aboughadareh et al., 2020; Ben-Amar et al., 2020). The main morphological changes include leaf wilting and elongation of root length as well as reduced plant height, leaf area and peduncle length (Ben-Amar et al., 2020). Moving to the physiological traits, drought stress causes a decline in the water content of leaves and progressively diminishes the rate at which plants absorb CO_2. Additionally higher levels of alcohols, sugars, proline, glycine betaine, and putrescine content could be observed as biochemical changes in stressed plants (Saghouri El Idrissi et al., 2023). In terms of agronomic parameters, the lack of water availability leads to a decrease in seed yield. This decrease is associated with a shorter period of grain filling, a reduced number of spikes per plot, a lower number of grains per spike, a lighter thousand grains weight, a decrease in biomass, and a reduced harvest index (Liu et al., 2019; Pour-Aboughadareh et al., 2020; Liu et al., 2015).

Together with the increasing water demand of durum wheat over the growth cycle, there is a corresponding amplification in its vulnerability to drought. A water deficit in the early stages, such as tillering and stem elongation, may already negatively affect the growth of the crop, but the effects are comparatively small (Moragues et al., 2006; Habash et al., 2009). More significant changes can be observed at heading where the number of grains per spike is reduced due to increased rates of pollen sterility and spikelet abortion as consequence of drought stress. The reduction in grain number, rather than in grain size, primarily contributes to yield decline under abiotic stress conditions (Liu et al., 2015). Since the critical stages for cereal reproduction are anthesis, including pollination and flowering, together with grain filling, both periods are highly vulnerable to drought resulting in significant yield loss (Liu et al., 2019; Pour-Aboughadareh et al., 2020; Saghouri El Idrissi et al., 2023). The plant's lowered water status due to shortage of soil moisture in drought conditions leads to reduced photosynthetic activity. During the reproductive stages this loss of photosynthetic activity can result in reduced pollen viability, leading to an increase in spikelet abortion. Eventually, the resulting reduction in grain number has a significant effect on the overall grain yield (Liu et al., 2015). In addition, the quality of the grain is reduced by water limitations during grain filling. Particularly traits like starch content, protein accumulation, and ash content are severely impacted by the altered physiological processes, including photosynthesis and assimilate transport (Liu et al., 2019; Li et al., 2013).

To fully apprehend the different effects of drought on durum wheat, an understanding of the crop's resistance and adaption mechanisms to drought is of great importance. Resistance to drought is a complex phenomenon comprising numerous adaptive mechanisms at molecular, physiological, biochemical and crop level (Ben-Amar et al., 2020; Habash et al., 2009). As summarized by Habash et al. (2009) drought resistance can be defined in terms of dehydration avoidance, tolerance or escape. The first strategy includes several mechanisms aiming to retain cellular moisture such as increasing the plant's ability to capture moisture from the soil by modifying root traits and reducing water usage or increasing water use efficiency by changing attributes like plant size, leaf area and plant density. Another crucial defence mechanism employed to avoid drought-induced harm is osmotic adjustment in plant cells. Plants have the ability to modify certain characteristics, like reducing leaf size or inducing leaf rolling, when faced with temporary water scarcity to maintain the osmotic balance (Ben-Amar et al., 2020). Dehydration tolerance is the second major drought resistance strategy, which can for instance be achieved through a functional "stay green" phenotype, stem reserve mobilization, or mechanisms observed in resurrection plants. The third strategy is dehydration escape, which can mainly be found in form of early flowering, helping the plant accumulate biomass before the onset of drought (Habash et al., 2009). To put it in a nutshell, several morphological traits of durum wheat, including spike length, plant height, leaf size, and fertile tiller number, show adaptive abilities (Liu et al., 2015). To assess the drought response in durum wheat, essential physio-chemical parameters encompass photosynthetic and transpiration rate, leaf water potential, chlorophyll content, and stomatal conductance (Pour-Aboughadareh et al., 2020). The selection of drought-adapted cultivars is considered the most effective method to prevent yield loss in drought conditions, as the ability to withstand drought varies among different cultivars (Ben-Amar et al., 2020). Consequently, the development of resistant durum wheat crops is a key objective in numerous breeding programmes. These programmes implement various strategies aiming for tolerance enhancing effects such as increased leaf rolling, high photosynthesis rates, and early flowering (Ben-Amar et al., 2020; Habash et al., 2009; Allahverdiyev, 2015).

When drought conditions occur simultaneous with high temperature, the combined effect may lead to a significantly higher yield loss (Liu et al., 2019). The interdependence of climatic conditions such as temperature and rainfall often promote a joint appearance of drought and heat-stress, exacerbating the negative effects on durum wheat yield (Li et al., 2013). There is a lack of consensus within the scientific community whether water availability or temperature is having the greater impact on durum wheat yield as it depends on various factors, including the duration and intensity of the climatic events, the growth stage of the crop and the specific cultivar of durum wheat. Based on long-term historical yield data for Dalby, Australia, Yu et al. (2014) found precipitation during vegetative stage to be the most determining factor for wheat yields. This finding is also supported by Cetin et al. (2022), who examined the effects of changing temperature and rainfall on the durum wheat yield in the South-eastern Anatolia Region of Turkey. However, a study conducted by Tajibayev et al. (2021) for spring durum wheat in Kazakhstan and Russia found that temperature had a greater impact on yield compared to rainfall. Further, Dettori et al. (2017), who studied the potential effects of different climate change scenarios on durum wheat yield in Southern Sardinia, Italy, discovered that for extreme warming levels, temperature was the primary limiting factor. Water scarcity had minimal effect on yield under these warming conditions. For lower warming conditions precipitation showed increasing influence.

3.3. CO_2 concentration

Another influential factor for durum wheat cultivation is the carbon dioxide (CO_2) concentration. For plants with C3 photosynthetic metabolism, such as durum wheat, atmospheric CO_2 is an important limiting factor in photosynthesis (Goicoechea et al., 2016; Kaddour and Fuller, 2004). At the current CO_2 concentration C3 plants are usually not photosynthetically saturated, therefore the potential photosynthetic capacity is expected to increase under CO_2 exposure as a result of the CO_2-fertilization effect (Sabella et al., 2020). However, if plants are subject to prolonged elevated CO_2 concentrations the potential photosynthetic capacity is downregulated, a process also known as "photosynthetic acclimation" or "downward acclimation" to CO_2 (Kirschbaum, 2011; Vicente et al., 2015). In other words, under rising CO_2 levels the amount and activity of Rubisco, the enzyme responsible for carbon dioxide fixation, and correspondingly photorespiration might be reduced to save energy and biomass. Simultaneously the net photosynthesis increases which ultimately leads to greater biomass production (Kaddour and Fuller, 2004; Vicente et al., 2015).

In field experiments durum wheat grown under elevated CO_2 concentrations showed increased biomass production, mainly due to denser leaves, spikes and stems and enhanced tillering (Sabella et al., 2020; Goicoechea et al., 2016; Kaddour and Fuller, 2004). The simultaneous absence of an increase in the leaf area index (LAI) is seen as proof for enhanced assimilation and water use efficiency (Kaddour and Fuller, 2004). In contrast to the positive effect of improving durum wheat yield, the elevation of CO_2 concentration is also shown to deteriorate grain quality (Sabella et al., 2020; Fares et al., 2016). In multiple experiments a general depletion of micro-nutrients, macro-nutrient and gliadin contents was observed as consequence of increasing CO_2. In particular grain protein, gluten and yellow pigment content (Fares et al., 2016), as well as Iron, Zinc, Manganese, Phosphorus, Magnesium, Molybdenum, Potassium and Calcium contents (Beleggia et al., 2018; Goicoechea et al., 2016), N-concentration, soluble protein (especially Rubisco) content, amino acid, and total Chl (Vicente et al., 2015) decreased compared to ambient conditions. This poses a significant risk, particular in regions such as Africa or India, where diets in undeveloped regions heavily rely on wheats and pulses. Public health could face substantial implications if minimum daily requirements for certain micro- and macronutrients such as iron, zinc, and protein are not met due to lower grain qualities (Beleggia et al., 2018). Additionally, the decrease in grain quality accordingly affects the quality of the end-product. For instance, the protein content of the grain determines rheological and technological characteristics of the dough and therefore also the quality of pasta (De Vita and Taranto, 2019). It was shown that pa sta made from durum wheat grown under elevated CO_2 conditions was characterized by a decline in quality attributes such as firmness and weight (Fares et al., 2016) as well as further decreased mineral contents in comparison to the grain (Beleggia et al., 2018).

Several durum wheat field studies have investigated the effect of rising CO_2 levels in interaction with other environmental stress factors such as heat and drought. The fertilizing effect of increased CO_2 concentration on the plant productivity might be altered or even lowered as result of the interaction with other drivers (Goicoechea et al., 2016) whereas the negative impact of the stress factors is potentially weakened or even offset (Kaddour and Fuller, 2004). Studies focusing on the consequences of simultaneous rise of ambient temperature and CO_2 concentration mostly predict an increase in yield, accompanied by a shorter lifecycle of the plant, reduced quality, and decreased harvest index (Sabella et al., 2020; Vicente et al., 2015).

Further, several field experiments have included multiple durum wheat genotypes while investigating the influence of ambient CO_2 on the plant. The results showed significant differences in response among the tested genotypes indicating that some genotypes have higher potential to adapt to future climatic conditions (Beleggia et al., 2018; Fares et al., 2016; Sabella et al., 2020).

Next to field experiments, studies based on numerical modelling are also used to investigate the effect of CO_2 on durum wheat cultivation. The simulations also take into account changing climatic variables, such as precipitation and temperature, and the combined effects on durum wheat vary depending on the research study. In most cases the fertilizing effect of CO_2 is found to be able to compensate the negative effects of other changing climatic factors and increase durum wheat yield (Ventrella et al., 2012; Kourat et al., 2022), but also decreasing yields are predicted (Chourghal et al., 2015).

3.4. Agricultural practices

Alongside the aforementioned drivers, there exist several factors that can be effectively managed through agricultural practices in order to enhance crop yield potential. These agronomic factors include soil tillage, weed and disease management, fertilization practices, support irrigation, and crop rotations amongst others. In durum wheat cultivation parameters like transpiration and photosynthetic rate, chlorophyll content, and water use efficiency are affected by agricultural methods, further influencing the yields and yield components (Bozek et al., 2021). The effects of individual practices might vary greatly depending on the durum wheat cultivar, location, and climatic conditions (Grahmann et al., 2014; Morari et al., 2017; Ercoli et al., 2017; Seddaiu et al., 2016). In this regard, tillage management and fertilization are the primary agricultural practices adopted by farmers to ensure high crop productivity (Mancinelli et al., 2023).

Given that durum wheat productivity is very dependent on optimal soil conditions, it is common practice to alter the soil structure before sowing using mechanized equipment. This practice known as tillage includes cutting, breaking down and inverting soil layers, reducing clod size, and rearranging aggregates (Tabatabaeefar et al., 2009; Wozniak, 2013). Conventional tillage practices, such as ploughing, disking and harrowing, have been shown to directly and indirectly impact environment and environmental pollution (Mancinelli et al., 2023) as these procedures might make the soil vulnerable to nitrate leaching and erosion (Seddaiu et al., 2016). Therefore, conservation tillage, as a form of sustainable agriculture, has received increased attention with the objective to create optimal soil conditions without exposing the soil to degradation (Wozniak, 2013; Campiglia et al., 2015). It is based on minimal soil disturbance, retention of residue cover and crop rotation (Seddaiu et al., 2016; Grahmann et al., 2014). Conservational practices, such as reduced or minimum tillage and no-tillage, offer a wide range of positive effects including improved soil physical properties and increased soil water content deriving from higher organic matter content and a reduced soil infiltration rate (Wozniak, 2013). Additionally, rotating durum wheat with other crops, especially with grain legumes, might provide yield increasing services such as the supply of nitrogen to the subsequent crops, phosphorus mobilization, benefits to soil structure and organic matter as well as breaking of crop disease cycles (Reckling et al., 2022). Thus the demand for nitrogen fertilizers applied to the ground is potentially reduced, which can also be achieved with incorporating crop residues (Ventrella et al., 2012).

Further, the impact on durum wheat productivity of conservation tillage, in comparison to conventional tillage, varies greatly dependent on extent and place of implementation as well as the associated climatic conditions and soil properties (Ercoli et al., 2017). In areas with low rainfall levels and high temperatures larger yields are produced with conservational practices (Grahmann et al., 2014; Wozniak, 2013), as these systems are able to retain more soil moisture (Baiamonte et al., 2019). Further, it was shown that in sandy soils yield increases with reduced tillage whereas loam and clay soils as well as higher rainfall levels offer disadvantageous condition for conservational management due to increased development of weeds and pests and reduced plant establishment (Ercoli et al., 2017).

Another common agricultural practice is nitrogen (N) fertilization which incorporates a number of positive effects on the durum wheat plant but simultaneously poses a risk for the environment. Next to reportedly increasing durum wheat yield (Yu et al., 2014; Cossani et al., 2012), N is also shown to improve the grain quality in terms of protein, gluten content (Wozniak, 2013; Morari et al., 2017), plant vitality, and chlorophyll content (Bozek et al., 2021). Moreover, it was reported to potentially reduce yellowberry in durum wheat, a physiological disorder characterized by a low content of protein and high starch content (Marinaccio et al., 2016; Solís and De León, 2001). As already observed with the previously discussed factors influencing durum wheat yield, the individual effect of N-fertilization might differ depending on the application parameters, such as timing, rate, and splitting (Grahmann et al., 2014; Morari et al., 2017), as well as water availability. With increasing drought stress the efficiency of fertilization was shown to decline which could become a serious problem under future climatic conditions (De Vita and Taranto, 2019). At the same time environmental risks associated with the use of N-fertilizer including pollution of soil, water, and air as well as microbial biomass loss oppose intensive application (Morari et al., 2017; Liu et al., 2010; Lupini et al., 2020). Further, organic fertilizers offer a more sustainable alternative and have been reported to enhance soil quality and nutrient availability (Mancinelli et al., 2023). Next to environmental aspects the economic viability is a central factor to evaluate when using N-fertilization. As fertilizers are often very capital intensive, in some cases the maximum possible durum wheat yield, as a result of increased N application, might not be economical (Panayotova and Kostadinova, 2018). All in all, the application of fertilizer should always include balancing ecological, economic, and social interests.

A rather small intervention with relatively large effect on durum wheat cultivation is the adjustment of the sowing date as it is a critical determinant of yield (Bassu et al., 2009). The main objective of this management strategy is to ensure flowering in a period that is least exposed to yield limiting stresses, such as water deficits and extreme temperatures, by matching the sowing date accordingly (Mccallum et al., 2019). In the Mediterranean environment, which is marked by hot summers and relatively mild winters, the sowing window usually falls into the autumn period starting from the first substantial rainfall after summer (Bassu et al., 2009). In regions with more extreme winters, like North America and Central Europe, durum wheat is normally sown in spring (Sieber et al., 2014). In the face of climate change this no-cost management practice is seen as a potential adaption method to the changing conditions (Moriondo et al., 2010a). In regions where temperatures are expected to rise within the next decades, adjusting the time of sowing could allow the plants to escape the higher temperatures in the end of the growing season (Moriondo et al., 2021). Additionally early sowing might present a potential avenue to benefit from changing climatic conditions such as the precipitation increase in the fall as shown for durum wheat cultivation in Algeria (Kourat et al., 2022).

3.5. Additional stress factors

In addition to the stress factors previously discussed, durum wheat is affected by numerous other abiotic and biotic stresses. A high salinity level of the soil is one of them, occurring frequently due to drought, extensive irrigation and increasing seawater levels and affecting yield and quality traits of the wheat. Even though durum is considered to be moderately tolerant to this abiotic stress factor (De Vita and Taranto, 2019), salt stress still potentially disturbs plant growth by inhibiting seed germination (Almansouri et al., 2001) and inducing changes in C and N accumulation during grain filling (De Santis et al., 2021). Further the plant's ability to absorb water is reduced by salt in the soil whereas salt in plant cells damages the photosynthetic and metabolic capacity (De Vita and Taranto, 2019). This potentially influences the amount of starch and storage protein and the grain composition, resulting in declining yields (De Santis et al., 2021). The degree to which durum wheat growth is affected by salt stress differs between cultivars. However, it was shown that breeding for salt tolerance might reduce plants' yield potentials and it could therefore be advisable to grow high-yielding cultivars rather than high tolerant ones (Isla et al., 2003).

Moreover, soil pollution can potentially constrain durum wheat cultivation. Worldwide a large number of agricultural lands is affected by soil contamination due to potentially toxic elements further threatening crop yields, food safety, and human health (Rascio et al., 2023). In many cases anthropogenic activities such as the application of fertilizers and pest control, use of wastewater for irrigation and waste burning or disposal are the primary causes of potentially toxic elements in agricultural soil (Capra et al., 2014). Certain elements, such as Arsenic, Lead, Cadmium, and Mercury, show significant toxicity towards plants even at low levels, whereas others like Copper, Manganese, Cobalt, Chromium and Zinc are considered essential micronutrients for plants in trace amounts but can exhibit phytotoxicity at high concentrations (Nagajyoti et al., 2010). However due to the so-called "soil buffer capacity", which relies on the stabilization of potentially toxic elements by organic matter and soil minerals through mechanisms such as sorption and complexation, and the selectivity and exclusion mechanisms of plants that help them limit their uptake of toxic elements, crops are not necessarily threatened by the accumulation of potentially toxic elements in agricultural soil (Rascio et al., 2023).

Moving to biotic threats, a wide range of diseases, weeds, and insect pests emerges. In many cases they are closely linked to abiotic conditions. The propagation of diseases, for example, was shown to be dependent on certain temperature and moisture levels (De Vita and Taranto, 2019). In general, diseases can potentially reduce the quality and yield of durum wheat. Fungal diseases, in particular, put of lot of pressure on wheat cultivation and include Fusarium diseases, crown rot, rust diseases, leaf blotch, tan spot, and bacterial leaf streak (Beres et al., 2020). The most economically significant fungal threats are rust diseases, primarily occurring as stem rust, stripe rust, and leaf rust. The first rust type is usually found in cultivation areas with warm temperatures and moist conditions whereas the second, stripe rust, is prevalent in cool climates. The latter occurs in regions where mild and moist environments dominate (De Vita and Taranto, 2019). Likewise rather to be found in temperate growing regions with high humidity is the Septoria leaf blotch (SLB), another important leaf disease of wheat (Berraies et al., 2014). Currently it is regarded as one of the most devastating threats to wheat production in Europe (Fones and Gurr, 2015). However, in other regions, such as Canada and the US, the durum wheat industry is primarily impacted by Fusarium head blight (FHB) (Beres et al., 2020), which in epidemic years significantly reduces kernel quality and yield and is almost impossible to control due to the deficit of immune germplasm (De Vita and Taranto, 2019).

Another large contributor to durum wheat yield loss are weeds. The competition for elementary resources like water, sunlight, and soil nutrients (Da Silva et al., 2022), results in wheat yield losses ranging from 5% to more than 80% (Beres et al., 2020). Further, the total biomass, the plant's height, the number of ears and grains per plant can be significantly reduced as consequence of resources to be shared. The most dominant weeds constraining durum wheat can be separated in monocotyledon and dicotyledons, each comprising several botanical families such as fabaceae, polygonaceae, and poaceae. Examples for commonly occurring weeds are ryegrass, sterile oat, vetch, hawkweed and ripgut brome (Bourouhou and Badouna, 2023).

Furthermore, pests as the third major biotic threat, impacts all stages of durum wheat development from germination to maturity through direct feeding and as vectors of diseases. Many factors such as climatic conditions and genotype of the host determine the severity and prevalence of the insect threats (Trematerra and Throne, 2012). However, the cyclical nature of pests tends to alternate phases in which insect pests are a main constraint for durum wheat production with years or even a decade in which their presence does not exert a significant impact on productivity (Beres et al., 2020). In the durum fields a relatively small group of insect species is of probable economic importance, including the wheat stem sawfly, the orange wheat blossom midge, aphids, worms, grasshoppers, the Hessian fly, the wheat stem maggot and more. On the contrary, numerous arthropod species, such as insects and mice, have undergone adaptations allowing them to survive and reproduce on the harvested grains and the processed end products. Thus economic damages are created through the direct loss of biomass as well as loss of product quality and value (Trematerra and Throne, 2012).

Fire events, whether arising from natural causes or influenced by human activities, have the potential to impact durum wheat cultivation both directly and indirectly. Next to the potential destruction of yields, fires can modify physical, chemical, and biogeochemical characteristics of soil and surface materials rendering it a potential source of pollution and threat to human health (Abraham et al., 2017). The high temperatures might enhance bioavailability and mobility of certain potentially toxic elements, particularly when associated with organic matter. The rate of soil organic matter mineralization and mineral weathering can be increased, which in turn leads to the liberation of linked potentially toxic elements (Rascio et al., 2023). Semi-arid environments, where durum wheat is commonly cultivated (Martínez-Moreno et al., 2022), are highly prone to fire events as seen in Canada, North America, Australia, Chile and Spain among others (Abraham et al., 2017).

4. Climate change impacts on Durum wheat yield

Agriculture and climate change are highly interrelated in various aspects as climate determines agronomic outputs and agriculture itself is recognized as one of the major contributors to global warming. The emission of greenhouse gases, such as carbon dioxide, methane, and nitrous oxide, is identified as main factor for the increasing global temperatures (Sabella et al., 2020). The agricultural sector itself is responsible for a significant share of these gases particularly through practices like land-use change, deforestation, and the use of synthetic fertilizers (Mancinelli et al., 2023). Climate change is a global phenomenon which adversely effects precipitation patterns, average and extreme temperatures, humidity and greenhouse gas concentrations and therefore affects growth and development of crops (Kourat et al., 2022; De Vita and Taranto, 2019).

Even in present days, changes in weather extremes and average temperatures are perceptible, the average global surface temperature between 2011–2020, for instance, was 1.1 °C above the 1850–1900 level (IPCC, 2023). The mean temperature increases in recent decades were shown to already negatively affect wheat yields around the world (De Vita and Taranto, 2019) and will most probably continue to do so in the future. Additionally, many regions will face a reduction in precipitation as well as an increase in evaporative demand resulting in a decrease in water availability, further restricting crop production (Goicoechea et al., 2016). The effect of rising CO_2 concentrations, on the other hand, was shown to have an enhancing effect on wheat yields while simultaneously deteriorating grain quality (Sabella et al., 2020; Fares et al., 2016). Moreover, indirect effects of climate change might include the promotion of biotic stressors such as weeds, pests, and insects, by creating more favourable growing conditions. For example, increased temperature and higher atmospheric moisture are predicted to favour disease development and warmer winter temperatures could reduce winter mortality of insects (De Vita and Taranto, 2019; Habash et al., 2009). Exploring how and to what extent these different factors combined might affect future durum wheat cultivation across diverse regions of the world constitutes a highly complex endeavour in scientific research. It further forms a crucial pillar for the formulation and implementation of effective adaptation strategies in the field of wheat cultivation and food security (Fares et al., 2016; Hussain et al., 2018).

Approaches for quantifying these impacts on durum wheat mainly rely on model simulations and field experiments. The utilization of crop models allows researchers to simulate and predict the response of durum wheat to changing climatic conditions, while field experiments conducted in diverse settings such as open fields, greenhouses, and growth chambers provide empirical data to validate and enhance the accuracy of model simulations. By employing these methodologies, researchers are able to gain valuable insights into the complex dynamics between climate change and the yield of durum wheat. Other approaches are also available, such as biomass and yield calculation models, as seen in Constantinidou et al. (2016), but not discussed further due to the rarity of their application.

This chapter firstly discusses simulation modelling and secondly field experiments as methods of quantifying the impacts of climate change on durum wheat. The state of research on the expected effects is subsequently explored on regional and global scale.

4.1. Simulation modelling (SM)

Crop models are an indispensable and widely used tool for predicting and understanding crop responses to climate change. The outputs are further used to analyse and develop adaption strategies and thereby increase climate resilience (Sabella et al., 2020). Crop models are computer-based systems that describe growth and development processes of crops and vary in complexity depending on the model used (Yu et al., 2014). As previously discussed, plant development and the associated physiological processes are affected by a wide number of parameters, such as soil characteristics, weather conditions and agricultural practices. Simulation models usually account for a detailed set of these parameters and incorporate fundamental aspects of plant-growth theory such as vernalization requirements and CO_2-fertilization effects (Gammans and Mérel, 2017).

All in all, there are numerous useful crop models available, some with a stronger focus on the physiological processes of plant growth (e.g., CERES-Wheat) and others emphasizing the hydrological aspects (e.g., AquaCrop). In research on climate change impacts on durum wheat yield, several simulation models have been used so far as summarized in Table 2.

Frequently applied is the CERES-Wheat (Crop Estimation through Resource and Environment Synthesis Wheat) model which is embedded in the DSSAT (Decision Support System for Agrotechnology Transfer), a software system incorporating a collection of crop simulation models (Jones et al., 2003). It is a process-based model, simulating crop growth and development based on the soil water balance, light interceptions, soil nitrogen dynamics, and environmental stresses. Furthermore, the radiation use efficiency approach is used to calculate biomass growth and the produced biomass is portioned between grains, ears, leaves, stems, and roots (Ritchie et al., 1998). Required input data include weather parameters, plant characteristics, soil conditions, and crop management. The minimum climatic inputs needed are rainfall, minimum and maximum air temperature, and solar radiation. Crop genetic inputs include coefficients related to grain filling, photoperiod sensitivity, vernalization requirements, cold hardiness, and stem size. In terms of soil the programme requires drainage and runoff coefficients, water holding-characteristics, first-stage evaporation and soil albedo, rooting preference coefficient, and initial and saturated soil water content. The main management input information evolve around planting and irrigation. The purpose of the model is to provide users with estimations for final grain yield, which is calculated as the product of plant population, weight per kernel and kernels per plant (Ritchie and Otter, 1985). This crop model was used in studies conducted by Ventrella et al. (2012) and Dettori et al. (2011, 2017).

Another important crop model in future wheat cultivation research is AquaCrop, developed by the Food and Agriculture Organization of the United Nations (FAO). In the model attainable yields of major crops are simulated based on their water consumption under various irrigation conditions, including rainfed, deficit, supplemental, and full irrigation. AquaCrop's growth engine is water-driven, whereby transpiration is initially estimated and then converted into biomass using a crop-specific parameter called biomass water productivity. This parameter takes into account air CO_2 concentration and atmospheric evaporative demand (Steduto et al., 2009). The model input data comprise weather data, crop and soil characteristics, as well as crop management. Climatic data includes rainfall, minimum and maximum air temperature, reference evapotranspiration and CO_2 concentration. Crop data is divided into conservative parameters, which do not change with location, time or management practice and are provided as default values in the model, and user-specific parameters concerning the planting, the duration of different growth stages, and crop's stress response. Soil parameters evolve around water content at saturation, saturated hydraulic conductivity, field capacity, and permanent wilting point. In terms of crop management information on irrigation method and schedule, as well as the application of further field management techniques, such as mulching and tillage practices, are requested. Based on soil water budgeting and plant physiological concepts, daily biomass production and crop yield are calculated in relation to agronomic management and water supply (Raes et al., 2009). AquaCrop was applied to simulate future durum wheat yield in studies conducted by Soddu et al. (2013) and Kourat et al. (2022).

Further crop models used for durum wheat yield simulation are CropSyst (Cropping Systems Simulation Modell), Sirius and STAMINA. The first crop model, CropSyst, has been developed to help study the effects of cropping system management on environment and productivity (Stockle and Nelson, 1996). As it uses the same approach for all herbaceous crops in order to simulate crop growth and development, simplifications have been introduced in the description of some processes. This leads to an overall reduced number of crop parameters compared to other crop models such as CERES-Wheat (Singh et al., 2008). CropSyst simulates the soil-plant nitrogen and soil water budget, crop canopy and root growth, crop phenology, biomass, crop yield, pesticide fate, and soil erosion by water. These are impacted by weather, crop and soil characteristics as well as cropping system management (Stockle and Nelson, 1996).

Another wheat simulation model is Sirius that computes biomass production through the interception of photosynthetically active radiation, while grain growth is determined by employing simple partitioning rules. Other than most crop models it does not estimate tiller dynamics or any yield components such as grain number. The required input data comprise, as with the other models, climatic parameters, cultivar genetic coefficients, soil properties and crop management (Jamieson et al., 1997). Although the model was originally developed for bread wheat, it can be calibrated to reproduce durum wheat crops as seen in Ferrise et al. (2011).

Finally, the STAMINA modelling system simulates crop development and growth in different terrains under consideration of spatial information on topography and soil. It is composed of three physically based and linked sub-models: a micrometeorological model, a soil water balance model, and a physical-based crop model. The latter uses the micrometeorological model's outputs and relies on net carbon assimilation, which is determined as the balance of growth respiration and gross CO_2 assimilation and maintenance. The terrain is divided into squared cells, in which the relevant parameters are assumed to be homogeneous. Next to meteorological, crop, soil, and management input data, the model also requires information on topography for each cell and the overall catchment (Acutis et al., 2007). The STAMINA model was used by Ferrara et al. (2009) to compare future durum wheat yield in hilly terrain with future yield in flat terrain.

Future climatic conditions for crop modelling can be obtained from General or Regional Circulation Models (GCMs and RCMs respectively), the latter nested in the former to increase the resolution and better represent local features. Their outputs are integrated into the model to enable climate change impact assessments (Moriondo et al., 2010a,b). These Circulation Models are computer models that numerically represent natural climate systems and simulate the physical processes that influence the climate on a global or regional level (Valizadeh et al., 2014). For the simulation of the future climate, different emission scenarios, provided by the IPCC, are employed as input for the models. These emission scenarios build a crucial part of the IPCC's Assessment Reports, which compile the state of research on climate change and have been published since 1990 (Cointe, 2024). The most recent climate change scenarios rely on the combination of Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). While the former describe possible future socioeconomic developments, the latter depict possible concentration paths of atmospheric greenhouse gases and thus possible future climate developments (IPCC, 2023). Nevertheless, in research on climate change impacts on durum wheat yield the Special Report on Emissions Scenarios (SRES) scenarios, such as A1B, A2, B1 and B2, have been predominantly used so far since they are commonly available. These emission scenarios vary in their extremity and progression over time based on different narrative storylines representing divers demographic, environmental, social, economic, and technological developments (IPCC, 2000). The highest global surface warming and CO_2 concentrations by the end of the century are predicted by the A2 scenario within the SRES (IPCC, 2007) and the RCP8.5 scenario within the RCPs (IPCC, 2023).

Durum wheat yield simulations have been conducted on both small (e.g. Kourat et al., 2022; Ventrella et al., 2012) and large scale (e.g. Ferrise et al., 2011; Moriondo et al., 2010b). However, most studies on future durum wheat yields focus on a smaller territorial scale using "point-based models" to look at individual fields. To comprehend

Table 2
Crop Models used in studies on climate change impact on durum wheat.

Name	Description	Main Input Data	Main Output Parameters	Examples of Application
CERES-Wheat model	Process-bases wheat simulation model	Daily climatic data, coefficients related to grain filling, photoperiod sensitivity, vernalization requirements, parameters to describe water status of soil, planting and irrigation management parameters	Crop yield, Harvest Index, crop evapotranspiration, water use efficiency	Dettori et al. (2017) Ventrella et al. (2012)
AquaCrop Model	Crop water productivity model	Daily climate data, daily reference evapotranspiration data, parameters concerning the planting, the duration of different growth stages and crop's stress response, parameters to describe (initial) water status of soil, irrigation and field management parameters	Crop yields, soil water balance, evapotranspiration	Kourat et al. (2022) Soddu et al. (2013)
CropSyst	Crop growth simulation model	Location data including weather data and latitude, crop coefficients on phenology, morphology and growth, soil profile properties, agricultural management parameters	Crop yield, biomass accumulated, soil-plant nitrogen and soil water budget	Moriondo et al. (2010b)
Sirius	Wheat simulation model	Weather variables, topographical characteristics, crop coefficients, soil variables, management parameters	Yields, biomass, nitrogen uptake, evapotranspiration	Ferrise et al. (2011)
STAMINA model	Modelling system for crop development and growth in different terrains	Weather variables, topographical characteristics, crop coefficients, soil variables, management parameters	Spatial distribution of agrometeorological variables, soil water variables and crop yields	Ferrara et al. (2009)

and explain plant biophysical processes, point-based models assume homogeneous unit support, meaning that weather, soil conditions, and management practices are consistent in the simulated area (Heuvelink et al., 2010). In the case of larger territorial scales, the underlying hypothesis of spatial uniformity (e.g. for soil, vegetation, climate) might fail to correctly reproduce the actual conditions. In spatialised models, each point, irrespective of its spatial extent, is an independent simulation (Pasquel et al., 2022). For durum wheat research this approach can for example be found in Moriondo et al. (2010b).

In addition to the spatial inconsistency crop models might have additional limitations. For instance, while it is possible to include a vast number of parameters into simulation models, these parameters are often calibrated based on limited data (Sabella et al., 2020). Another concern is that these models typically treat agricultural management decisions as exogenous and may not properly assess the effect of pests on crop yields (Gammans and Mérel, 2017).

4.2. Field experiments (FE)

Another essential tools for predicting the impacts of climate change on durum wheat cultivation are field experiments. By intentionally manipulating environmental factors in a controlled setting to investigate how they affect the growth and productivity of durum wheat plants, these experiments aim to simulate the response to future scenarios. In general, it can be distinguished between open field, greenhouse and crop growth chamber experiments. The first type allows variety and agricultural management adjustments, such as tillering practice and timing of sowing (Hussain et al., 2018). Additionally, limitations due to certain stress factors can be created, to some degree, by an appropriate choice of experimental site. Growing durum wheat in regions with a particular climate, low-rainfall areas for instance, can be used to investigate to influences of abiotic stresses as seen in Mccallum et al. (2019).

A further control of the water availability and temperature levels might be realized in greenhouse experiments. Inside irrigation systems ensure consistent and sufficient water supply, which can easily be adopted to imitate certain precipitation conditions. Temperature can be managed to varying degrees with the help of ventilation systems, heaters, shading material, cooling pads and more. In this way heat and water stress conditions can easily be created as seen in a study by Cosentino et al. (2018).

More accurate experiments can be conducted by growing durum wheat in crop growth chambers, which are considered the most complex type of a controlled-environment facility (Sabella et al., 2020). These chambers allow the control of main environmental parameters such as temperatures, light, humidity, and CO_2-concentrations, thus enable the imitation of future conditions under climate change (Ren et al., 2022). To date chamber-based experiments were utilized in several studies on the effect of individual or combined parameters influencing durum wheat growth (Vicente et al., 2015; Sabella et al., 2020; Goicoechea et al., 2016).

4.3. Climate change impact quantification

Given that climate change is affecting the major drivers and constraints of durum wheat growth, such as temperature, water availability and ambient CO_2 concentrations, future yield changes seem inevitable. The interaction of these factors is very complex since they might exert contradicting effects under changing climatic conditions. For instance, as examined in Chapter 3.1, rising temperatures potentially accelerate the crop development, leading to a crop cycle shortening and a decreased timeframe for biomass accumulation. Additionally, reduced rainfall rates may exacerbate crop water stress. However, elevated CO_2 concentration is anticipated to enhance the utilization of water and radiation, thereby mitigating the adverse effects on crop yield (Kourat et al., 2022; Ferrise et al., 2011; Kaddour and Fuller, 2004).

In this section the findings of research studies on climate change's impact on durum wheat cultivation are presented in the following structure. Firstly, Fig. 3, which provides an overview of global durum wheat productivity in the present and the future, is described. Secondly, results from different large-scale assessments for future durum wheat productivity in the Mediterranean region are discussed in detail. Subsequently it is moved to small-scale productivity research, starting with studies conducted in Italy, Spain and finally Algeria. Within each country SM studies based on crop models are present first, followed by research conducted in the form of field experiments. The sub-chapter concludes with discussing the state of research on climate changes impact on climatically suitable areas for durum wheat cultivation.

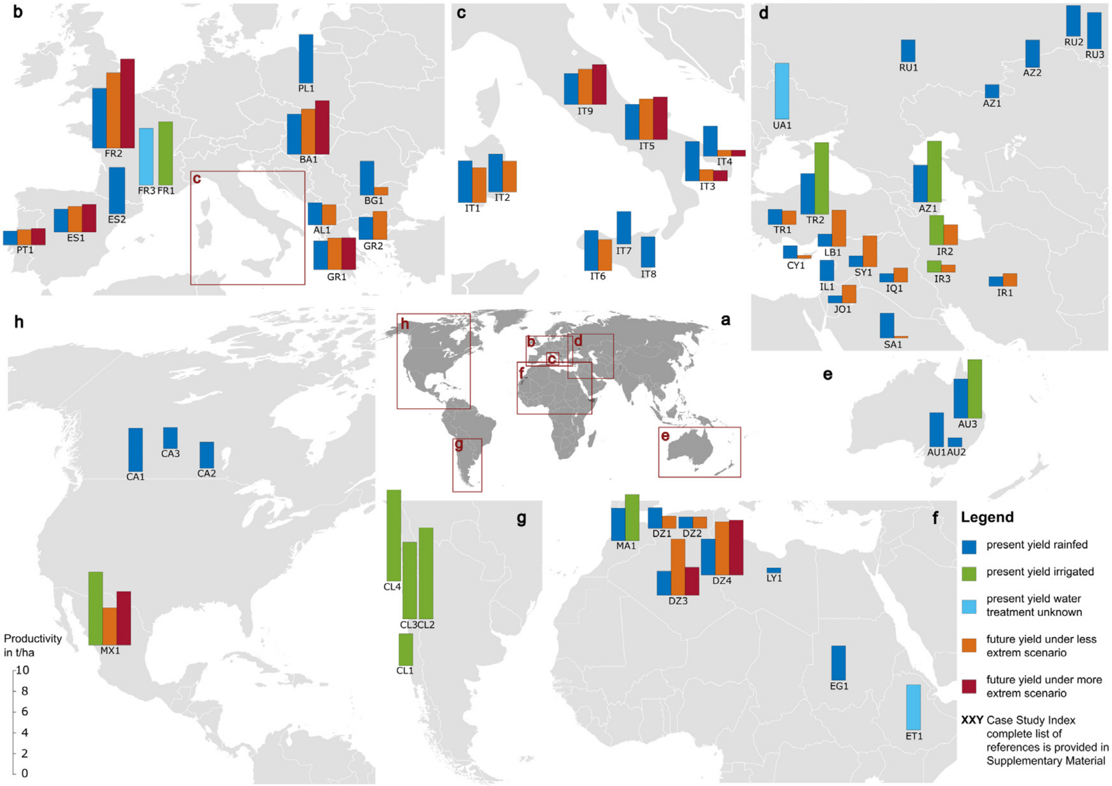


Fig. 3. Global durum wheat productivity in tons per hectare at present state and under climate change conditions. The colour of the bars indicates the water treatment (dark blue: rainfed, green: irrigated, light blue: water treatment unknown) and the temporal reference (blue and green: present state, orange and red: potential future scenarios under climate change conditions). The world map (a) is divided into subsection (b–h) to provide a clearer view. More details about the individual sources for the data can be found in the Supplementary Material in Table S1, where it is given full correspondence between labels, countries and references. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 3 provides an overview of the durum wheat productivity worldwide in tons per hectare at the present state and its predicted status for the future. The data was taken from scientific research papers and includes values at country-level as well as values for specific sites. In instances where multiple values for a specific location at a specific time were obtained within a single study, the mean value was calculated. A distinction was made between yields under rainfed (dark blue) and irrigated (green) cultivation, as well as productivity data from studies without information about the water management (light blue). Furthermore, the figure presents one or two potential future durum wheat productivity scenarios, highlighting the one with higher temperature and CO_2 concentration changes in red, the other in orange. More details about the sources for the individual data can be found in the Supplementary Material in Table S1.

Commencing with large scale research, one example can be witnessed through Moriondo et al. (2010b)'s study on climate change impact, in which future durum wheat and sunflower yields under the A2 and B2 scenarios were simulated with CropSyst for various countries in the Mediterranean basin. Results, which are shown in Fig. 3b, indicated increasing yields across all the regions considered, which are higher under the A2 scenario. Furthermore, when heat stress was included in the simulation, the enhancement in productivity was observed to be lower than in the cases without considering heat stress. The authors conclude that the effects of higher CO_2 were able to overcompensate impacts of heat-stress and drought as well as the observed slight decrease in grain filling duration.

These results are not in concordance with those of Ferrise et al. (2011) who evaluated the risk of a yield shortfall for durum wheat over the Mediterranean using the Sirius crop model. Their simulations, which were based on the A1B scenario, indicate that the positive effects of elevated CO_2 levels will not be able to completely counterbalance the effect of the projected warmer and drier climate in the Mediterranean. By dividing the period from 2010 to 2090 in four 20-year time windows with corresponding CO_2-levels, they were further able to demonstrate the temporal evolution of the risk of yield shortfall: peaking in the middle of the century, the risk first increases and then slightly decreases after 2070 underlining the complex interplay of the different influential factors.

Interestingly, a study by Constantinidou et al. (2016) on the effects of climate change on durum wheat yields in the eastern Mediterranean and Middle East, that did not include the increasing atmospheric CO_2 concentrations in the analysis, also projected an increase in productivity in several countries such as Italy, Greece, Turkey, Iran, Albania, and Bulgaria under the A1B scenario as visualized in Fig. 3b and Fig. 3d. However, these yield gains were predicted to be lower or even negative under emission scenario A2, which is considering higher temperature rises. In addition, the methodology applied, a biomass and yield calculation model, relied on mean climatic conditions, thus not taking into account the potentially significant role of climate extremes. Less suitable conditions for future durum wheat cultivation were found in Egypt, Libya, Saudi Arabia, and southern Iraq.

These contradicting results regarding future yields continue when turning to regional scale studies and can even be found in studies on similar locations. Starting with SM studies conducted in Italy, for Ussana in South Sardinia, Dettori et al. (2017) predicted decreasing durum wheat yields as shown in Fig. 3c (IT1 and IT2), considering rising temperatures and decreasing precipitation but no changes in CO_2 levels. This stands in contrast with Soddu et al. (2013)'s study results which indicate a clear increasing trend in yield for the same site. They attribute the potential improved productivity to the increase of CO_2 concentration.

The same discrepancy can be found in research on future durum wheat cultivation in Puglia. While Ferrara et al. (2009) predicted increasing crop failure and strong yield reduction under the A2 and B2 scenarios, which is visualized in Fig. 3c (IT3 and IT4), Ventrella et al. (2012)'s research showed potential enhancement in durum wheat productivity under the A2 and B1 scenarios (IT5) due to the dominating CO_2-fertilization, even though it was not as pronounced as the predicted crop decline of the former study.

Another study, not accounting for future increases in atmospheric CO_2 concentration, was conducted by Cosentino et al. (2018) as field experiment in Sicily, Italy, focussing on the effect of heat stress. Next to decreased grain yields, as presented in Fig. 3c (IT6), and kernel weight, an increase in grain protein content was observed. An additional finding of this study was that, as reaction to heat stress, the crop life cycle was shortened by 7 days in average.

When looking at field experiments conducted in Italy, likewise, the growth chamber experiments by Sabella et al. (2020) showed an in average two weeks shorter life cycle for durum wheat plants grown under increased temperature and CO_2 concentrations, accordingly with the RCP8.5 scenario. Between the nine different cultivars studied, divers effects on the yield could be detected. In some cases, the yields increased, whereas for other cultivars declining yield were observed. It was concluded that the responsive capacity of durum wheat in tillering and spike number increase majorly influences the cultivars' yield response to the CO_2-fertilization and that the shortened plant cycle could help plants to escape high summer temperatures.

This was also witnessed in field experiments in Spain, namely in Goicoechea et al. (2016)'s combined greenhouse and chamber experiments in Pamplona, which included enhanced CO_2 levels. Even though crop yield increased under elevated CO_2 concentration, durum wheat grains were impoverished in micro- and macro nutrients and gliadins as CO_2 was found to be the factor that most influenced mineral concentration in grains.

Moving to North Africa, rather than the crop cycle shortening, the application of dynamical, earlier sowing is seen as an opportunity to escape drought conditions in the end of the growth cycle. Chourghal et al. (2015), who investigated climate change's impact on durum wheat cropping in two sites in Algeria in a SM study, showed that in the future conditions for early sowing are potentially improved due to the predicted increase in autumn precipitations under the AB1 SRES scenario. Even though the crop cycle shortening was reduced with adapted sowing dates compared to prescribed sowing and the CO_2-fertilization was accounted for, yields were still observed to decrease in Algiers in the future as visualized in Fig. 3f (DZ1), where as in Bordj Bou Arreridj early sowing was found help to keep yields at their current level (DZ2). However, a later conducted SM study by Kourat et al. (2022) predicted that the early sowing and elevated CO_2 concentrations under the RCP4.5 and RCP8.5 scenarios will be able to offset climate change's negative impacts and results in increasing yields in Bordj Bou Arreridj (DZ3) and Setif (DZ4). Further, the shortened growing cycle length was found to induce a water loss drop which results in an increasing wheat water productivity. It is worth noting that these predictions were made for 2035–2064, whereas the former study addresses the timespan from 2071 to 2100.

Further research was conducted on climate changes impact on climatically suitable areas for durum wheat cultivation. A recent study by Ceglar et al. (2021), conducted with a support vector machine (SVM) model, predicts that the current share of suitable arable land for rainfed durum wheat cultivation of about 13% could decrease by 19% at the middle of the century and by 48% at the century's end. The study was based on different SSP scenarios. Moreover, a clear shift of suitable land towards the north is foreseen with the greatest losses in the Mediterranean region as well as northern America and possible gains in central and western Europe as well as in Russia. This northern expansion of suitable area is further supported by Constantinidou et al. (2016)'s research on the Mediterranean basin. Unsuitability for durum wheat cultivation under future climatic conditions is predicted for northern Africa as well as some parts of southern European countries and the Middle East, whereas in the northern part of the study area such, as Bulgaria, Anatolia, Azerbaijan and Turkmenistan, suitability might increase.

5. Conclusion

This work presented a review of the factors influencing durum wheat productivity and the expected development in the face of climate change. Crop production is mainly limited to semi-arid environments although durum wheat is exported to many regions of the world. Further, yields are subject to several drivers and constraints, the effects of which are highly dependent on the growth stage in which they occur. Projections on future durum wheat productivity cover a wide range of possible scenarios, as climate change will promote both limiting as well as beneficial factors for durum wheat growth, thus no clear trend can be crystallized.

Durum wheat cultivation is influenced by various drivers as well as biotic and abiotic stressors, including temperature, water availability, CO_2 concentration, and agricultural management. The susceptibility of durum wheat to these influencing factors depends on the duration, intensity, and growth stage of the crop, as each stage has varying responses to external influences. In the context of temperature, the level required for the phenological stages, as well as the heat tolerance, increase over the plant's lifecycle. Further, high temperatures were found to be a main constraint to durum wheat cultivation, as they shorten the growth cycle and lead to reductions in yield. Additionally, frost damage is another temperature-related abiotic stress that impairs durum wheat, leading to yield losses through sterility. The second major influencing factor is water availability, as adequate water supply is crucial for various essential plant processes, including nutrient uptake and photosynthesis. Compared to other crops, durum wheat is considered to offer relatively high adaptability to water related stresses, but still drought stress can lead reduced yield and grain quality. Its vulnerability to drought, as well as the demand for water, increases with progressing growth stages. Moreover, at the current CO_2 concentration, durum wheat is not photosynthetically saturated, an increase in CO_2 exposure can therefore enhance photosynthetic capacity. It was found to increase biomass production in durum wheat but also deteriorate grain quality. Agricultural management are a way to further increase or stabilize grain yields by improving soil's physical and chemical properties and water content. Furthermore, durum wheat is affected by various abiotic and biotic stresses, including high salinity levels in the soil, pollution, diseases, and fire events. Fungal diseases, weeds, and insect pests are the main biotic stresses responsible for major declines in yields.

As durum wheat productivity is highly dependent on climatic conditions, climate change is expected to strongly impact future yields. Understanding the extent and versatility of these effects remains crucial for developing adaptation strategies and ensuring food security. Approaches for quantifying climate change impacts mainly rely on model simulations and field experiments. The former utilizes crop models to explore the impacts of changing temperatures, precipitation, and CO_2 concentrations based on different climate scenarios. The latter includes open field, greenhouse and crop growth chamber experiments and is based on the manipulation of environmental factors, such as water availability and temperature levels, to simulate future scenarios. So far studies assessing climate change impact on durum wheat have predominantly focused on the Mediterranean region, examining various aspects such as agricultural productivity, wheat quality, and changes in arable land. For future durum productivity no clear trend can be identified as predictions of future yields range from a doubling of current values to complete declines. In other words, increasing CO_2 levels were sometimes shown to compensate the negative effects of heat stress and drought, whereas in other cases the adverse impact of high temperatures and decreased water availability outweighed the CO_2-fertilization effects. This contradiction highlights the complexity of the topic and shows that there is no universally applicable pattern for future yields. Regarding durum wheat quality traits, the future increased CO_2 levels were shown to deteriorate nutrient concentrations and gliadin content. Moreover, looking at changes in suitable cultivation areas, predictions include a decrease in total area with a shift of suitable areas towards the north.

Overall, there remains uncertainty surrounding the impacts of climate change on durum wheat cultivation. It is imperative that further scientific research be carried out to determine the complex interactions between the effects of CO_2-fertilization, rising temperatures, and limitations in water availability on the growth and development of durum wheat. Additionally, current predictions often only focus on the direct effect of climatic conditions yet overlooking the indirect effects such as the altering of interactions between durum wheat with diseases, weeds and insect pests. As previously mentioned, these biotic stressors can significantly influence crop yield and quality. As they are often correlated with abiotic conditions, the changing climate might alter the effect of biotic factors as well, potentially creating more favourable conditions for their propagation. The presented studies, which quantify the effect of climate change on durum wheat productivity, primarily focus on direct climatic changes, while largely neglecting the effects mediated by changes in biotic stressors. This oversight could lead to an overestimation of the potential benefits of CO_2-fertilization on durum wheat yields in future climatic scenarios. It is therefore crucial that future research incorporates the quantification of the indirect effects of climate change and addresses this research question taking into account changes in abiotic and biotic stressors simultaneously. Furthermore, future research endeavours should take into account agricultural management decisions. Even though a few studies already include agricultural management strategies, such as the adaption of sowing dates and selection of more drought resistant variety, there are still lingering uncertainties regarding the potential impacts they could have on future durum wheat cultivation. Moreover, it is crucial to investigate changes in both the quantity and quality of durum wheat yield as a collective entity. If attention is solely devoted to one area at a time, the adverse consequences of climate change could be under- or overestimated. As highlighted in this review, durum wheat yields might increase with a simultaneous deterioration in crop quality, for instance. In conclusion, this study emphasizes the importance of understanding climate change impacts on durum wheat cultivation while also highlighting the persisting uncertainty surrounding these effects.

CRediT authorship contribution statement

Malin Grosse-Heilmann: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Elena Cristiano:** Writing – review & editing, Visualization, Supervision, Investigation, Conceptualization. **Roberto Deidda:** Writing – review & editing, Supervision, Conceptualization. **Francesco Viola:** Writing – review & editing, Supervision, Conceptualization.

Declaration of competing interest

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

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Appendix A. Supplementary data

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