Chapter

Building Stress Resilience of Cereals under Future Climatic Scenarios: 'The Case of Maize, Wheat, Rice and Sorghum'

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Abstract

World population is projected to reach 10 billion by 2050 and the phenomenon is expected to cause a surge in demand for food, feed and industrial raw materials. Cereals (i.e., carbohydrate-rich grain crops) are the most widely grown and consumed crops worldwide. All cereals combined provide approximately 56% and 50% of global energy and protein needs, respectively. Maize, wheat, rice, barley and sorghum are the most produced and consumed cereals, globally. These are widely grown across the world from the tropics to the temperate regions. Although efforts are being done by governments, research organizations and academic institutions to increase productivity of these important crops, huge yield deficits still exist. Climate induced biotic (e.g., pests and diseases) as well as abiotic stresses (especially; heat and drought) are widely regarded as the key yield-constraining factors of most cereal crops. Given the contribution of cereals in global food and nutrition security, improvements in productivity of cereal production systems is mandatory if livelihoods are to be guaranteed. This chapter discusses the global production and utilization of four of the major global cereals, limiting factors to their productivity and possible solutions to the production constraints.

Keywords: cereals, cereal production, cereal utilization, constraints to production, sustainable solutions to constraints

1. Introduction

With the ever-increasing world population (expected to reach 10 billion by 2050) [1, 2] and the changes in human dietary structure, global food demand is projected to keep increasing. All cereals combined, account for approximately 56% and 50% of global energy and protein needs, respectively, making them a major source of calories and protein for the human populace directly through human consumption and indirectly via consumption of cereal fed animals and animal products [3, 4]. The term "cereals" refers to members of the *Graminae* family which are cultivated for their edible seeds [3, 5]. The group consists of nine crop species: wheat (*Triticum*), rye (*Secale*), barley (*Hordeum*), oat (*Avena*), rice (*Oryza*), millet (*Pennisetum*), corn (*Zea*), sorghum (*Sorghum*) and triticale a hybrid of wheat and rye [3]. A variety of cereals are produced worldwide in different climates and production systems ranging from the tropics to the temperate regions. The five major cereals on the global scale, in-terms of area under production and yield are; maize (*Zea mays*), rice (*Oryza sativa*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*), and sorghum (*Sorghum bicolor*) [4, 6]. Combined, these five crops contributes to about 50% of world food [7].

Although huge strides have been made in agricultural research and development (R and D) to increase crop productivity and efficiency of food production systems, global food deficits are still in existence [6]. In 2019, approximately 690 million were reportedly food-insecure with most of the affected people found in African and Asian countries [8]. Given the importance of cereals in the human diet, increasing their production will significantly improve current and future global food and nutrition security. To meet the projected high demand for food, food production should at least double by 2050 [8]. In particular, cereal production need to be increased by 60 to 110% by 2050 to meetup with the expected high demand for human consumption, livestock feed and industrial purposes needs [2].

Although cereals are notably important in global food and nutrition security, productivity of these crops is continually being hampered by biotic (e.g., pests and diseases) and abiotic (particularly; heat and drought) stresses [9]. These reduce crop yield and quality in field and post-harvest during storage [10]. The magnitude of the impact of these constraints on cereal productivity and yield quality however depends on crop species and variety, the extent and length of the stress on the crop, and the developmental stage at which the stress occur [11, 12]. If comparisons are made, global crop losses due to abiotic stresses are higher than those caused by biotic stresses [13].

If current and future food and nutrition security is to be guaranteed, cereal productivity should be increased to match food, feed and industrial demand [14]. This is done by increasing the efficiency of the cereal production systems, reducing the impact of biotic and abiotic stresses on cereals and policy changes. In addition, genetic crop improvement using both, the conventional and molecular breeding technologies, is also widely known as an important adaptation strategy for crops under the future predicted socio-climatic scenarios.

2. Global cereal production and utilization

2.1 Global cereal production

Cereals in their broad category are historically the major type of crops produced and traded across the world for food, feed and industrial uses [8]. In 2019, a global total of 2 719 million tonnes of cereals were harvested on 6,006 million ha of land [15]. This represents 60% and 50% of global food production on all cropped land, respectively. Of all the cereals produced in 2019, Africa accounted for 46.9%, Asia 49.1%, Europe 3.7%, the Americas 0.3% and Oceania 0.1% [15]. For decades, global leaders in cereal production are the United States of America, China and India [2]. However, different individual cereals are produced in large quantities in different regions of the world with the distribution driven by the prevailing climatic conditions, soil types, and general preference by local consumers. For instance, sorghum is widely produced and consumed in Africa while rice is widely produced and consumed in Asia [16]. Cereals including wheat, maize, rice and sorghum (*see* **Figure 1**) have a global cropping area of almost 700 million ha and together, they supply approximately 50% of the world's caloric intake [17]. At the global scale, wheat is the most important food security crop with a production of 750 Mtonnes on about 220 Mha in 2017 [11], followed by maize, rice, barley and

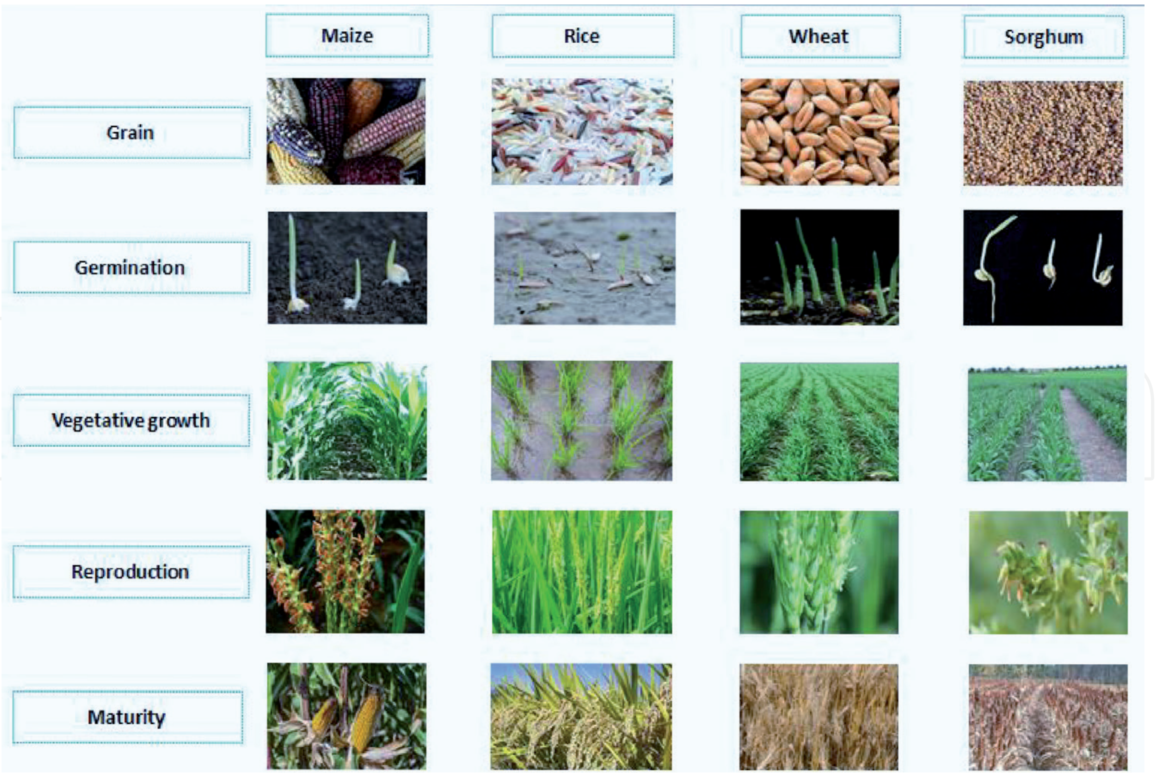

Figure 1.
Major cereals produced for food and feed on the global scale.

sorghum [8]. These are the major cereals produced across the world for human consumption and industrial utilization [7].

Global production of cereals is projected to increase as new crop production technologies are discovered and old ones being improved. The increase is projected to be 13% between 2015 and 2027 [18]. This projected increase in global production is attributed to the expected increase in production area and yield per area [18]. In 2020, global cereal production was expected to reach a record high of 2 742 million tonnes, which is an increase of 1.3% from the production in 2019 [2]. Area under wheat and maize are projected to increase by 1.4% and 3.2% respectively while other coarse grain cereals such as sorghum and barley are expected to increase by 2.4% by 2027 [18]. Global yields for wheat, maize and rice are projected to increase by 9%, 10% and 12% respectively between 2015 and 2027 [18].

In Africa and Asia, sorghum is a primarily produced as a subsistence crop using open pollinated varieties with low or no inputs and thus the productivity is usually very low, averaging 1.2 t/ha [19]. Production of sorghum in these regions is declining due to lack of established markets, consumer preferences and social pressure [19]. However, this decline in production is expected to be offset by increased production in the developed world, where demand is projected to increase as modern high yielding sorghum hybrids are becoming popular.

2.2 Global cereal utilization

The main uses for cereals are as food for human consumption in assorted whole grain and processed products, as stockfeed for animals such as pigs, cattle and poultry, and as raw materials for industrial production of chemicals and other non-food products. Given the importance of cereals as staple crops and the discrepancy between consumption and production in many countries, increase in cereal production can significantly reduce prevalence of undernourishment and hunger, thereby improving food and nutrition security on the global scale.

2.2.1 Human food uses

All major cereals are generally prospective sources of food for consumption by both humans and animals for energy and general nutrition [20, 21]. Cereals are nutritionally rich with very high starch content to meet human and animal energy needs [20], some harbor proteins, but in low quantities [22], but they are limited for most of the important micronutrients for a healthy being such as zinc, iron [23], and some vitamins [24], although nutritional levels vary between crop species and varieties. The most important cereals worldwide are rice, wheat, maize, barley, and sorghum [21]. Due to the ever increasing human population, demand for cereals is expected to increase [21, 25]. The increasing demand for food weighs mainly on cereals such wheat, rice and maize which are some of the most important global sources for energy and nutrition.

In terms of total global cereal consumption, wheat provides 41% of the calories and 50% of the proteins [26]. In developing countries, it provides about 18% of daily caloric needs as compared to 19% of globally and 21% in high income countries [26]. It is usually ground to different flour types according to the rate of extraction and the flour is used to produce a wide range of products such as different bread types, cakes, biscuits, breakfast cereals, noodles, pies, pastries, bran, and alcoholic beverages [12]. Traditionally, wheat was not a crop of economic importance in some regions such as sub-Saharan Africa (SSA) but, it is now gaining popularity, especially in the urban areas [11].

Sorghum is mostly important as a food crop in the tropics and subtropics, particularly in Africa and Asia, where it is grown as a yield bank although it is now losing its popularity to maize. Like wheat, sorghum is mainly consumed after processing into flour and is used for baking and brewing purposes [19]. The flour which comes in different colors due to different grain colors (i.e., red, yellow and white) is used in baking and cooking. Sorghum colored four is now being considered as an alternative to using artificial food coloring products in production of cakes (velvet cake) [27]. Sorghum leaf sheaths can be used to produce an orange/red food dye that comes from its high content of antioxidants [27]. Its nutritional value and preference over wheat is that it is gluten free and has high content of several antioxidants and micronutrients that offer health benefits to humans [19]. Although sorghum is gaining importance as a nutritionally-rich food crop, its consumption in the developing world is declining [19]. In order to offset this narrative, the benefits of growing and consuming sorghum need to be effectively communicated in the developing world [19].

Maize is one of the most important food crops worldwide [16]. It is of great importance as a food and nutrition crop in SSA where more than 300 million people depend on it as their staple [16, 28]. Of all the major cereals, maize is eaten is several dishes and preparations more than all of them. For instance, the physiologically immature maize cobs are roasted or boiled and consumed as a snack, dry maize grain can swell and burst when heated to produce popcorn (i.e., a popular snack food), dry milling of maize grain produces maize meal, corn flour, and corn oil [16, 28]. Maize flour is used to make porridges, soups, pastes and for baking [29]. Various alcoholic and non-alcoholic beverages are prepared from maize flour [16]. Maize also produces a syrup which is used as a sweetener in food production [16]. Global maize consumption is projected to increase by 16% by 2027 and the increase is expected to be highest in the developing countries [18].

Rice is the principle food crop for more than 50% of the world's population [30, 31]. Ninety percent of the global rice is consumed in Asia where nearly 2.4 billion depends on it as a staple [2]. It provides two thirds of all calories to Asians who eat rice-based diets [2]. On a global level, rice contributes about 19% and

13% of the calories and proteins, respectively [26]. Rice consumption is on the rise particularly among urban populations in traditionally non-rice eating regions such SSA and this is expected to accentuate the global rice demand [32]. The bulk of the rice produced worldwide is consumed in the form of rice kernels, rice noodles and other rice-based value-added products such as breakfast cereals, gluten-free rice pasta, rice flakes and crackers [32].

2.2.2 Livestock feed uses

Maize, wheat, rice, and sorghum are primarily grown for human consumption, but they are also extensively used directly as animal feed or as inputs in the production of livestock feed [33]. Approximately 30% of global cereal production goes toward production of livestock feeds and this uses about 40% of global arable land [33]. This has led to some global debates on the competition between livestock and humans for land and other resources required in the production of crops for animal feed [33, 34]. Due to their high starch content, animal feed formulation predominantly comprises cereal grains or their by-products as energy sources [34]. Traditionally, cereal grains and straw were used to feed animals directly, but, with the advent of modern stockfeed formulations these crops are being used as ingredients in the manufacture of commercial rations especially for beef and dairy cattle, pigs, and poultry [35]. Cereals are used for animal feed in different ways. Maize, wheat and sorghum grains can be directly fed to livestock such as poultry and cattle (beef and dairy) [36] or can be processed and used as ingredients in production of feed. The stover can be used as dry grazing material or harvested for feeding [36, 37], whole plants (maize and sorghum) can be harvested for silage and fed to animals after ensiling [36]. Demand for cereals for livestock feed production is expected to increase as demand for animal products is increasing in many parts of the world [33]. The projected increase in demand for animal products is driven by human population growth, rising incomes and urbanization [33] and dietary preference towards western diets.

Maize is the major cereal used as livestock feed directly or as an ingredient in livestock feed production for swine, poultry, and cattle [36]. In the U.S, approximately 42.9% of maize grain is fed to livestock and poultry while only 11.2% is used for human consumption [36]. In Pakistan and some Asian countries, maize is the second most important cereal in the production of livestock feed, where the cereal component of poultry feed is composed of 40% maize, 40% rice by-products, 18% wheat and 2% sorghum [35]. In Africa, maize grain is mainly used for human consumption, while animals particularly cattle, is fed on dry maize fodder in winter. In some East and Southern African countries such as Ethiopia and Tanzania, dual-purpose maize varieties with increased fodder quantity combined with high grain yield are preferred by some rural farmers [38].

Wheat is usually not used in commercial stockfeed formulations. Its use in poultry feed formulations in Pakistan does not exceed 15% due to its negative effect on egg laying [35]. The same goes to rice, in which milled rice is not directly incorporated into livestock and poultry rations, but its by-products such as rice bran, rice tips, rice polish are utilized for commercial poultry and livestock feeds [35]. Use of rice straw as a source of feed for ruminant animals is limited due to high polysaccharides, lignin and silica content which reduce degradability by ruminal microorganisms [37]. However, it is still used for animal feed in some southeast Asian countries such as Thailand and Indonesia where rice straw is abundant due to high rice production [37]. Sorghum grains are widely used in production of poultry feeds. After harvesting, sorghum stover is used as a dry fodder just like other cereals. Sorghum stover represents up to 50% of the total value of the crop and its value and contribution to feed and food security increases in drought years [35]. Sorghum is an important crop that serves multiple purposes as human food, animal feed and bioenergy production. It is also planted as a forage crop for livestock and the straw can be used as a ruminant feed component or construction material [12].

2.2.3 Industrial uses

Besides being used for food and feed, cereals are also used in industry as inputs and raw materials for the manufacture of a range of chemicals and other food and non-food products. Sorghum and maize are used in the brewery industry to manufacture alcoholic drinks by fermentation [16, 39]. Distillation and fermentation of cereal grains produce solvents and acids for instance ethyl alcohol, butyl alcohol, propyl alcohols, acetaldehyde, acetic acid, acetone, lactic acid, citric acid glycerol and whisky [16]. Cereal straw and starches are used to improve the quality of recycled paper. Cornstarch obtained from the wet milling process is used for food, textile and paper sizing adhesives [16]. Cereal grain residues and straw dehulling are used in the production of energy in anaerobic biogas digesters. The gas produced from cereals has high methane, making it suitable to for use in internal combustion engines or to drive turbines for power generation. Corn syrup from wet milling of maize is used as a natural sweetener [16]. Currently, the major industrial use of cereals is in production of bioenergy. Cereals, especially maize [16], wheat [39], and sorghum [28] are used for ethanol (ethyl alcohol) production. This is the same type of alcohol found in alcoholic beverages, and is most often used as a motor fuel, mainly as a biofuel additive for gasoline [16]. Increasing demand for ethanol production and the anticipated expansion of the industry has resulted in increased maize prices and has provided incentives to increasing maize acreage [28, 36]. Production of bioenergy crops offers opportunities for agriculture to be part of the solution for global energy challenges and mitigation of climate change impacts [19].

3. Major current and emerging constraints to cereal production

The historical and current importance of cereals in the human diet clearly shows that global food supply and human nutrition are anchored on cereal production [2]. Major constraints to global cereal production can be broadly grouped into biotic and abiotic factors [9]. These are continually reducing potential yield and crop quality during production and post-harvest despite efforts to increase food supply to meet demand [10]. The magnitude of the impact of these constraints on cereal productivity and yield quality depend on the crop species and variety, the extent and length of the stress factor on the crop, and the developmental stage at-which the stress affects the crop [11, 12]. If comparisons are made, crop losses due to abiotic stresses are higher than losses effected biotic stresses [13]. A lot of scientific studies have been done to understand the physiological and molecular response of plants to different biotic and abiotic stresses that limit grain yield production yet huge yield gaps still exist between optimal and stressful conditions. More studies are therefore paramount if future food and nutrition security is to be guaranteed.

3.1 Climate change

While some of the constraints, for instance, extremely low temperatures, flooding and some specific pests and diseases usually exhibit regional importance, some of the stresses, of-note; drought (water scarcity), heat (extremely high temperatures) and some pests and diseases have global significance and require global cooperation to reduce their impact. Climate change is the most critical environmental challenge currently facing humanity [40, 41]. It has brought with it extremes of weather events such as extremely high temperatures, a shift in rainfall patterns, uneven and unpredictable rainfall and increased frequency of dry spells [9, 40]. Because of these climatic factors, usually, food deficit on one region can be compensated by surpluses from another region. However, if climate-induced droughts and temperature increases continue, whole regions will be rendered inhospitable to crop production resulting in global food deficits [40]. Climate change effects on crop production are not uniformly distributed across all regions. It is expected to have far reaching impacts on the global production of maize, rice and wheat, especially in the developing countries [6]. Climate change could have catastrophic effects on cereal production with an expected 20% reduction in wheat and maize production in Africa alone [6]. Globally, it is estimated that higher temperatures and a shift in precipitation trends observed since 1980, have lowered yields of wheat by 5.5% and maize by 3.8%, below what could have been had the climate remained stable [42]. Climate change is expected to bring further increases in temperature, rising sea levels, more intense biotic stress (i.e., pests and diseases) incidences, emergence of new pests and diseases, water shortages, extreme weather events and loss of biodiversity [30].

3.2 Main climate-induced abiotic stresses

3.2.1 Drought

Globally, the major abiotic stresses impacting cereal production are droughts (water scarcity) [12, 40], extremely high temperatures (heat stress) [43], and poor soil fertility [4]. In the history of global crop production, drought has always been regarded as one of the major cause of poor crop yields [40, 42]. Droughts can occur in virtually all climatic regions [44]. Frequency of droughts is expected to intensify in most parts of the world due to climate change which could make cereal production exceedingly challenging in the future [45]. The effects of droughts are being exacerbated by the increase in global temperatures, the shift in rainfall patterns, and declining availability of irrigation water [40, 45]. Water is essential for plant growth and functioning as it is involved in various physiological, chemical and metabolic activities in the plant [46, 47]. As a result, water scarcity leads to reduced tissue dehydration, damage to the photosynthetic apparatus [26], plant growth and development and in extreme cases, total plant failure [48]. Drought can reduce nutrient uptake by reduced root growth and it can also aggravate effects of pests and diseases in the case of sorghum [49]. Sensitivity to moisture deficit stress depends on crop type (i.e., species or variety), the duration and extent of the stress and the developmental stage at which the stress strikes out but, for most cereals, including the relatively drought tolerant sorghum, water deficit conditions are most devastating if they occur during the reproductive stage [49, 50]. Yield losses due to water deficit stress conditions are more imperative if they occur during the reproductive stage [51]. Different crops have different physical and physiological traits that confer tolerance to drought and these include, presence of a highly efficient rooting system for water uptake such as the one in sorghum whereas some crop demonstrate ability to quickly recover after occurrence of the stress [52]. Studies to develop and/or identify drought tolerant crop species and varieties therefore mainly focus on reproductive traits such as a small anthesis-silking interval (ASI) in maize [16, 52].

In developing countries, 60% of all crop production is done under irrigation [51]. Declining availability of irrigation water due to over-exploitation of ground water resources, competition with other crops, restrictive government policies and deterioration of irrigation infrastructure [46], constitute several production challenges in the developing world. Drought consistently decrease maize yield due to water deficiency and concurrent heat, with greater yield loss for rainfed maize in wetter areas [4].

Wheat is very sensitive to moisture stress with the reproductive growth stage more sensitive than the vegetative stage [11, 26]. In the developing countries, approximately 50.4% of wheat yield is lost as a result of droughts [46]. In the wheat growth cycle, tillering is more sensitive to moisture stress compared to pre-anthesis [50], while water stress during the anthesis and post-anthesis stages is most devastating [47]. Studies have shown that wheat exposed to moisture stress throughout its growth stages had reduced plant growth rate, total dry matter, 1000-grain weight and grain yield [48]. In some studies, water stress increased grain protein content, however, with a serious yield penalty [43].

Moisture deficit stress affects all growth stages of maize growth and development [13, 16]. In some studies, moisture deficit stress reduced the development and growth of all maize hybrids at different stages and had a negative effect on grain yield. However, the period from one week before silking to two weeks after silking is the most sensitive stage [16]. Moisture stress during this period can lead to delayed silking, abortion of ovules, kernels and ears, low pollen production and viability [13]. Moisture deficit stress delay silking more than it delays pollen shedding in maize, resulting in increased ASI [53]. This lack of synchrony in male and female flowering is the main reason underlying maize yield loss under drought stress since ASI is directly correlated to kernel setting, number of kernels formed and cob filling [53].

Although sorghum is reputed for its ability to tolerate both intermittent and terminal water deficit stress, drought is still mentioned as a major factor limiting its production [53, 54]. Despite its drought tolerance abilities, long-term and severe drought stress can still be devastating to sorghum grain yield [49]. Due to its natural tolerance to mild droughts, it is a preferred crop when long dry periods are expected in the growing season or in naturally dry environments, especially in the tropics and sub-tropics, where it is grown as a yield assurance crop [49, 55]. Drought tolerance in sorghum is conferred by the ability of its root system to deeply penetrate the soil which allows high water uptake capacity [54], and the adaptation of its photosynthetic apparatus to withstand drought stress [52]. Drought reduces yield by up to 27, 27 and 12% respectively if it occurs during the early boot, heading and early grain filling stages [49]. Yield reductions are because of reduced number of panicles, seeds per panicle and seed weight [49].

The predominantly rice-growing areas in Asia are often threatened by severe abiotic stresses of-which the most common is drought [56]. Lowland rainfed rice ecosystems (about 25% of global rice areas) are drastically affected by drought stress due to unpredictable, insufficient, and uneven rainfall during the growing period [56]. Losses influenced by drought in rain-fed rice in Thailand are estimated to be as high as 45% [57]. The intensity of water-deficit stress depends on the duration and frequency of the stress [58]. Rice is most susceptible to drought stress particularly if stress coincides with the irreversible reproductive processes [59]. Rice is greatly susceptible to water deficit stress due to its small root system, rapid stomatal closure and little circular wax during mild stress [60].

3.2.2 Heat/extremely high temperature stress

Heat stress is one of the major abiotic stress limiting crop productivity worldwide [45, 60]. Many studies on the effects of high temperatures (heat stress) on crop productivity did not sufficiently separate the effects of heat stress from those of moisture stress [61]. This is because high air temperatures are highly correlated to high evapotranspiration, hence, low soil moisture content [62], therefore, studies are usually done on combined heat and drought stress. However, there is a possibility of determining the effects of heat stress divorced from the effects of moisture stress since heat stress impact on crop yield through physiological pathways different from those affected by moisture stress conditions [61]. High temperature stress causes a myriad of plant morpho-anatomical, physiological, and biochemical changes that affect the plant's capacity to produce yield [49, 63]. Heat stress affects all stages of the plant growth from germination to maturity resulting in yield threatening shifts to phenological developments [64]. However, the magnitude of the effects largely depends on plant species, varietal type and the growth stage [60, 63]. During germination, heat stress slows down or totally inhibit growth, during the vegetative stage it reduces photosynthesis and respiration capacity, affects water relations, and membrane stability [60, 63], while at reproductive phase, it reduces yield, mainly by reducing pollen production and viability [65]. In response to heat stress, plants produce a variety of stress-related proteins and reactive oxygen species (ROS) [61]. Some plants withstands heat stress by maintaining membrane stability, scavenging for ROS as well as production of antioxidants [61]. Heat stress incidences are mostly rampant in the tropics and sub-tropics and in the low altitude areas. However, on a global level, an estimated average surface temperature increase of 0.2 °C per decade in the next 30 years is expected [40]. This climate change-induced temperature increase is expected to be accompanied by increased frequencies of extreme weather events drastically reducing crop yields in general [66].

Heat stress has devastating results on maize production if the daily maximum temperatures exceed 30 °C [67]. These findings support the projections that the increasing seasonal temperatures will further lead to declines in maize yields as climate induced temperature changes continue [68]. Heat stress has greater impact on maize productivity compared to drought stress [69]. In a study conducted in the US Corn Belt, irrigated maize did not respond to heat stress and this demonstrated that good agronomic management and sufficient water supply can solve heat stress in maize production [62]. In East and Southern Africa, heat stress, as it occurs alone or in combination with drought stress, is projected to become an increasing constraint to maize productivity in those regions [65]. Heat stress in maize is associated with shortened life cycle, reduced light interception, increased respiration, reduced photosynthesis and increased pollen sterility [65].

Heat stress was identified as the most devastating abiotic stress limiting wheat production in developing countries [46]. Climate induced temperature increases are estimated to reduce wheat production in developing countries by 20–30% [70]. Heat stress during the anthesis and grain filling period accelerates maturity and significantly reduce grain size, weight, and yield [46]. For every 1 °C rise of temperature, global wheat production is predicted to decline by 6% [71]. In China, wheat yield reductions of up to 10% is estimated for each 1 °C temperature increase during the growing season [72]. Climate induced temperature increases are expected to reduce wheat production in developing countries by 29% [73]. Wheat farming systems in south and west Asia as well as in north Africa are projected to suffer most from heat stress and water scarcity due to climate change [26].

3.3 Main biotic factors

Biotic stresses are ravaging cereals globally as much as the abiotic factors [46]. These type of stresses rapidly evolve hence they are very difficult to manage. For instance, crop varieties developed as tolerant/resistant to certain pests and diseases are rendered susceptible within a short time when a new strain of a pathogen comes up [74]. Biotic factors include insect pests and diseases and weeds and all these significantly reduce crop yield through physical damage to plant tissue, physiological and biochemical effects. Climate change (global warming) [75] and increase in international grain trade has brought with it waves of new crop pest and disease epidemics such as the migratory locusts in the east and southern Africa (ESA).

3.3.1 Diseases

Yield losses due to diseases can reach 100% as in the case of rice blast [76]. Plant disease can cause significant yield losses if they occur during any of the plant growth stages but major damage occurs if the pathogens attack during certain critical and weak stages such as the seedling stage in rice production [76]. Diseases of economic importance in cereal production are those caused by fungal, bacterial and viral pathogens, but importance varies with regions. This is because the aggressivity and virulence of some pests and diseases depends on the prevailing climate, presence of natural enemies, type of crops cultivated, and the availability of their wild types. Pests and diseases that are native and not significant in other regions could be great threats to crop productivity in other regions. For example, the fall armyworm (FAW; *Spodoptera frugipeda*) is a native insect pest of cereals in north and south America where the pest is not is really a yield constrain, but in Africa, where it only emerged in 2016, FAW was reported to cause yield loses of 100% in some instances [77].

Diseases of economic importance in global maize production are turcicum leaf blight (*Exserohilum turcicum*), grey leaf spot (*Cercospora zeae-maydis*), maize streak virus disease, leaf rusts (*Puccinia sorghi*) and maize lethal necrosis (MLN) caused by a combination of maize chlorotic mottle virus (MCMV) and the sugarcane mosaic virus (SCMV), as well as ear rots (several fungal pathogens) [74]. Among all diseases that constrain global wheat production, three rusts caused by *Puccinia triticina* (Leaf rust), *P. striiiformis* (yellow rust) and *P. graminis* (stem rust), and the most feared Ug99 race of wheat stem rust caused by the fungus *Puccia graminis* Pers. F. sp. *tritici* Eriks. And E. Henn [76–79] are the most damaging and aggressive, worldwide. Of all biotic factors that constrain rice production, disease is the most important factor [74]. In rice production systems, disease occurrence is high in upland rainfed rice production systems compared to lowland systems (Ithisham). The major diseases of rice are bacterial blight (*Xanthomonas oryzaepypv. Oryzae* (Xoo)), sheath blight (*Rhizoctonia solani*), rice blast (*Pyricularia grisea*), rice yellow mottle virus disease, sheath rots (a combination of fungal and viral infections) and brown spot (*Bipolaris oryzae*) [76]. Bacterial diseases mostly occurs in the tropical and temperate regions of the world, but incidences are common in irrigated crops and in rainfed fields, especially when heavy rains will be coupled with strong winds.

Common diseases of sorghum are; anthracnose (*Colletotrichum graminicola*), charcoal rot (*Macrophomina phaseolina*), gray leaf spot (*Cercospora sorghi*), rough spot (*Ascochyta sorghi*), smut (Covered Kernel) (*Sporisorium sorghi*) and zonate leaf spot (*Gloeocercospora sorgh*).

3.3.2 Insect pests

Like in any other crop, insect pests cause yield losses in cereals by chewing tissues (e.g., FAW), boring into stems and leaves (e.g., maize stalk borer), sucking plant saps (such as aphids), and transmitting plant disease pathogens (e.g., white flies) [76]. Postharvest insect pests [e.g., maize weevil (*Sitophilus zeamais*) and the larger grain borer (*Prostephanus truncates*)] cause substantial yield losses of up to

40% of global maize grain [80]. Modelling studies have shown that the yield lost as a result of insect pests in the world's three most important crops (i.e., wheat, rice and maize) will increase by 10–25% per 1 °C increase in temperature [81]. Insect pest of economic importance to rice production depends on the region [82]. They are grouped into root and stem feeders, stem borers, gall midges, defoliators, leaf and planthoppers, and panicle feeders all of-which significantly constraining global wheat production [83]. The rice plant is vulnerable to insect attack throughout its growth cycle [82]. Of all the insects that can attack the wheat crop, it is the wheat stem sawfly and Russia wheat aphids, that cause significant economic losses in SSA [11]. The United States of America (USA) is the world's top maize producer of maize. In that country, maize production is limited by four key insect pests which are; corn earworm (*H. zea*), European corn borer (*O. nubilalis*), northern corn rootworm (*Diabrotica barberi* Smith and Lawrence and the western corn rootworm (*Diabrotica virgifera virgifera* LeConte) [75]. With global climate change, effects of these insect pests on maize production is expected to increase [75]. In SSA, maize stem borers (*Busiola fusca*), fall armyworm (*Spodopetera frugiperda*) [84] and migratory locusts (*Locusta migratoria*) [85], are of economic importance in cereal production. FAW is a recent insect pest in ESA, being reported first in 2016 [86]. It has over 100 hosts including cereals such as maize, sorghum, rice and wheat [84]. Stem bores are a serious threat to maize production in the humid forest and mid-altitude agro-ecologies of western central Africa [16]. In Africa where most of the world sorghum is produced, 42 sorghum panicle feeding insect pests have been identified as serious pests including the recently introduced FAW [87]. Most of these insect pests also feed on other crops such as maize [87].

4. Increasing the resilience of cereal production systems

4.1 Breeding for stress tolerance/resistance

Crop improvement for tolerance/resistance to biotic and abiotic stresses is regarded as the most sustainable and cost effective strategy that can be used to combat the current and the future food supply–demand discrepancies (**Figure 2**) [40]. Through plant breeding, many crop pest and disease challenges [89] and yield losses due to heat and drought stress factors [65] have been solved in Africa. Biotic stresses are quickly changing due to natural evolutions and climate-induced causes making new crop varieties quickly obsolete. Modern breeding strategies such as the doubled haploid technology, mutation breeding and genomic selection are being used to develop new varieties quickly, particularly in maize hybrid production [14]. Wheat improvement programs targeting drought and heat tolerance in rainfed lowland rice production systems are using marker-assisted selection (MAS) and rapid generation advance techniques to produce new rice varieties [57].

The climate change-induced abiotic stresses (especially, heat and drought) and biotic stresses (i.e., pests and diseases) are the major factors projected to continue constraining cereal production, especially in the developing countries. Stress tolerance/resistance can be: (i) identified among crop genotypes; (ii) improved in relatively tolerant/resistant genotypes; and, (iii) introduced into non-tolerant crop types [90]. Identification of stress resistance/tolerance in crop genotypes is one of the major ways to control crop pests and diseases and reduce the impact of abiotic stresses through crop improvement. For instance, sorghum genotypes tolerant to witchweed in Zimbabwe were identified which could be grown in areas prone to witchweed infestations [91]. The breeding techniques of screening genotypes for stress tolerance/resistance is also being used in identifying maize,

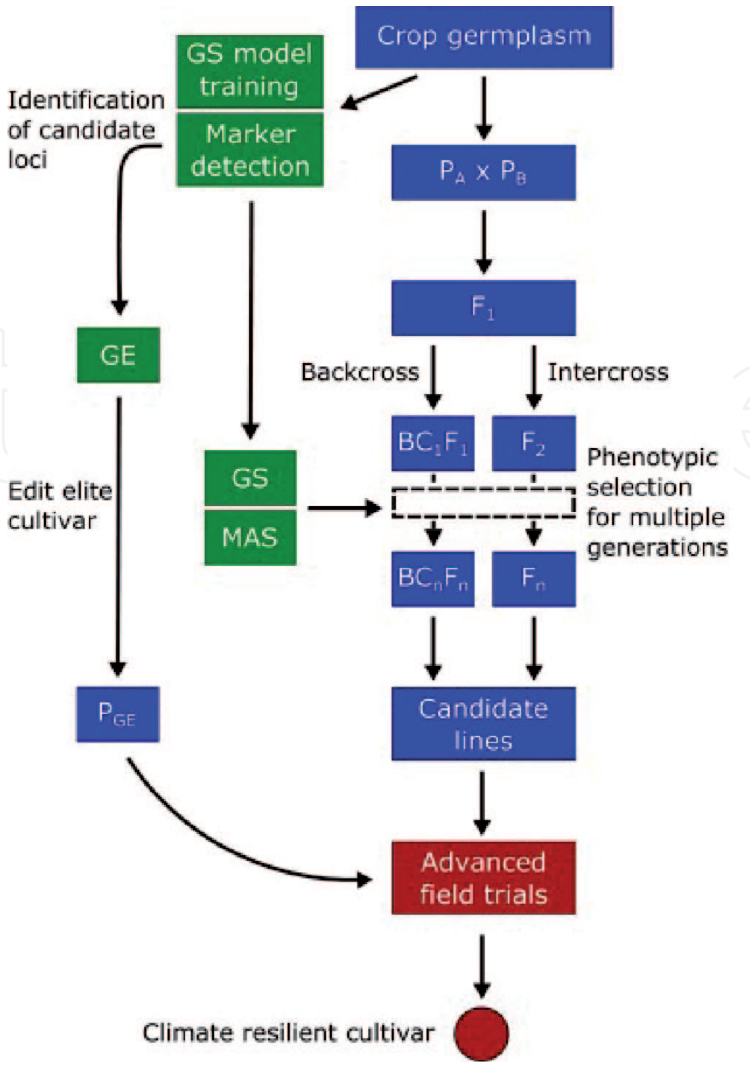

Figure 2.
Genomics-assisted breeding scheme for developing climate resilient cultivars. Steps for developing candidate lines from the initial crop germplasm pool and a selected parental cross (PA x PB) or genome edited elite cultivar (PGE) are shown in blue. Genomic methods assisting the conventional backcrossing (BC1F1 to BCnFn) and intercrossing (F2 to Fn) approaches are shown in green. In a final step, shown in red, genome edited cultivars and candidate lines selected from the successive generations of backcrosses or intercrosses are tested for broad viability in advanced multi-environment field trials to select novel climate resilient cultivars. Abbreviations: genomic selection (GS), marker-assisted selection (MAS), genome editing (GE), breeding generations resulting from intercrosses (F1 to Fn), breeding generations resulting from backcrossing to a parental cultivar (BC1F1 to BCnFn) (Adapted from Scheben et al. [88]).

wheat and sorghum genotypes with tolerance to heat, drought and combined heat and drought stress conditions [42, 52]. In breeding for stress tolerance, traits that confer either stress escape or stress avoidance are selected for but selecting for yield under these stress factors is also known to be effective [43]. For drought tolerance, crops (e.g., maize) with an efficient root system for water uptake, high water use efficiency, a canopy that loses less water, and high grain yield under stressful environments are selected for [43]. Stress resistance or tolerance can be outsourced from exotic genepools and can be introduced into local elite genotypes.

Development of new drought resistant rice varieties is the objective of rainfed lowland rice breeding programs in Asia. In ESA, breeding efforts for drought and heat stress tolerance [65] are being combined with tolerance to low soil nutrients (phosphorous and nitrogen for maize) [92], for maize, wheat, sorghum and rice [43]. Many studies on the effects of heat stress and drought on cereal production have combined since they are closely related [61]. Some studies estimated a 13% decrease in maize yields by a projected 2% increase in temperature while a 20%

increase in intra-seasonal variability reduced maize yields by only 4.2% [65]. These studies highlight the need to incorporate heat tolerance as well as increased drought tolerance into maize germplasm in order to offset these predicted yield losses [65]. The international Center for Maize and Wheat Improvement (CIMMYT) has been leading for decades, in breeding for drought and heat stress tolerance in maize, both in the tropical and subtropical regions [65]. However, relatively less effort has been devoted to breeding specifically for heat stress tolerance in maize. Short season varieties use drought avoidance [13].

Breeding efforts for disease and pest tolerance in cereals have successfully solved some of the biotic constraints to cereal production. Genetically modified (GM) maize varieties resistant to pests of the lepidopteran family such as FAW and the stem borers are being successfully grown in some countries such as the U.S and in South Africa [93]. Breeding crops to resist abiotic and biotic stresses should not compromise other desirable traits of the crops such as high yield and quality. Modern sorghum varieties are a blend of the desirable characteristics of both white and colored sorghum to provide consumers with colored sorghum with higher antioxidants levels while being suitable for farming through resistance to molds, bird and insect pest damage [27]. In SSA, breeding of cereals has also produced high yielding and stable maize hybrids with good post-harvest qualities [16].

4.2 Agronomic practices

Understanding the nature of the stress and crop response to abiotic and biotic stresses allows the farmer to employ agronomic practices that effectively reduce the impact of the stress on crop yield [42]. Agricultural practices that conserve soil moisture or use of varieties that has high water use efficiency will reduce the impact of climate-induced droughts and heat stress on crop production. Agricultural practices such as proper crop rotations, proper fertilizer application, proper planting time, proper tillage practices, good varietal selection, optimum seed rate, effective weed management, proper soil nutrient management and sufficient water supply have been reported to mitigate both abiotic and biotic stresses in cereal production [42]. In Zimbabwean smallholder farming systems, maize damage from FAW was significantly reduced by frequent weeding, zero and minimum tillage [94]. Effective weed control directly and indirectly controls crop pests and diseases and the impact of drought under rainfed lowland rice production systems [76]. At farm level, cereal productivity could be increased by prioritizing adoption of new and improved agricultural technologies [95].

Techniques such as conservation agriculture (minimum soil tillage, mulching, and crop rotations) are effective in conserving soil moisture in moisture deficit areas, especially in small and medium-scale farms [41, 87]. Irrigation with good quality water eliminates drought stress in crop production. High maize yield can be maintained in areas with insufficient precipitation by appropriate irrigation [4]. However, drip irrigation combined with mulching was shown to reduce water loss by 45% compared to sprinkler irrigation in some farming systems [96]. Proper weed control reduces water deficit stresses in cereal production since weeds directly compete with crops for available moisture [76].

5. Conclusion

Cereals are important as human food, animal feed and industrial raw materials. Their production is under threat from climate-induced stresses such as high temperatures, droughts, pests and diseases. Climate change is projected to continue

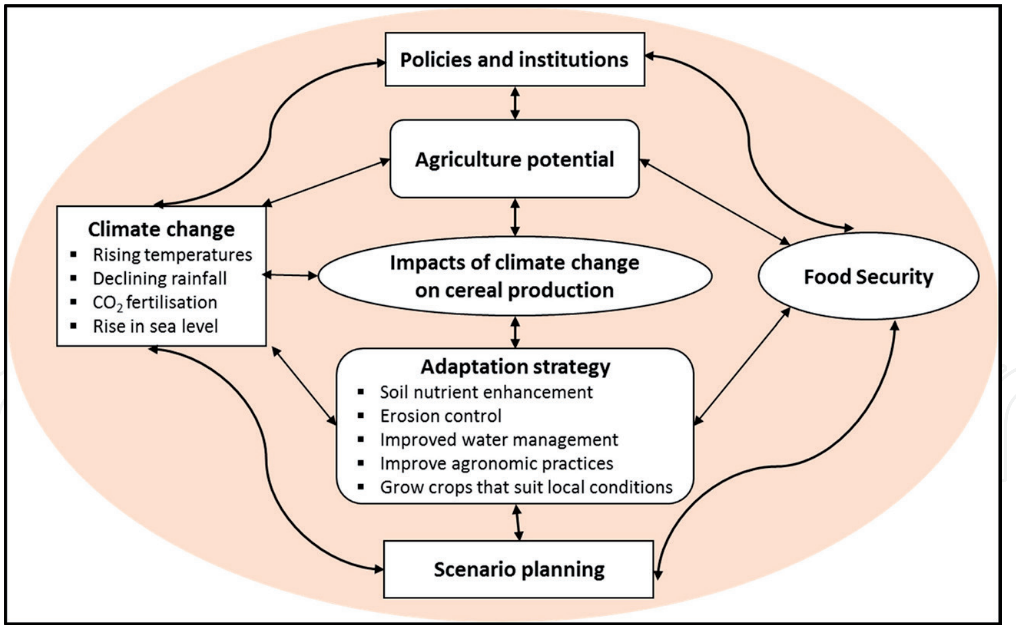

Figure 3.
Methodological flowchart for climate change, cereal yield and food security (Adapted from Nhamo et al. [97]).

threatening crop production and if it continues at the current rate, many regions of the world will be inhospitable to crop production. If future food and nutrition security is to be guaranteed, investments in crop breeding and efficient crop production systems are needed. Crop breeding produces crop varieties suitable for growth in stressful environments. Proper agronomic practices such as proper tillage, planting dates, water management, nutrition management, pests and disease management, coupled with appropriate crop genetics, together with holistic policies at institutional, governmental or regional levels (**Figure 3**), can offset any climate related yield losses expected in the future.

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