ADVANCES IN SOIL SCIENCE

MANAGING SOIL DROUGHT

EDITED BY

RATTAN LAL

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Managing Soil Drought

Global drylands, covering over 40% of Earth's land surface, are important among worldwide ecoregions and support large human and livestock populations. However, these ecologically sensitive ecoregions are undergoing a rapid transformation resulting from climate change, socioeconomic and political factors, increases in population, and ever-growing demands for goods and services.

Managing Soil Drought addresses basic processes and provides specific case studies throughout covering the protection, restoration, and sustainable management goals of global drylands under changing and harsh climatic conditions, including fragile and vulnerable ecosystems. The book is written by numerous researchers, academicians, practitioners, advocates, land managers, and policymakers involved in bringing about transformation in these regions important to human and nature. It includes information on basic strategies for sustainable management of global drylands aimed at improving water use efficiency through choosing appropriate species, developing new varieties, using organic and inorganic amendments, and scaling up innovative farming systems.

This volume in the *Advances in Soil Sciences* series is an essential read for development organizations and policymakers involved in improving crop productivity and sustainability in drought-prone regions; students, researchers, and academicians interested in sustainable management of water resources; and those involved in emerging concepts of regenerative agriculture, agroecology, and conservation agriculture.

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Contents

Preface

Global drylands, covering over 40% of Earth's land surface, are important among global eco-regions and support large populations of human and livestock. These ecologically sensitive ecoregions are also undergoing a rapid transformation because of climate change, socio-economic and political factors, increase in population and of their ever-growing demands for goods and services. Ecologically, global drylands are also the largest sources of inter-annual variability in the global carbon (C) sink because of uncertainties associated with changes in vegetation, soil organic carbon (SOC) stocks and effects on the formation of secondary carbonates through both biotic and abiotic drivers. Furthermore, drylands may expand over the next century primarily into formally productive ecosystems. Thus, gross primary productivity of global drylands may decrease and lead to a net reduction in ecosystem services because of the increase in frequency and severity of extreme climatic events. However, strategies for mitigation of and adaptation to these extreme events may vary because of regional differences due to biophysical and socio-economic, political, and cultural factors.

Basic strategies for sustainable management of global drylands include those aimed at improving water use efficiency (WUE) through the choice of appropriate species, the development of new varieties, the use of organic and inorganic amendments, and the identification/upscaling of innovative farming systems. Furthermore, sustainable agriculture must also be based on conservation agriculture, mulch farming, and innovative options that conserve soil, water, nutrients, biodiversity, and other critical resources.

This is the second volume in the series aimed at sustainable management of global drylands. This timely publication addresses the basic processes and provides examples of specific case studies for protection, restoration, and sustainable management of global drylands under changing and harsh climatic conditions and fragile and vulnerable ecosystems. The information collated and synthesized in this book is based on collective action of numerous researchers, academicians, practitioners, advocates, land managers, and policymakers involved in bringing about a transformation change in these regions important to human and nature. This volume is indicative of dedication, commitment, and professional experience of the authors in conducting research, analyzing and synthesizing a vast amount of data from field and laboratory studies and farm survey. Several authors have provided examples of case studies under site-specific conditions, representing diverse biophysical and socio-economic conditions.

Authors from around the world have confirmed that sustainable management of global drylands is critical to strengthening critical ecosystem services and eliminating disservices. As complementary to the first volume on Dryland Farming dedicated to Dr. B.A. Stewart, this book is also a major contribution to processes governing the ecosystem functions of global drylands and outlines the principles and practices of their sustainable management. Indeed, these two volumes are important reference material for researchers, students, practitioners (e.g., farmers, ranchers, and foresters) and policymakers. The material presented is also of interest to researchers and students in soil science, agronomy, forestry, animal husbandry, ecology, and management of natural resources. These two volumes present useful information on Global Drylands and their management with specific focus on food and nutritional security, soil quality, carbon sequestration, water resources and their management. The information presented herein will stimulate discussions and resolve toward advancing sustainable development goals (SDGs) of the United Nations. The information presented herein is also important to accomplishing the mission of transformation of the World Food Systems as outlined in the U.N. Food System Summit. The importance of the information presented in this volume is also relevant to achieving zero net land degradation as promoted by the United Nations Convention to Combat Desertification (U.N.C.C.D.).

I thank the authors for sharing their knowledge and wisdom and for their timely submission and revision of their chapter. I also thank the staff of the CFAES Rattan Lal Center for Carbon

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Rattan Lal
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1 Enhancing Resilience to Pedological and Agronomic Droughts in Dryland Farming

Rattan Lal

1.1 INTRODUCTION

The term "dryland farming" means growing crops on soil water storage without any supplemental irrigation. The term is also synonymous with "dryland agriculture," rain-fed agriculture or "dry farming." Rain-fed farming is practiced during the rainy season, and dry farming involves growing crops during the dry season by using the residual moisture in the soil. Thus, dry farming may be limited to eco-regions that receive at least 500 mm/year of rainfall. By nature, dryland farming produces lower agronomic yield than that with supplemental irrigation. Nonetheless, the adoption of innovative and sustainable practices of soil, crop (species and varieties of cultivators), and nutrient management by adopting regenerative practices and innovation can minimize losses of soil water by reducing evaporation and surface runoff and optimizing water use efficiency (WUE). The overall strategy is to adopt management practices (soil, crop, plant nutrients, species, cultivators, rotation, etc.), which ensure minimal productivity even in the worst year (below average precipitation) than during the best season characterized by optimal precipitations. Cultivation without supplemental irrigation and growing crops during the dry season makes dry farming a more challenging system and demands high technical skills and the use of innovative strategies to enhance and curtain soil health and restore its plant-available water capacity (PAWC).

The objective of this chapter is to deliberate technological options for soil, water, crop, and nutrient management that enhance WUE and sustain agronomic productivity. The specific objective is to explain the significance of site-specific management practices to conserve water in the root zone, conserve and manage soil water judiciously, and sustain agronomic productivity by adopting practices that restore and sustain soil health by increasing green water supply in the root zone.

1.2 SOIL MANAGEMENT

The strategy of soil management is to protect, restore, and manage soil structure, minimize risks of water and wind erosion, and improve structural stability with a specific focus on retention pores. Soil management is also aimed at improving water infiltrability, minimizing risks of crust formation, and reducing losses of soil water by evaporation and uptake by weeds. Thus, the soil surface must be protected by mulch of one type or another to moderate temperature and decrease evaporation. Mulching is also useful to improve water infiltrability.

1.2.1 Crop Residues as Mulch

Rather than removing or in-field burning, crop residues must be returned to the soil as mulch, as a component of conservation agriculture. In addition to providing protection against wind and water erosion, mulch also conserves water, recycles nutrients, moderates soil temperature, increases soil biodiversity, and sequesters carbon as soil organic matter (SOM) and secondary bicarbonates. There are numerous

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examples of the beneficial impacts of residue mulch on soil health and productivity in diverse soils and ecoregions around the world. In China, Yang et al. (2022) reported the moisture-conserving effects of a mulch-based no-till (NT) system on the proportion of fertile spikes and grain yield increase of 20% in wheat for environments with rainfall of less than 200 mm. This increase was attributed to an increased first tiller emergence rate resulting from increased N uptake, leaf N content and N remobilization from tillers to their grain. Furthermore, second and third tillers, with additional photosynthesis contributed to the tiller survival rate because of more leaf numbers. In semi-arid East Africa, Tuure et al. (2021) observed that the use of crop residue mulching increased the efficient utilization of seasonal precipitation and even reduced the risk of complete crop failure. Tuure and colleagues concluded that maize residue mulching is an accessible and feasible method for conserving soil moisture in the effective root zone in dryland small holder systems in East Africa. Mulching patterns can all be beneficial for rainwater harvesting by prolonging the growing season (Ren et al., 2016).

1.2.2 PLASTIC MULCH

Rather than using crop residues, plastic film has been widely used for sustainable dryland agriculture because of its multiple benefits in conserving water, moderating soil temperature and controlling weeds. In the Loess Plateau of China, with a cool and semi-arid to arid climate prone to pedologic drought, Li et al. (2020) observed positive effects of ridge-furrow plastic film mulching (RFM) for dryland agriculture. Li and colleagues observed that crop productivity in the RFM system was double or more than that for the un-mulched control. Furthermore, the RFM system promoted the coordinated development of grain, forage and livestock and more profit. Li and colleagues claimed that the RFM system alleviated poverty and helped develop a moderately prosperous society in these harsh environments. In another study, Zhang et al. (2020) also observed increased soil water content and improved yield and WUE of potatoes compared with those of control. Zhang and colleagues concluded that plastic film mulching is a promising method to address seasonal drought stress and increase potato production in semi-arid rainfed areas of Loessial soils. In another study, Zhang et al. (2022) observed the soil carbon sequestration effects of plastic mulching in the Loess Plateau region of China. The use of plastic mulching along with rotation cropping maintained better soil conditions, sustained crop development, and increased soil C sequestration in semi-arid rainfed agriculture. In an enrichment experiment, Zhang et al. (2019b) repeated the positive effects of plastic film cover in rainfed agriculture in the semi-arid Khorchin area in northeast China for rainfed maize. Zhang Z and colleagues observed that autumn mulching with plastic film advanced crop development, increased crop yield and WUE, and reduced climate risks.

Similar positive effects were reported by Zhang et al. (2019a) who considered plastic mulching of a ridge-furrow system as a superior technique for overcoming simultaneous drought and cold stresses in northwestern China, Ren et al. (2016) reported that plastic mulching led to an increase in the soil water at 0–20 cm depth for wheat and 0–80 cm depth for potatoes. This increased the available water to guarantee the crops' water demand at the dry seedling stage for maize and the revival stage for wheat against the threat of seasonal drought and ensured high crop yield.

1.2.3 GRAVEL MULCH

In regions with low rainfall (< 250 mm/annum) and where crop residue mulches are scarce, gravel mulch is a big industry and extremely useful to grow a range of crops and vegetables. In the low rainfall regions of China, the production and use of gravel mulch is a profitable enterprise in the development of dry, arid areas. Zhao et al. (2013) reported that gravel mulch is a unique mode of conservation tillage, but the ecological effect gradually decreases over time. Zhao WJ suggested paying attention to increasing the replenishment fertilization to the gravel-mulch field, improving the planting patterns, selecting new varieties of drought-resistant crops, establishing modern water-saving supporting systems, etc. for sustainable development of gravel-mulched field agriculture (Figure 1.1).

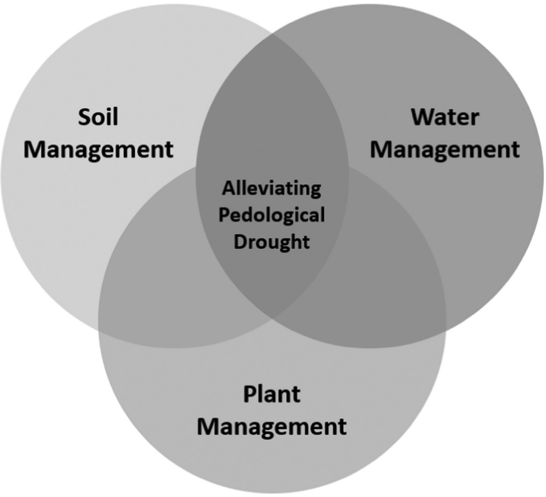

FIGURE 1.1 Strategies of sustainable dryland farming through adaptation and mitigation of drought.

1.3 CONSERVATION TILLAGE METHODS

1.3.1 CONSERVATION AGRICULTURE

These mulch farming techniques are often used in conjunction with no-till on ridge-furrow methods of seedbed preparation to enhance their effectiveness in conserving water in the root zone and ensuring agronomic productivity. A system-based conservation agriculture (CA), practiced on some 200 Mha globally, is effective in conserving soil and water and sequestering atmospheric CO_2 in the soil as humus (Lal, 2015). Schillinger et al. (2022) explored the impact of biosolids vs synthetic fertilizers in Washington State and observed that the application of biosolids combined with low disturbance is an agronomically and environmentally sound practice for dryland wheat production. The presence of residue mulch is critical to the effectiveness of CA. Papendick and Parr (1997) observed overwhelming evidence that mechanical tillage is destroying soil resource base and causing adverse environmental impacts. They recommended that continuing no-till is the most effective and practical approach for restoring and improving soil quality, increasing SOC content, enhancing soil structure, controlling soil erosion, and improving water relations and nutrient availability.

In China's Loess Plateau, Liu et al. (2018) observed that straw-mulched furrows greatly enhanced soil water storage in 0–60 cm depth but decreased from 61–100 cm depth. Mulching also decreased soil temperature in the cold season by 2–2.2°C but increased WUE by 44.04%. Liu and colleagues concluded that ridge-furrow planting with plastic film-mulched ridge and straw-mulched furrow has a good potential for raising wheat production on the Loess Plateau. Also in China, Ren et al. (2016) observed that using a plastic-covered ridge for rainwater harvesting and a furrow as a planting zone increases water availability for crops and stabilizes crop production in northwest China. However, the rainwater-harvesting effect increased with the ridge width increasing to 60 cm. In the sub-humid region of China, Xiaoli et al. (2012) observed that WUE increased with the plastic-covered ridge and furrow rainwater harvesting. This system, used with biodegradable film and straw mulches, is a viable option with high potential to increase agronomic productivity in dryland farming systems without irrigation capability (Xiaoli et al., 2012). Also, in the Loess Plateau of China, Liu et al. (2011) reported that film mulching and straw mulching had different trends in soil temperature. The seasonally averaged soil temperature was the highest under film mulching and the lowest under straw mulching treatment. Film mulching also improved the crop grain yield and yield components.

In northern China, Wang et al. (2011) observed that maize grain yields were greatly influenced by the soil water contents at sowing. Further, grain yields under no-till were generally higher (+19%) in dry years but lower (–7%) in wet years. The no-till treatment has 8%–12% more water in the soil profiles and improved WUE than the conventional and reduced tillage system. Thus, the no-till system has the potential for drought mitigation and economic use of fertilizers in drought-prone rainfed conditions in northern China. Similar observations on the use of plastic mulch ridges were made in northwest China by Zhang et al. (2019) and Wei et al. (2018).

1.3.2 Traditional Tillage

Based on a study conducted in northeastern Tanzania, Enfors et al. (2011) observed crop yield benefits of CA in dryland farming and concluded that the CA system can boost productivity during already good seasons rather than stabilizing harvests during poor rainfall seasons by improving water availability in the crop root zone. Traditional tillage systems, based on local knowledge on ecosystem management, have also been found relevant in Tanzania. A study conducted in dryland areas of Mpwapwa District, Central Tanzania, showed that the use of a no-till system by small landholder contributes to low soil fertility, low soil moisture retention, and poor crop yield. Thus, the choice of site-specific tillage systems to improve soil water retention and enhance nutrient availability is essential to achieving agronomic sustainability under resource-poor small landholder conditions. In the North Wollo zone of the Ethiopian high lands, McHugh et al. (2007) observed that during a season with moderate intensity rainfall open and tied ridges increased sorghum yield by 67%–73% over that of the control (730 kg/ha) while no-till decreased yield by 25%. On the contrary, during a season when high rainfall intensity damaged the ridges, sub-soiling had the best sorghum yield with a 42% increase over the control (1,430 kg/ha). McHugh and colleagues concluded that on slopes below 8% gradient, oxen-drawn ridge-tillage and sub-soiling, to a lesser degree, can mitigate the adverse impacts of short dry spells, especially during seasons with less intense rainfall events (Figure 1.2).

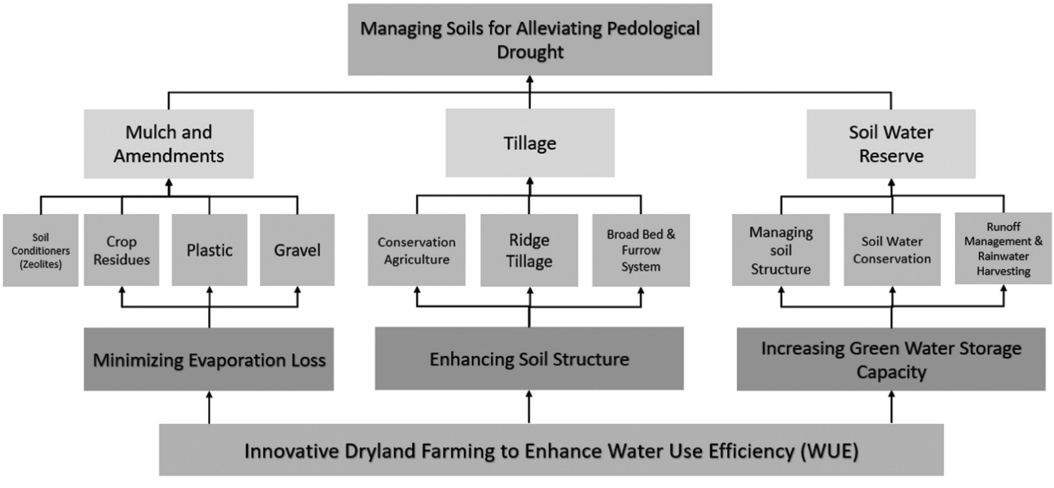

FIGURE 1.2 Managing pedological drought through innovative soil management options for a successful dryland farming.

1.4 GREEN WATER STORAGE

Green water is the amount of PAWC in the rootzone soil, and on it depend crop growth and agronomic yield in dryland farming. PAWC is the difference between field water capacity and the permanent wilting point, expressed on a volumetric basis and summed for all soil depths on the root zone. Green water supply, affected by soil structure and factors affecting it such as SOC and clay contents, can be sustained by the management of soil, crops, and cropping/farming systems. Therefore, increasing retention pores (Greenland, 1979) would enhance field water capacity and thus increase green water supply. In general, increasing SOC content would enhance moisture retention at the field water capacity (Lal, 2020). Bagnall et al. (2022) developed carbon-sensitive pedotransfer functions and showed substantial effects of soil calcareousness and SOC on PAWC. Bagnall and colleagues saw an increase in SOC of 10 g/kg (1%) in calcareous soil. The average increase in SOC-related increase in PAWC is about double the previous estimates. In other words, 1–2 mm per 100 mm soil is associated with a 10 g/kg increase in SOC across all soil classes. This model provides a quantitative measure of the benefits of soil management practices that increase SOC content for drought resilience. Similar to SOC, soil amendments are also used to enhance soil structure and improve PAWC. Ma et al. (2020) observed that multiple years of annual application of polyacrylamide (PAM) significantly increased soil profile water storage while also reducing soil bulk density. Ma B. and colleagues concluded that repeated annual PAM application for 2–3 years would be an effective strategy to combat drought and land degradation and foster sustainable crop production in dryland agriculture.

1.5 CROP MANAGEMENT

In addition to the choice of drought-resilience species and varieties, improved crop management also involves other practices such as management of soil fertility, root system characteristics, and canopy attributes, aimed at enhancing WUE and crop yield. For example, Yan et al. (2023) conducted experiments to assess the effects of root pruning and observed that it significantly decreased root: shoot ratio and increased grain yield of maize by 12.9%.

In Southeast Africa, Ndoye et al. (2022) observed that breeding for specific root traits could improve crop resilience. Ndoye and colleagues observed that basal root whorl number and longer and dense root hairs increase P acquisition efficiency and yield of common bean. With regard to water-saving strategies, root hair density and deep root growth could improve sorghum and pearl millet yield in West Africa. Similarly, denser root systems and mycorrhizal fungi could benefit rice growth.

Sun et al. (2020) studied the root traits of eight cultivars of winter wheat adapted to dryland conditions in Shaanxi Province of China. They observed that the overall root size of dryland wheat cultivars in Shaanxi Province changed with the planting decade. For example, modern cultivars developed after the 2000s had larger root surface areas than older cultivars under drought conditions, especially at 0–40 cm depth. Consequently, there was an improvement in WUE of about 47.0% from the earliest to the most recent cultivars. Furthermore, water stress promoted larger root sizes than those found in the irrigation treatment.

Yan and Zhang (2017) recommended the introduction of dwarfing genes to achieve genetic advantages in grain yields and WUE under rainfed conditions. These genes reduce plant height and affect root and coleoptile length and enhance yield and WUE. Drought stress can inhibit physiological traits (plant uptake) (Yan et al., 2016). Thus, genetic improvement can enhance resilience.

Some effects of root pruning at the stem elongation stage were also reported on drought tolerance and WUE of winter wheat by Ma et al. (2013). Whereas root pruning had no effect on grain yield in well-watered and medium drought soil, but it significantly decreased grain yield under severe drought conditions. Thus, Ma, S. and colleagues suggested possible direction toward drought-resistance breeding.

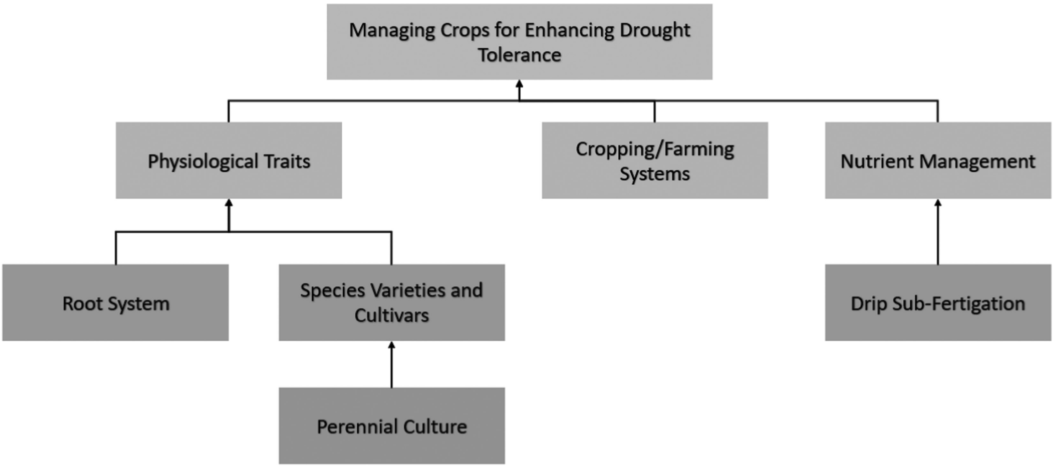

FIGURE 1.3 Adapting crops through choice of species and cultivars, cropping/farming systems, and plant nutrient management.

The benefits of crop rotations have also been observed in enhancing SOC sequestration and erosion control (Schillinger, 2016). Van der Pol et al. (2022) observed that incorporating legumes into a continuous rotation influences the form and amount of soil organic matter (SOM) as well as productivity in farms of the Central Great Plains region of the U.S. Van der Pol and colleagues reported that intensifying rotations with continuous grains led to 1.5-fold increase in aggregate size but did not change SOC stocks. In comparison, incorporating a legume into the continuous grain rotation resulted in 1 mgC/ha more SOC on average in surface soil compared to wheat-fallow rotations, but no significant changes in SOC content were observed at depths. Van der Pol et al. hypothesized that longer-term adoption of legume-based rotations could allow for 10% greater SOC gains over time compared to wheat-fallow systems.

Deng et al. (2021) studied the effects of extreme drought on SOC and N cycles and observed that the effects of drought were regulated by the ecosystem type, and drought duration and intensity. Deng and colleagues reported that drought reduced SOC content mainly because of reduced plant litter input. Drought increased mineral N contents but reduced N mineralization rate and nitrification rate, and this left total N unchanged. However, there is a lack of understanding of the effects of long-term drought on ecosystem C and N dynamics (Figure 1.3).

1.6 DROUGHT-TOLERANT SPECIES

Adoption of drought-tolerant crops, forages, and trees can have strong development potential in dryland. Emam et al. (2012) reported that common bean cultivars with a determinate growth habit appeared to have a potential as a dryland rotation crop for farming in arid regions. In semi-arid areas of China, Huang et al. (2020) compared soil water consumption of sweet sorghum, sudan grass, and forage maize under natural rainfall conditions. They observed that the yield of sweet sorghum was significantly higher than that of sudan grass and forage maize. Soil water consumption mostly happened in 0–150 cm layer in the forage maize, and in 0–100 cm layer for sweet sorghum and sudan grass. Furthermore, the average daily evapotranspiration of forage maize was about 10% and 15% higher than that of sweet sorghum and sudan grass, respectively. They recommended sweet sorghum for forage production because it presented the highest yield, less soil water consumption, and similar nutritional quality to that of forage maize.

Growing mixed species plantations can also alleviate drought stress and create many economic benefits. In the Loess Plateau of China, Gong et al. (2020) conducted a meta-analysis based on 457 field observations to assess the effects of different planting patterns on the soil moisture regime to 5 m depth. They observed that compared with monoculture plantations, mixed species plantations were better able to maintain the soil moisture at 0–4 m depth. Gong et al. concluded that mixed-species plantations (arbors with shrubs) were conducive to enhancing drought resistance in arid and semi-arid regions.

Perennial wheat and cereals are recommended for saving labor and tillage imports (Glover et al., 2010). In Australia, Bell et al. (2010) suggested perennial wheat for rectifying several ecological issues including hydrological imbalance, nutrient losses, soil erosion, depleting SOC content and degrading soil health. Perennial wheat may also have direct production benefits from lower external inputs, providing extra grazing for livestock in mixed farming systems and whole farm benefits that may offset lower grain yield (Bell et al., 2010). Perennial wheat can also diversify current cropping systems.

Similar to perennial cereals, there are also perennial pastures. Hayes et al. (2010) argued that perennial-based pasture swards provide land managers control in temperate cropping zone environments to satisfy the dual role of fostering increased agricultural productivity and reduced deep drainage in NSW, Australia. Breeding and adaptation of perennial pasture species under site-specific conditions could diversify farming systems under harsh arid environments. There are also new pasture plant species to achieve sustainable systems which require strengthening of screening and breeding program (Dear and Ewing, 2008). Perennial legumes are also important in the Mediterranean region and in environment ranging from mountains to deserts (Cocks, 2003). In the Mediterranean environment, and elsewhere in dry regions, genetic improvements including changing the phenological development to better match the rainfall, increases early vision, deeper rooting, osmotic adjustment, increased transpiration, efficiency and improved assimilage storage and remobilization (Turner, 2004). Breeding of new varieties for high WUE of wheat under limited water availability is critical (Deng et al., 2003).

History of 125 years of dryland wheat farming in the Inland Pacific Northwest of the U.S. indicates that the yield of wheat has increased from <1.0 to 3.4 mg/ha by innovative management (Schillinger and Papendick, 2008). Therefore, a substantial yield improvement in dryland farming is possible through the adoption of innovation in the management of soil, water, crops, species, and farming systems.

In accordance with the concept of adopting the approach of integrated agro-ecosystem approach to the management of drought (Solh and Van Ginkel, 2014), and along with K-fertilization (Zhang et al., 2014), application of N fertilization may in some cases ameliorate negative effects of long-term drought. Zhang et al. (2012) reported that moderate N application also plays a physiological role in the alleviation of drought stress effects on plant growth by improving water status on N metabolism, especially for drought-sensitive cultivars.

Rotations are also an integral component of the integrated approach (see Section 1.5). Data from a wheat-based rotation under drought-stress conditions in Northern Syria's medium rainfall zone obtained by Christiansen et al. (2011) recommended that barley rather than wheat is the desired cereal in rotation with legume in regions with rainfall of 350 mm. Because of the importance of sheet in the region's farming systems of Syria, incorporating vetch in the rotation cycle is of critical importance (Figure 1.4).

1.7 DROUGHT RESILIENT RAINFED TECHNOLOGIES

Key drought-resilient technologies include the choice of appropriate crops (species and varieties) and cropping systems and integrated farming systems. Soil management options include CA, ridge-tillage, mulch farming. Crop management includes rotations and inter-cropping (Rao and Gopinath, 2016). Reducing runoff losses and achieving effective erosion control, by mulching and the use of organic amendments and deep-rooted crops (pigeon peas), can improve rainwater consumption and alleviate drought. In Cabo Verde, Baptista et al. (2015) observed that for sloping land, mulch with pigeon peas and organic amendments reduced runoff and soil erosion.

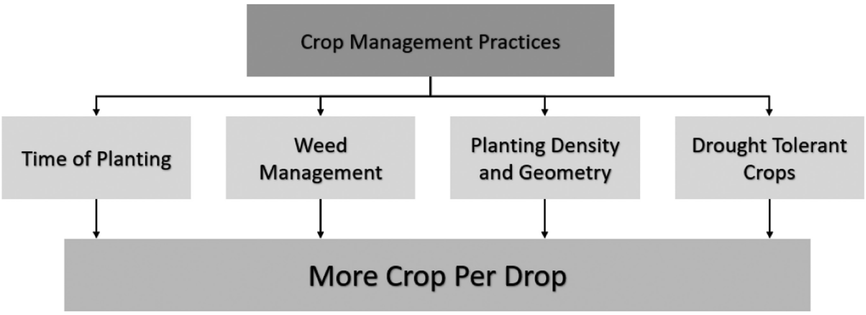

FIGURE 1.4 Innovative crop management for sustainable dry farming.

Rainfed agriculture is practiced on 58% of cropland and is home to 40% of human and 60% of livestock population in India. Recommended interventions for drought management are those related to natural resource management; crop, livestock and fisheries production systems; and capacity building (Prasad et al., 2015).

It is all about water, and the strategy is to improve water productivity. For the Australian Grain industry, a nationally coordinated approach was adapted for the 300–700 mm annual rainfall zone. Kirkegaard et al. (2014) outlined The Water Use Efficiency Initiative which challenged growers and researchers to increase WUE by 10%. As stated above, the judicious use of K fertilizer can also mitigate the adverse effects of drought. Zhang et al. (2014) provided direct evidence of the beneficial physiological formation of K fertilization in mitigating the adverse effects of drought stress in maize by increased nitrate assimilation and osmotic regulation, but not due to its nutritive role. Hao et al. (2005) reported that long-term P application enhanced yield in normal years but not so in the drought years. In most cases, P uptake efficiency rarely exceeds 15%–20% in the first year, with progressively smaller percentages in subsequent years (Ryan, 2003). The focus, therefore, should be in developing innovative options of managing soil fertility which increase the use efficiency of fertilizer but decrease the rate of fertilizer inputs.

In addition to using PAM, green water storage can also be increased by using amendments such as zeolite (He and Huang, 2001, 2004). Zeolite can absorb water because of its high CEC, free structural water storage and surface absorption. The data by He H. and Huang Z. showed that input of zeolite increased water infiltration by 7%–30% on gentle slope and >50% on steep land. Furthermore, zeolite-treated soil increases moisture by 0.4%–1.3% under extreme drought and 5%–15% in mild conditions. It also reduces runoff and minimizes the risks of soil erosion.

1.8 POLICY AND INSTITUTIONAL SUPPORT

Dryland regions contribute 41% of the world's land surface (Solh and Van Ginkel, 2014). Drought preparedness by farmers, especially the resource-poor and small landholders, would also benefit from structured institutional support along with favorable government policies, and cooperation with the private sector. The dryland regions also have a high poverty, and thus coping with drought and water scarcity are critical to advancing SDGs of the United Nations. Policy interventions are needed to promote the adoption of an integrated approach to addressing the challenges of dryland agro-ecosystems.

Policy focus must involve integrated management of soils, crops, livestock, rangeland, and trees based on system thinking. It must also involve all stakeholders in the value chain along a research-to-impact pathway for enhanced food security and improved livelihood in dry areas (Solh and Van Ginkel, 2014).

Policy interventions are needed for the adoption of CA to enhance soil water conservation which can lead to dry spell mitigation and erosion control in drought-prone regions such as the North

Wedlo zone of the Ethiopian highlands (McHugh et al., 2007) and drought-prone regions of China (Wang et al., 2011), India and elsewhere. The overall strategy is to improve WUE (Hsiao et al., 2007) leading to more crop per drop.

Policy interventions are also needed in the adaptation of crop management to drought. Adaptive management includes (Debaeke and Aboudrare, 2004): drought escape, avoidance or tolerance, and crop rotation. These strategies can be grouped under the following: (i) increasing green water storage, (ii) increasing soil water uptake, (iii) reducing evaporation (iv) optimizing the water use patterns between the pre- and post-antithesis, and (v) tolerating drought stress and enhancing chances of recovery. An additional option of water harvesting by using plastic mulch on ridge top and seeding crop in the furrow (see section 1.2.1 to 1.2.3 on mulching).

Marginal lands are increasingly being used for crop production in dryland and are less available for livestock grazing (Hamadeh et al., 1999). Policy interventions are needed to promote farming systems which can address the issue of shrinking rangeland and decreasing feed availability. These emerging and existing situations necessitate a comprehensive sustainable development of dryland agriculture. Such farming systems must focus on a form of sustainable agriculture and comprise a technical system for increased WUE and also for diverse crop products and by-products. For the dryland of Northwest China, Song et al. (1997) suggested that key features of the prototype system would include: (i) drought-resistant crops with low water requirements and high yield potential, (ii) intercropping systems with high yield and high benefits, (iii) nutrient management which can enhance WUE, CA, polythene or biodecomposable film, vetch or a perennial forage, etc. Pro-farmer policy must be in place to promote the adoption of appropriate practices and farming systems.

The Green Revolution of 1960 in India was centered on land equipped for irrigation, but drylands and drought-prone regions were not included in this endeavor (Ninan and Chandrashekar, 1993). Thus, there is a strong need to develop technologies, and policies, of eco-intensification that enhance productivity and restore the environment quality of drylands, under diverse environments and constraints.

It is precisely in this context that the concept of "climate-resilient villages" was implemented in India (Rao et al., 2016). Indian agriculture faces the daunting task of feeding 17.5% of the world population (1.4 B out of 8 B) on 24% of land and 4% of water resources with 60% of cropland under rainfed conditions. Sub-Saharan Africa is faced with an event bigger challenge.

1.9 CONCLUSIONS

Drylands of the world, predicted to be expanding from 40% in the 2020s to 50% of the Earth's surface by 2050, are also vulnerable to global warming and extreme events of drought and heat waves. Yet, dryland farming has a vast potential to increase productivity and sustainability. While additional research is needed to develop innovative technologies and farming systems which produce more crops per drop by conserving water in the root zone and enhancing the use efficiency of water through sustainable management of finite and fragile soil and water resources, there is a strong need to translate science into action. In addition to cooperation between researchers and farmers, involvement of the private sector is also critical to promote the adoption of innovative technologies. The private sector can facilitate access to essential inputs (seed, fertilizers, amendments, machinery, etc.), facilitate payments to farmers for ecosystem services and also provide support for additional research and upscaling of innovative technologies. Four-way cooperation between land managers (farmers, ranchers, and foresters), researchers, policymakers and private sector would be the best option.

Dryland farming has a bright future. More changes will happen between 2020 and 2050 than all the innovations before. In addition to innovation in science, policy intervention and involvement of private sector will also play a critical role in the transformation of dryland farming.

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2 Drought Management through Genetic Improvement in Dryland Cereals and Grain Legumes

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2.1 INTRODUCTION

Drought is one of the most important constraints in crop production in drylands in different parts of the world, adversely impacting not only crop productivity but also food security, livelihood, and economic growth (Bodner et al., 2015). Climate change is likely to make drought more severe in future, particularly in semi-arid and arid tropics of the drylands, in the form of its larger spread, greater intensity, longer duration and higher frequency (Cook et al., 2018; Rama Rao et al., 2019).

Drought hampers plant growth, development, and yield by changing the inherent agro-physiological and biochemical processes and pathways (Afzal et al., 2017). In addition, the temporal and spatial variation in drought across different environments has made it a complex problem to deal with (Zhou et al., 2021). Furthermore, crop production in drylands is likely to become more challenging due to predicted intense drought stress, increased temperature and incidences of diseases and insect-pests (Sultan et al., 2013; Rama Rao et al., 2019). Therefore, drought management remains the key intervention to make the dryland production system more resilient and less vulnerable to climatic vagaries through technological, institutional and policy options (Shiferaw et al., 2014).

From a technology point of view, both agronomic and genetic improvement approaches have a great role to play in drought management. Agronomic approaches such as mulching, tillage, intercropping, nutrient management, water conservation, early sowing and micro-irrigation are technically feasible and economically viable options to overcome the drought problem (Tyagi et al., 2020) which require additional resources and physical interventions.

Genetic improvement of field crops is an attractive option to develop and deploy crop cultivars that are inherently more tolerant to drought (Tuteja and Gill, 2013). Therefore, the development of crops with better adaptation to drought is critical to have sustainable food production in drylands. This article reviews the research efforts for understanding the adaptation to drought and breeding for drought tolerance in major dryland cereals and legumes that are grown largely under rainfed ecology, and which are naturally subjected to different degrees of water deficit during their growth period.

2.2 CHOICE OF FIELD CROP SPECIES FOR DROUGHT ECOLOGY

2.2.1 DROUGHT-TOLERANT FIELD CROPS AND THEIR DISTRIBUTION

Several cereals and legumes are important components of dryland farming systems. The different cereal-legume combinations have multiple benefits like maintenance of soil fertility, better use

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TABLE 2.1
Area, Production and Productivity of Major Dryland Cereals and Legumes in World

Crop	Area (million ha)	Production (million mg)	Productivity (mg/ha)	Top 5 Grower Countries	Major Production Constraints
Maize	202.00	1162.4	5.8	China, USA, Brazil, India, and Argentina	Drought, heat, excessive moisture, nutrient imbalance, diseases, and insect pests
Sorghum	46.00	57.9	1.4	USA, Nigeria, Ethiopia, India, and Mexico	Drought, heat, diseases, and insect-pests
Millets	32.10	30.5	2.3	India, Niger, China, Nigeria, and Mali	Drought, diseases, and weeds
Chickpea	14.84	15.1	1016.3	India, Turkey, Pakistan, Myanmar, and Ethiopia	Drought, heat, Fusarium wilt, Ascochyta blight, and pod borer
Pigeon pea	6.09	5.0	822.2	India, Malawi, Myanmar, Tanzania, and Kenya	Drought, water logging, diseases, and insect pests

of resources and nutrients, and management of the ecosystem. The choice of crops in drylands is determined by the crop duration, the length of season, and the productivity and ability of the crop to meet the food and fodder requirements of the household crop-livestock farming system. The main dryland cereals are maize (*Zea mays* L.), sorghum (*Sorghum bicolor* L. Moench), pearl millet (*Pennisetum glaucum* (L.). R. Br.), and other millets; while the major legumes in dryland include chickpea (*Cicer arietinum* L.) and pigeon pea (*Cajanus cajan* L. Millsp.).

Maize is the cereal with the largest global production and area (Table 2.1) and plays a critical role in the sustenance and livelihoods of millions of resource-poor smallholders in drylands, especially in tropical regions of Asia, Latin America, and Sub-Saharan Africa (SSA). Sorghum is adapted to dryland agro-ecosystems of the arid and semi-arid tropics of the world due to its higher inbuilt genetic resilience to drought and changing climatic conditions. Across the globe, sorghum is produced in >100 countries in Africa, Asia, Oceania, and the Americas. Pearl millet is an important crop grown in the semiarid and arid regions of South Asia (SA) and SSA that are characteristically challenged by low and erratic rainfall and high mean temperature and simultaneously have soils with low organic carbon content and poor water-holding capacity. Small millets like foxtail millet (*Setaria italica*), finger millet (*Eleusine coracana*), barnyard millet (*Echinochloa crusgalli*), proso millet (*Panicum miliaceum*), kodo millet (*Paspalum scrobiculatum*), and little millet (*Panicum sumatrense*) possess excellent potential to grow under water deficit conditions and provide an alternative choice in drought-prone areas. Once small millets were the regular part of farming in drylands and human diet but have been significantly marginalized in the post-Green Revolution period in arid and semi-arid regions across the globe. In addition to their in-built intolerance to abiotic stress, these crops are nutritionally superior to rice and wheat as they are rich in protein, fibre, vitamins, and antioxidant compounds (Singh et al., 2022). Chickpea, pigeon pea, and mung bean are important for food security and livelihood generation to resource-poor people in the semi-arid and subtropical world. As a source of affordable proteins, these crops are key ingredients of vegetarian diets in developing world. The inherent traits of legume crops, including biological nitrogen fixation (BNF) and a deep root system, make them crucial for the sustainability of farming systems in these regions.

All dryland cereals and legumes are known for their drought tolerance with built-in adaptive traits to produce yield under adverse conditions, yet drought stress adversely affects their production and productivity. In the context of climate change, their inherent resilience to drought needs to be further improved in the dryland regions in view of existing variation within a crop species.

2.2.2 Crop Response to Drought

Drought stress occurs in different patterns and intensities at different crop growth stages. Crops have been reported to exhibit a differential response to drought depending on the growth stage at which drought occurs. Much work has been done to understand the nature of drought in target dryland environments and the response of crops to moisture stress that occurs in different stages of growth to understand their adaptation to types of drought environments.

The probability of drought in dryland environments is highest at the start and in the latter part of the rainy season, and therefore, crops are highly prone to face water deficiency during the establishment and flowering/early grain-filling stages (Bänziger et al., 2000a). In dryland areas, seedling death is particularly high under the combined effects of drought and heat stress (Ndlovu et al., 2021). The basic requirement to obtain good yield in drylands is to have a sufficient plant stand. At the time of germination, emergence and early vegetative stages, moisture availability is a critical factor for proper growth and development of maize, sorghum, pearl millet and minor millets (Gregory, 1983; Carberry et al., 1985; Bänziger et al., 1997). Root, and shoot length and root/shoot ratio, leaf formation and secondary root development are strongly affected by drought stress and there are reported genetic differences for these traits. If drought stress severely reduces stand at the beginning of the season, farmers have a choice, though at additional cost, to replant fields with a shorter duration cultivar or a different species. Agronomic management plays an important role in reducing seedling mortality due to early-season moisture stress.

However, drought during the vegetative stage of growth may have a more pronounced effect on drought-sensitive than drought-tolerant cultivars (Fadoul et al., 2018). On the other hand, little adverse effect on productivity is observed by drought during the vegetative stage in pearl millet as there is a significant increase in the number of panicles (Bidinger et al., 1987a), which has been established as a compensation mechanism for a damaged main shoot (van Oosterom et al., 2003, 2006). Water stress during the vegetative phase also results in delayed flowering in pearl millet and sorghum (Mahalakshmi et al., 1987). Such developmental plasticity increases the chances for escape from the most sensitive stage of growth (Henson and Mahalakshmi, 1985).

Crops are relatively more sensitive to water deficit during the reproductive stage, especially around flowering, compared with other growth stages (Shaw, 1977; Grant et al., 1989). For example, during tassel emergence, anthesis and silking, maize is highly sensitive to drought that results in cob barrenness (Banziger et al., 2000a). Similarly, terminal drought stress at the reproductive stage, when drought occurs at flowering and grain-filling stages of pearl millet, has a strong adverse impact on grain yield (Mahalakshmi et al., 1987; Kholová and Vadez, 2013) due to a decrease in the number of fertile florets and grain size (Bidinger et al., 1987a; Fussell et al., 1991). Sorghum production is affected by drought stress during both panicle development and the post-flowering stages (Adugna and Tirfessa, 2014). A study on sorghum (Kapanigowda et al., 2013) showed that both pre- and post-flowering drought stress significantly reduces grain production due to a reduction in the number of grains per panicle (Manjarrez-Sandoval et al., 1989), a trait that directly contributes to grain yield.

Leguminous crops (pulses) often experience drought stress because of their cultivation on marginal lands under rainfed conditions. Drought stress influences various aspects of growth and development in legumes, including poor germination, marked decline in stomatal conductance, chlorophyll content, and photosynthesis, reduced number of pods, impaired root nodule development, poor nutrient uptake, increased leaf senescence and enhanced reactive oxygen species (ROS) activity (Khatun et al., 2021). All these reflect finally into a significant compromise in yielding capacities of leguminous crops under drought stress conditions. As a result, drought stress is reported to cause substantial yield losses in legume crops. For example, up to 50% of chickpea yield is reported to be lost to drought stress (Jha et al., 2019). In legumes, flowering and reproductive stages such as anthesis, pollen germination, and pollen fertility are highly vulnerable to drought stress.

2.2.3 UNDERSTANDING DROUGHT-COPING MECHANISM OF DRYLAND CROPS

Grain yield is a complex trait influenced by several component traits at the bottom of the structural organization of the plant and is also the consequence of an interaction between the environment and the genotype.

A range of morpho-physiological, biochemical, and molecular mechanisms operate in crops to impart adaptation to diverse environmental stresses including drought. Drought-coping mechanisms that allow plants to mitigate the negative effects of drought can be classified into three broad categories as escape, avoidance and tolerance (Levitt, 1980). Escape involves the completion of life cycle prior to the onset of drought stress, while avoidance is based on maintaining hydration despite water deficit through some specific morpho-physiological features such as deep rooting, stomatal closure etc., and finally, tolerance involves features that allow the plant to maintain, at least partially, proper functionality in a dehydrated state (Levitt, 1980).

2.2.3.1 Drought Escape

Early phenology (early flowering and maturity) has been reported to be the most important mechanism to escape terminal drought stress in cereal and leguminous crops (Bidinger et al., 1987b; Fussell et al., 1991; Banziger et al., 2000; Araus et al., 2002; Gaur et al., 2015). Early maturing genotypes with higher yields are preferred because of their ability to escape drought by completing their life cycle before stress is intensified. However, early maturing genotypes have relatively less total evapo-transpiration and leaf area index (LAI) with the result that there is a trade-off with yield potential (van Oosterom et al., 1995; Banziger et al., 2000).

2.2.3.2 Drought Avoidance

The maintenance of a proper water balance in plants is essential for adequate growth and development. In water stress situations, plants tend to increase water uptake and decrease water loss through coordinated regulation of root development (Blum, 2009; Zaidi et al., 2022) and stomatal conductance (Hepworth et al., 2016). One of the strategies for improved yields in drought-prone dryland system is to develop a deeper and more intense rooting system to access water from the deep soil profile (Vadez et al., 2011, 2015; Zaidi et al., 2016). Sorghum roots can grow to depths of 1–2 m by the booting stage and can efficiently extract water at a lateral distance of 1.6 m from the plant (Routley et al., 2003). Genotypes that have a large number of seminal roots and a large diameter vessel in both seminal and nodal roots show a better survival rate under drought stress conditions (Bawazir and Idle, 1989). The thick and deep root system in legumes such as chickpea, pigeon pea, mung bean, and common bean is conducive to the extraction of more water from soil, and length, density and biomass of roots are the main determinants of drought avoidance (Turner et al., 2001; Kavar et al., 2008). Research in chickpea and mung bean has demonstrated significant variations in root traits and indicate that prolific roots with maximum root depth with higher root length to weight ratio are the characteristics that ensure greater water uptake under prevailing drought stress conditions (Ramamoorthy et al., 2017; Bangar et al., 2019).

Stomatal conductance reduces transpiration and plays an essential role in regulating plant water balance in field crops experiencing drought (Hadi et al., 2016). Stomatal closure also reduces cell expansion and growth rate leading to a significant reduction in photosynthesis. There is genetic variation within species of dryland crops in terms of their drought avoidance (Nemeskeri et al., 2015; Rauf et al., 2015).

2.2.3.3 Drought Tolerance

Leaf-rolling and survival rate are two common physiological indexes that are used to measure drought tolerance at the seedling stage. Leaf rolling helps plants to temporarily reduce water loss and avoid stress injuries. At the cellular level, drought signals promote stomatal closure to save water, stimulate the production of stress-protectant metabolites, up-regulate the antioxidant system, and deploy peroxidase enzymes to prevent acute cellular damage and loss of membrane integrity (Gupta et al., 2020).

In the genetic improvement programme, the final target trait is the grain yield. Understanding drought tolerance in terms of physiology, phenology, and morphology of the crop has led to enhanced knowledge of the yield formation process under drought (van Oosterom et al., 2003; Yadav, 2011). This scientific progress has helped breeders to identify and target specific traits in different drought environments. In maize, the anthesis-silking interval (ASI) is the trait used to assess the degree of tolerance to drought. This simple and easy-to-measure trait at a large scale in field is an indirect measure of complex physiological functions such as – rate of current photosynthesis under drought stress and sink strength of developing kernels. Ears per plant (that is measurement of barrenness under stress), with high heritability is also a suitable target trait for improving maize drought tolerance (Monneveux et al., 2008; Xue et al., 2013; Jia et al., 2020), which is an indirect measure of another complex physiological trait, i.e. - assimilate remobilization efficiency towards kernel development. Low ASI (<5.0 days) under stress has been found to be significantly correlated with grain yield under drought conditions and other abiotic stresses as well (Bruce et al., 2002; Zaidi et al., 2004). Stay-green trait, i.e. reduced leaf senescence especially at the early grain-filling stage, when developing kernel are highly dependent on current supply of photo-assimilates helps in reducing kernel abortion after fertilization (Zaidi et al., 2003). Stay green, high chlorophyll content and chlorophyll fluorescence and cooler canopy temperature coupled with high transpiration efficiency are key physiological traits for drought tolerance in sorghum (Harris et al., 2007; Kapanigowda et al., 2013). In pearl millet, morphological traits such as high tillering, small grain size, and shorter grain filling periods that can be easily measured have been successfully manipulated in breeding programmes that target improved drought tolerance (Yadav et al., 2012).

As explained above, legumes cope with drought-challenged scenarios through a variety of mechanisms that include escape, avoidance, and tolerance. Completion of life cycle before the onset of dry conditions forms a key adaptation mechanism to escape drought in leguminous crops. In this context, early flowing and short maturity duration have been identified in several chickpea varieties and lines such as ICC 96029, ILC 1799, ILC 3832, KAK 2 that demonstrate the escape mechanism concerning drought stress. Drought avoidance helps curtail water loss while maximizing water use under water-limiting conditions. Drought escape and drought avoidance mechanisms are successful where crops are grown in stored soil moisture and high-water holding capacities. However, soils with low water retention capacities require plants with intrinsic tolerance mechanisms to withstand drought stress. Morphological features, such as root system architecture (RSA), also play an important role in imparting tolerance against dry conditions. A variety of physiological traits, such as photosynthetic efficiency, relative water content (RWC), and water use efficiency (WUE), are reported to have great relevance with respect to mitigating drought stress in legume crops. In mung bean, increase in activities of catalase, ascorbate peroxidase, superoxide dismutase and peroxidase has been associated with drought tolerance (Ali et al., 2017).

2.3 GENETIC IMPROVEMENT FOR DROUGHT TOLERANCE

Like any other trait, progress in drought tolerance is determined by the availability of germplasm sources with drought tolerance, variation in traits determining performance under drought and efficiency of selection to enhance drought tolerance in crops.

2.3.1 Genetic Resources of Dryland Crops

The genetic resources of dryland crops include local landraces, improved elite material, local cultivars, genetic stocks, and wild relatives. Systematic efforts at the global level led to the availability of germplasm of dryland crops. For instance, global germplasm collections of maize consist of 327,932 accessions. CIMMYT works as the global repository for maize germplasm collection and maintains

28,193 accessions from 64 countries. Apart from the germplasm collection, there is one primary maize bank, especially for genes, the Maize Genetic Stock Centre. This centre has conserved and annotated nearly 80,000 maize mutant stocks and are available to maize geneticists.

Global sorghum germplasm collections consist of 235,688 accessions. The largest global collection of sorghum from 93 countries is collected and conserved at ICRISAT, Patancheru (Upadhyaya et al., 2017). ICRISAT has a total of 41,023 accessions in the gene bank which include 35,632 landraces or traditional cultivars, 4,841 breeding material, 461 wild relatives and 89 improved cultivars (GENESYS-PGR, 2019).

At the global level, pearl millet germplasm collection consists of 65,447 accessions in more than 1,750 gene banks of 46 countries. Six large ex-situ holders are ICRISAT, India (33%); CNPMS, Brazil (11%); NBPGR, India (9%); ORSTOM, France (6%) and ICRISAT, Nairobi (4%). ICRISAT holds 23,841 germplasm accessions that include 20,628 traditional cultivar/landraces, 2,268 breeding materials, 816 wild relatives, and 129 advanced or improved cultivars from 50 countries (ICRISAT, 2019). Indigenous collections of ICAR-NBPGR are from 17 states and union territories (Yadav et al., 2017).

Dwivedi et al. (2012) summarized the collection of cultivated and wild relatives of different small millets across the continents in national and international gene banks. The major collections of germplasm accessions are stored in gene banks, viz., foxtail millet in China, India, France and Japan; finger millet in India and African countries; proso millet in the Russian Federation, China, Ukraine, and India; barnyard millet in Japan and India; kodo millet in India and USA; and little millet in India (Upadhyaya et al., 2016; Vetriventhan et al., 2016). ICRISAT is holding the global germplasm of small millets. Indigenous collection in ICAR-NBPGR for foxtail millet and finger millet is from 26 states, little millet from 20 states, and kodo millet from 13 states.

Globally over 86,533 cultivated and 1,032 wild germplasm accessions of chickpea are conserved in world gene banks. ICRISAT (20,267), International Centre for Agricultural Research in Dry Area (13,362) and NBPGR (15,131) have the major holdings of chickpea collections. Worldwide, a total of 43,027 mungbean accessions are held ex situ (Nair et al., 2012). ICRISAT holds 13,783 accessions of pigeon pea while more than 10,000 accessions are being maintained by the All India Coordinated Pigeon pea Improvement centres. The selection of suitable germplasm from the large collections is truly a herculean task. Hence tailor-made smaller sets like core, mini core, reference, and composite collections with minimum repetitiveness and maximum diversity, have been made available to researchers and breeders as workable germplasm subsets.

Research conducted so far has indicated that the genetic resources from drylands hold a unique advantage as they have evolved over centuries by natural and human selection under drought, high temperature or saline conditions. They are better adapted to the local conditions and would contribute to enhancing resilience at the farm level. These resources could be of immense importance, especially as sources of native genes conditioning resistance to various biotic and abiotic stresses and make unique study material to understand the mechanism of adaptation to abiotic stresses (Yadav et al., 2020).

Pearl millet landraces that evolved in dry areas because of natural and man-made selection over thousands of years demonstrate better adaptability to water stress (Yadav et al., 2000; Yadav, 2010, 2014). Efforts were made to utilize these landraces in pearl millet breeding practices in a regular approach. Cycles of mass selection in genetically heterogeneous landraces were found to increase yield considerably (Bidinger et al., 1995; Yadav and Bidinger, 2007) and have also been revealed as a valuable germplasm source to breed drought-tolerant lines (Yadav, 2004) and developing inbred pollinator lines for hybrid breeding (Yadav et al., 2009, 2012). There are also reports of successful introgression of drought tolerance in the agronomically desirable background from elite genetic resources (Presterl and Weltzien 2003; Yadav and Rai, 2011). Crosses between adapted landraces and elite genetic materials showed enhanced adaptation to drought combined with higher productivity up to 20%–30% (Yadav and Weltzien, 2000; Yadav, 2010). Dwivedi et al. (2016) have also proposed a systematic landrace evaluation to facilitate the identification of alleles for enhancing abiotic stress adaptation and yield to raise productivity and stability in vulnerable environments.

Sorghum landraces that are collected from arid/semi-arid environment showed greater osmotic adjustment than the landraces from humid environment (Blum and Sullivan, 1986), and registered 24% higher yield than genotypes with low osmotic adjustment (Ludlow and Muchow 1990). Landraces from Maharashtra and Andhra Pradesh states of India are drought tolerant (Elangovan et al., 2009). The Ethiopian *durras* are an excellent source for the stay-green (non-senescence) trait related to post-flowering drought-tolerance (Dahlberg et al., 2020). *Caudatum* sorghums are adapted to drought-stressed conditions. Drought-tolerant accessions have been widely identified (Reddy et al., 2004; Kumar et al., 2011; Upadhyaya et al., 2014; Venkateswaran et al., 2014).

Several potential donors have been reported across legume crops that carry specific traits that confer tolerance against water stress conditions. Crop wild relatives (CWRs) have a large potential for improving drought tolerance traits in different crops. These donors have applications in introgression breeding and in the development of experimental populations to understand the complex genetic architecture of drought tolerance. For example, wild *Cicer* species are the reservoir of the many beneficial genes for broadening the genetic base of the cultivars to survive in challenging environments. Vernalization treatment i.e., exposure to low temperatures will induce early flowering in the wild species therefore interspecific crosses help to escape drought in chickpea. A major QTL from an interspecific RIL population [ICC 4958 (*C. arietinum*)×PI 489777 (*C. reticulatum*)] has been identified on CaLG03 that explains 55% of phenotypic variation for vernalization response (Samineni et al., 2015). Early phenology such as early flowering, early podding and early maturity has been reported to be the crucial mechanism to escape drought stress across legumes and cereals. The early maturing genotypes have been used to identify the genomic regions or QTL for earliness trait, such as in chickpea (Gaur et al., 2015) and pigeon pea (Kumawat et al., 2012).

2.3.2 PHENOTYPIC TRAITS ASSOCIATED WITH DROUGHT TOLERANCE

Although yield is a trait of primary interest, partitioning it into its component traits that are significantly associated with yield under stress gives a better understanding of the targeted trait and helps to keep track with stress intensity for mid-term correction, if needed. Also partitioning complex traits such as grain yield under drought into components adds to the genomic region discovery efforts. Secondary traits can also be used as preliminary selection criteria when the turn-around time between seasons is short. A secondary trait could give greater gains for the primary trait (grain yield) than selection for yield alone when $hGY < rG \times hST$, where hGY and hST are the square roots of heritability of grain yield and the secondary trait, and rG is the genetic correlation between grain yield and the secondary trait (Falconer and McKay, 1996). This condition is rarely met except when yield is low, and the secondary traits are expressed best under stress. However, in most cases, secondary traits are added to a selection index along with the primary trait in the belief that the heritability of the index will exceed that of the primary trait and yield.

A range of secondary traits have been proposed for different types of abiotic stresses, including drought stress; all putatively related to improved survival or tolerance. However, for a secondary trait to be useful in a breeding programmeme, it must comply with some key requirements (Araus et al., 2002, 2008; Lafitte et al., 2003), such as:

- a high genetic correlation with grain yield under the environmental conditions of the target environment, i.e., the relationship with yield must be causal not casual,
- a lower effect of environment than grain yield is i.e., having a higher heritability than the yield itself, and so less genotype×environment interaction effects,
- a high genetic variability for the trait must exist within the species,
- a lesser association with poor yields in unstressed environments in case of traits being addressed in breeding for stress-prone environments,

- amenable to measuring the trait rapidly and more economically than yield itself, and in a reliable way, and
- enable to be assessed in individual plants or in very small plots, preferably by non-destructive means.

Studies have shown that key secondary traits for maize under drought are reduced barrenness (increased ears per plant under stress), anthesis-silking interval, stay green (reduced lower leaf senescence), leaf erectness and to a lesser extent, leaf rolling under drought (Banziger et al., 2000b). In index selection for drought tolerance weightage is assigned based on the correlation of traits with grain yield and heritability under drought stress (Bolanos and Edmeades, 1996). In addition, plant height and days to 50% anthesis are also used in the selection index to avoid extremes in selection for plant height and maintain maturity group, respectively. Other traits such as root growth are only useful when they have been field-tested and have met the criteria prescribed for an ideal secondary trait. Of course, roots have a very important role in water acquisition and a significant component of tolerance to water-deficit stress (Barker and Varughese, 1992; McCully, 1999), however, due to complications in the observation of root traits especially on a large number of genotypes in field conditions it is logically not possible to use them in routine selection process, except in strategic research such as selection of trait donors for new breeding start etc.

Tillering ability is the most important trait in pearl millet that has been strategically manipulated in mid-season drought stress breeding. There is a large variation in tillering capacity of pearl millet, which has been reported to be a moderately heritable trait (Appa Rao et al., 1986; Rai et al., 1997; Yadav et al., 2017). The greater tillering provides elasticity to the growth and development of pearl millet and is part of its mechanism for adaptation to severe drought conditions. Several drought tolerance studies conducted in the Sahel have indicated that pearl millet is tolerant to water deficit until early grain filling, predominantly because the main shoot can be compensated by basal tillering (Winkel et al., 1997).

Earliness and short and rapid grain filling periods have been manipulated to improve tolerance to terminal drought. Early flowering essentially determines grain productivity under water stress (Bidinger et al., 1987b; Fussell et al., 1991; van Oosterom et al., 1995). Genetic variation with respect to earliness is widely available in the germplasm (Rai et al., 1997; Yadav et al., 2017) and phenotype-based selection has been accomplished (Rattunde et al., 1989). The frequently exploited basis of earliness is the *Iniadi*-type landraces collected from western Africa (Andrews and Kumar, 1996). Promising lines with the early flowering trait have been developed from *Iniadi* landraces and adopted in Indian and African agroecosystems.

The proportion of the panicle threshing denoting seed setting potential under low soil moisture contents and integrating the effects of assimilation and translocation of photosynthates in drought environments is a measure of drought tolerance (Bidinger et al., 1987b). It exhibits a large variation in grain yield (Fussell et al., 1991; Bidinger and Mahalakshmi, 1993), is highly heritable (Yadav, 1994), and selection is effective (Bidinger and Mahalakshmi, 1993). Some mathematical models have also been used to recognize lines that are performing well in adverse conditions by comparing grain yields between stress and non-stress (optimum) conditions (Bidinger et al., 1987b; Yadav and Bhatnagar, 2001). Accordingly, multi-environmental data from a diverse range of growing conditions is used to identify the drought-tolerant genotypes.

Stay-green is an adaptive mechanism in sorghum and is an effective strategy for increasing grain and fodder production, particularly under water-limited conditions (Borrell et al., 2014). It also efficiently remobilizes and assimilates during the grain-filling stage, to maintain normal grain weight, quality, and nutrients. Root architecture is a key factor in understanding the interplay of drought stress, and there is significant variability for the root architectural traits. With higher root traits, CRS67, Phule Suchitra and STG44 were potential genotypes for use in breeding for drought tolerance in sorghum (Kiran et al., 2022). IS13540 was found to be a drought-tolerant line, and its tolerance was related to a deep prolific root system and reduced transpiration rate

(Gowsiga et al., 2021). Sorghum has a dense and deep root system and has the ability to reduce metabolic processes, transpiration through leaf rolling, and stomatal closure under drought. While tolerance to drought is mainly routed through osmotic adjustments, protective solutes, high proline, desiccation-tolerant enzymes and high stomatal conductance, the escape mechanism primarily includes early flowering, early maturity, high leaf nitrogen level, high photosynthetic capacity, and remobilization of assimilates.

Phenotypic traits that can serve as signature to identify stress situations in legumes include leaf rolling, stomatal conductance, root characteristics, osmotic adjustment, dehydration tolerance, transpiration efficiency, solute accumulation and stay green mechanism. Research has demonstrated stomatal conductance and leaf rolling as one of the most reliable physiological indicators of drought tolerance. Studies indicate that leaf rolling is caused by the reduction in leaf water potential, which can vary from species to species (Kadioglu et al., 2012). In legumes, drought induces a reduction in the leaf area and causes early leaf senescence. As has been observed in pigeon pea and cowpea, abscission, and senescence are promoted in leaves at the time of flower blooming and pod-filling stage. Drought stress is also reported to affect nitrogen uptake, leaf senescence, and chlorophyll efficiency in legumes (Khatun et al., 2021). Because dryness and monocarpy cause comparable patterns of acropetal leaf senescence in cowpea, their combined action appears to increase senescence under drought (Khatun et al., 2021). Many germplasm accessions among legumes such as chickpea, ICCs 8261, 4958, 16374B, 15510, 9586, 867, 14778 and ICCV 10 impart drought tolerance by controlling root traits root length density, dry weight, and deep rooting system (Jha et al., 2020). Changes in photosynthesis, osmotic regulatory substances, drought-induced proteins, and antioxidant enzymes represent the varying levels of influence under drought stress in legumes. Photosynthetic and transpiration rates decrease with the decrease in the relative water content of the soil. Studies have revealed that the rate of photosynthesis is reduced in response to drought which could be stomatal under drought stress and can be non-stomatal under severe drought stress. Under water-limiting conditions, it leads to a decrease in photosynthesis due to reduced CO_2 availability, resulting in diffusion limitations of the stomata and the mesophyll. Stress also reduces nodule formation, as is evident from the study in faba bean, which revealed a lesser number of root hairs under stress conditions. The impact on chlorophyll level is also revealed by Mafakheri et al. (2010) who compared a sensitive and the resistance chickpea under different stages of water deficiency.

2.3.3 BREEDING FOR ENHANCING DROUGHT TOLERANCE

2.3.3.1 Characterizing Target Environment

The interaction of genotypes with the environment restricts the genetic gain in developing insights into drought adaptation. Therefore, it is important to characterize the environment in which the crop is grown. A clear understanding of the target population of environment (TPE) is essential for identifying the best selection environment where the phenotyping site should be established. The phenotyping site does not necessarily have to be in the target environment but should have a relevant relationship that represents the key constraints, such as the timing and intensity of drought stress in TPE. Therefore, a minimum amount of information about the TPE required includes the following:

- Daily weather data, preferably from the past 5 years, including maximum temperature (Tmax), minimum temperature (Tmin), relative humidity (RH), and rainfall with its distribution pattern, for understanding and defining the most relevant type of drought stress in TPE.
- Soil type, cropping season and cropping system, especially the planting window for maize.
- Other relevant information, such as major biotic stresses and socio-economic constraints.

Analysing these data helps to understand the requirements for establishing a phenotyping site that is significantly related to the TPE.

A crop modelling approach would help in the detailed characterization of the growing area and identify production constraints (drought stress patterns) to enable the breeder to understand the need for breed-specific cultivars for each target agro-ecoregion using a suitable breeding strategy. Crop modelling is highly useful for designing ideal plant ideotypes based on the evaluation of past genetic improvements for the selected environment. The efficiency of crop improvement for constantly changing environments can be improved if the physiological and morphological traits associated with drought adaptation are identified and integrated into breeding programmes. Singh et al. (2017) used a modified CSM-CERES-Pearl millet model to study the effect of altered traits determining the maturity of the crop, its yield and adaptation to heat and drought prevailing in semi-arid regions of India and Africa. It was found that decreasing crop maturity duration had a negative impact on yield although increasing the maturity duration benefitted yield in a few locations in current and future climatic conditions. In addition, increasing radiation use efficiency (RUE) resulted in higher yields under climate change conditions. Also improving the length and depth of roots are recommended as important mechanisms for drought adaptation and achieving better yield (Vadez et al., 2012). The interaction of genotypes with the environment usually results in hampering the progress of crop breeding programmes. Therefore, it is essential to understand the underlying physiological process behind the interactions (Basford and Cooper, 1998).

Most crop improvement programmes have divided all crop-growing regions of India into different mega zones based on the geographic boundaries, rainfall pattern and local adaptation of the crop (Gupta et al., 2013). The differences in the water use response and growth clearly showed that breeding for various agro-ecological zones also resulted in the breeding of specific plant strategies associated with traits like plant water use (Medina et al., 2017). A detailed characterization of crop growing area through a modelling approach and identification of crop production constraints (drought stress patterns) will enable the breeder to understand each target agro ecology for breeding specific cultivars.

2.3.3.2 Selection Environment

Choosing an appropriate selection environment to improve productivity under drought has been the subject of a major debate in plant breeding, and several theoretical and empirical studies have been reported.

The difficulty in choosing the appropriate selection environment has often restricted the progress of breeding for tolerance to drought in highly variable TPEs. Even though there is extensive evidence that selection under targeted stress may accelerate breeding gains for TPE (Bänziger et al., 1997), the difficulty of choosing appropriate environments, given a highly variable target environment, may limit the identification of superior genotypes. While breeding programmemes in high-income countries can access real-time geographic information system (GIS) data for adequately weighting results from multi-environments trials (Podlich et al., 1999), those opportunities rarely exist in low-income countries because there is a lack of both real-time GIS information and resources for conducting a large number of multi-environment trials. Therefore, based on a systematic analysis of TPE, a suitable field phenotyping location can be selected to establish a dedicated phenotyping site for managed drought stress phenotyping. Location for managed stress phenotyping needs to be chosen carefully so that the targeted crop stages (e.g., flowering, and early grain-filling stage) coincide with a rain-free period to avoid early relief from the indented stress. This is done based on long-term weather data (at least the last 5 years), including Tmax, Tmin, relative humidity, and rainfall, which could be used in identifying suitable planting window. *For example* – at Hyderabad location in India (17.3850°N, 78.4867°E, 545 masl), November to February is usually the dry season, i.e. most part is almost rain-free. Also, Tmax is <35°C and Tmin is >8°C in most part of this period. Such a site is suitable for managed drought stress phenotyping, where planting can be taken up during the last week of November and a field trial with medium maturity group of entries reaches the flowering stage sometime in the first week of February, and most critical stages of the reproductive stage complete within February, which is usually a dry period.

a. Stress timing is managed in such a way that the targeted growth stage(s) are exposed to the desired level of drought stress.
b. Stress intensity is severe enough so that traits that are important for yield under stress become distinct from those which affect yield under non-stressed conditions, e.g., mean ASI, increased senescence, etc.
c. Stress uniformity occurs over space and time for the expression of genotypic variation within a trial.

Some researchers believe that cultivars targeted for drought conditions can be identified under non-drought conditions (indirect approach) while others think that selection for drought environments should be undertaken under drought stress (direct approach). The indirect approach involves selection for high yielding potential under non-stress conditions with the assumption that genotypes selected under optimum conditions would also perform well under drought. In this approach, drought resistance is an unidentified component of performance over different environments and more emphasis is laid on yield potential. The main advantage of this approach is that yield potential, and its components have higher heritability under optimum conditions than that under stress conditions (Ceccarelli, 1994). Since yield potential has been reported to be a significant factor in determining the yield under moisture stress (Fussell et al., 1991), improvement in yield potential may have some spill over effects under water stress conditions.

The direct approach recommends that varieties for drought-prone areas must be selected, developed, and tested under the target drought environments. Theoretical analyses also indicate that selection for stress environments should be done in stress environments (Rosielle and Hamblin, 1981; Simmonds, 1991). In this approach, improvement of yield under moisture stress requires dissociation from yield potential under optimum conditions as a major selection criterion (Ceccarelli and Grando, 1991; Ceccarelli et al., 1992) and the emphasis is placed on drought adaptation and yield under drought.

Many studies have compared relative gains in performance under drought conditions through selection in drought versus non-drought environments. Low correlations are often reported between yields measured in stress and optimum conditions which indicate that yield performance under drought and non-drought conditions are separate genetic entities, and direct selection for yield performance in the target drought environments would be required to make greater gains in productivity. This is further substantiated by the existence of significant cross-over genotype×environment interactions observed across optimum and stress environments (Virk and Mangat, 1991). Using evaluation data from drought-stressed and non-stressed environments, many studies showed that drought tolerance and escape were major determinants of performance in drought environments (Virk et al., 1991; van Oosterom et al., 1995). On the other hand, high yield potential accounted for 10%–15% variation towards performance under drought. This has highlighted the importance of evaluation and selection in drought-prone locations and early maturity and suggested *in-situ* breeding for drought environments.

An osmotic solution with polyethylene glycol (PEG) is often used for inducing drought conditions and also for maintaining constant water potential during the entire experimental process (Lu and Neumann, 1998). It has been observed that the percentage of germination and plant growth are affected by drought (Zhang et al., 2015). This simple and cost-effective *in vitro* method is useful in the screening of large germplasm materials.

Screening for drought tolerance using pots is simple and cost-effective but is difficult to evaluate large populations with sufficient replication for traits like leaf area as it involves a destructive method and assessing transpiration is also laborious. Therefore, high throughput and automated phenotyping platform, LeasyScan are considered as more effective to screen various plant materials in a non-destructive manner during the vegetative stage using an optical system (PlantEye®; www.phenospex.com). This can be used for precise measurements of plant canopy traits such as digital biomass, 3D-leaf area, plant height, leaf area index, leaf angle, leaf inclination and light penetration depth (Vadez et al., 2015). Screening by using a lysimeter is also similar to the field environment in which an additional benefit of water use could also be followed throughout the crop cycle (Vadez et al., 2013).

Screening under field conditions is done by evaluating the test material through multi-locational trials conducted in drought-prone regions or by growing crops in a rain-free season under adequate water supply but withholding irrigations to expose the test material to drought at the desired stage. Field screening is still the most preferred method to assess the drought response of breeding materials and experimental test cultivars in large breeding experiments.

At CIMMYT in El Batan, Mexico, an intensive effort for developing improved maize germplasm with tolerance to drought stress was launched during the mid- to late-1970s (Fischer et al., 1983; Bänziger et al., 1997; Edmeades et al., 1997, 2017). The targeted breeding for drought tolerance in maize was started in 1975 with recurrent selection in a tropical white dent population, namely - *Tuxpeño Sequia*. A total of eight cycles of full-sib recurrent selection under managed drought stress were completed at the CIMMYT station in Tlaltizapán, Morelos, Mexico, where the rain-free period between November and April allowed precise timing and intensity of stress levels. Later during the 1980s, S_1 recurrent selection was implemented in other populations, including the Drought Tolerant Population (DTP), La Posta Sequia, and Pool 26 Sequia. The recurrent selection programmes produced improved populations, notably Tuxpeño Sequia c6, La Posta Sequia c7, and the DTPY c9 and DTPW c9, that served as source germplasm for deriving drought tolerant lines and moving towards hybrid breeding for drought tolerance. Drought-tolerant lines extracted from these populations have been used as donors in tropical maize breeding programme of SSA, Asia and Latin America, and some were elite enough to be released as CIMMYT Maize Lines (CMLs). Later a series of bi- and multi-parent populations were developed, followed by several cycles of recurrent selections and improvement for tolerance to drought, in SSA, Asia and Latin America (Edmeades et al., 2017). Using base population developed at CIMMYT-Mexico, breeding for drought stress tolerance for the mid-altitudes of eastern Africa, was initiated in 1998 in Kenya (Banziger and Diallo, 2004). Over time, more lines from La Posta Sequía c7 and DTPW c9 were used to increase the frequency of alleles for drought tolerance in new breeding starts. Thus, using various selection approaches across diverse testing environments, many inbred lines with good combining ability for drought tolerance and other adaptive traits were identified, and several elite CMLs and improved maize hybrids/synthetics were released (Prasanna et al., 2021).

Breeding and selection under carefully managed high-priority abiotic stresses, such as drought stress, have significantly increased maize yields in highly variable drought-prone environments and particularly in severely stressed environment conditions with lower average yields (Figure 2.1). Similar results were also reported from a recent study on gains with trait-based breeding under managed stress environment conducted in CIMMYT's Asia regional maize programme (Zaidi et al., 2020).

Many of the new drought-tolerant maize lines were recycled through conventional pedigree or doubled haploid (DH) to develop better drought-tolerant donor lines with higher productivity. These new donor lines have been used to develop multiple stress-tolerant hybrids and deployed across SSA (Cairns and Prasanna, 2018). In the CIMMYT Asia maize programme, breeding for drought tolerance was initiated in 2008 with the introgression of drought-tolerant yellow and white donors from CIMMYT-Mexico and white donor lines from CIMMYT-Zimbabwe and Kenya. These donors were crossed to elite Asia-adapted CIMMYT lines primarily bred for yield potential and local adaptation, especially for resistance to diseases like downy mildews and *Turcicum* leaf blight (TLB). Three sets of new drought-tolerant Asia-adapted CMLs, including CML-562 to 565, CML-578 to 582, and CML-615 to 618 were released in the past 5 years and made available to public and private sector maize breeding programme in the region.

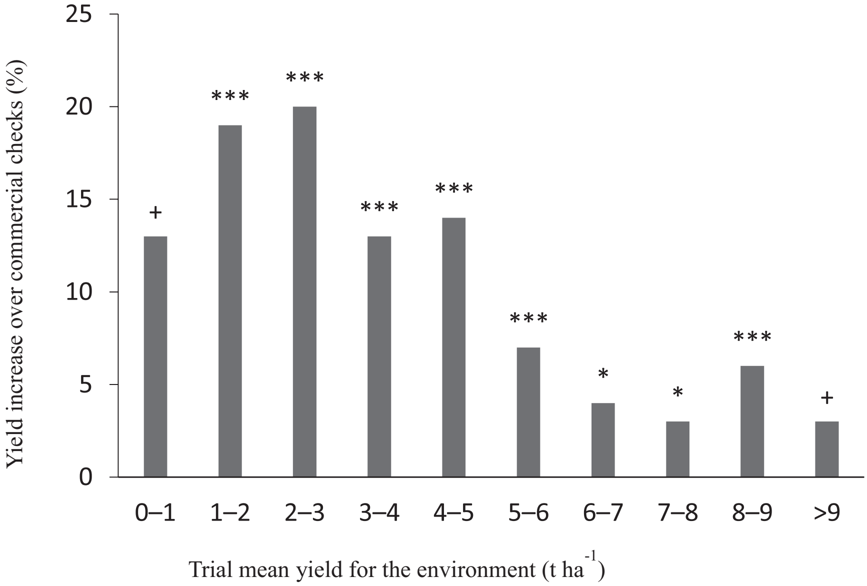

FIGURE 2.1 Selection differentials in trials grown across eastern and southern Africa of 42 CIMMYT hybrids selected for drought (and nitrogen stress) tolerance in Zimbabwe as compared to 41 private company check hybrids. *** and * indicate statistically significant ($P<0.001$) gains; + indicates non-significant gains. (Banziger et al., 2006)

2.3.3.3 Molecular Techniques

Conventional breeding methods like pedigree and backcross for improved grain production resulted in the development of improved cultivars with a significant increase in the productivity of crops. The progress in genetic improvement for drought tolerance using traditional plant breeding practices has been slow due to the complex interaction between genotype and environment, stress levels, and stages at which drought occurs. In view of the difficulties in unravelling genetic mechanisms controlling drought tolerance, genomics-assisted breeding offers a greater opportunity to develop drought-tolerant crops faster.

2.3.3.3.1 Trait-QTL Association

During the past two decades or more, different types of molecular (DNA) marker systems have been devised and used for various genetic applications like assessing genetic variability, population structure, detecting genomic regions associated with agriculturally important traits etc.

A series of studies have been conducted on QTL mapping of drought tolerance in maize (Liu and Qin, 2021). By analysing a RIL population derived from a cross between CML444 (drought tolerant) and SC-Malawi (drought sensitive), 81, 57, 51, and 34 QTLs were uncovered for six target traits (male flowering, ASI, grain yield, kernel number, 100-kernel fresh weight, and plant height) (Messmer et al., 2009). Nine QTLs related to leaf temperature have been reported on chromosomes 1, 2, 9, and 10 that were identified based on 248 SSR markers using 187 recombinant inbred lines (RILs) (Liu et al., 2011). Five QTLs related to grain yield have been reported on chromosomes 1, 3, 5, 6, and 8, which explain 50% of the phenotypic variance (Agrama and Moussa 1996). Ribaut et al. (1996) reported QTLs associated with flowering time and ASI in maize under well-watered conditions and two water-stressed regimes (Ribaut et al., 1996). In further study, the group identified several small to moderate effects QTL associated with grain yield under different levels of drought stress. However, these QTLs, in general, were not stable across different drought environments (Ribaut et al., 1997). Using a larger population and higher marker density, Messmer et al.

(2009) identified six QTLs associated with grain yield under optimal and drought environments, with limited overlap of genomic regions identified across environments. Almeida et al. (2013) identified 83 QTL associated with yield under drought stress, each QTL explained 2.6 to 17.8% of the phenotypic variation. Seven meta-QTL (mQTL) were identified across three populations, with six mQTL expressed under drought and optimal conditions. A meta-analysis of 18 bi-parental populations evaluated under a range of drought and optimal environments revealed 15 mQTL associated with grain yield (Semagn et al., 2013). However, mQTL were not stable across environments and genetic backgrounds. Genome wide association mapping studies (GWAS) on grain yield under drought, heat and optimal conditions identified several single nucleotide polymorphisms (SNPs) and candidate genes across locations; however, no overlapping SNPs were observed across treatments (Yuan et al., 2019).

The high genetic variability among sorghum genotypes and the relatively small size of its genome (730 Mb) (Paterson et al., 2009) has helped in the identification of several QTLs in sorghum related to drought tolerance. CO_2 assimilation, transpiration rate (Kapanigowda et al., 2014), stomatal conductance and density (Lopez et al., 2017), epicuticular wax (Uttam et al., 2017), crown root angle at seedling (Mace et al., 2012) and maturity (Lopez et al., 2017), nodes with brace roots (Li et al., 2014), seedling root dry weight (Mace et al., 2012), root length, roots/plant, root: shoot ratio, root volume and weight (Fakrudin et al., 2013), pre-flowering drought (Kebede et al., 2001) and post-flowering drought tolerance (Hayes et al., 2016). Furthermore, *Stg2, Stg3* and *StgB* were identified as the three key QTLs for MAS to improve terminal drought tolerance (Reddy et al., 2014). Genes associated with delayed senescence have been reported (Kiranmayee et al., 2020; Johnson et al., 2015; Abebe et al., 2021; Aquib and Nafis, 2022). These *stg* loci were also found to reduce the canopy size during flowering, reduce tillering and promote the overall root growth (Harris-Shultz et al., 2019).

In pearl millet also, DNA markers have been used to dissect QTL to investigate the molecular and biochemical basis of tolerance to abiotic stress and to devise an efficient approach for crop improvement for yields under drought stresses. Subsequently, the dissection of quantitative trait loci pertaining to drought tolerance (DT-QTLs) and high grain yield was identified under independent studies using different pearl millet mapping populations (Yadav et al., 2002, 2004; Bidinger et al., 2007). The milestone breakthrough to detect major DT-QTL on LG2 related to grain yield, explaining 32% phenotypic variance was carried out (Yadav et al., 2002) using bi-parental populations of individuals of different crosses. Afterward, a minor QTL on LG5 linked with drought tolerance, explaining 14.8% phenotypic variance was also detected (Yadav et al., 2004). The putative drought-tolerant QTL on LG2 was evaluated using near-isogenic lines derived from H 77/833-2 into which DT-QTL has been introgressed from PRLT 2/89-33 (Serraj et al., 2005). In the same direction, three major QTLs (positioned on LG2, LG3, and LG4) pertaining to grain yield with limited QTL×environment interactions were analysed as key components of MAB for improved grain yield under variable post-flowering water stresses in pearl millet (Serraj et al., 2005; Bidinger et al., 2007). The major QTLs mapped on LG2 and LG3 accounted for a wide (13%–25%) range of phenotypic variations for grain yield traits under drought stress conditions. At the same time, minor QTLs were also co-mapped for harvest index under drought stress, and QTLs for both grain number and individual grain mass in water deficits were identified (Bidinger et al., 2007).

These QTL mapping findings have been validated in follow-up research that mapped QTLs linked to high grain yield and its related traits under terminal drought stresses in pearl millet (Yadav et al., 2011). In this study, one major QTL associated with grain yield and drought tolerance of grain yield in water stress conditions was detected on LG2 which explains about 32% of the phenotypic variance in testcross progenies (Yadav et al., 2011). This major QTL explaining 32% of the variance under drought stress was confirmed in different marker-aided backcross programmes, where the 30% increase in the general combining ability (GCA) of grain yield anticipated of DT-QTL in water deficits was recovered in the QTL introgression lines (Yadav et al., 2011). The QTL associated with low transpiration rates that contribute to water stress tolerance by lodging soil water contents to be used at the grain filling stage by limiting moisture loss at the vegetative phase has been co-mapped with that of terminal DT-QTL (Kholová et al., 2012). A low rate of transpiration is maintained by physiological and morphological interactions (Kholová et al., 2012). The DT-QTLs associated with terminal drought tolerance have been introgressed into elite pearl millet lines to improve terminal drought tolerance (Jangra et al., 2019). Marker-aided foreground selection has been performed with robust SSR markers mapped on LG2 and LG5 to select the plants harbouring alleles that render resistance to bi-parental progenies (BC_4F_2) along with rigorous phenotypic selection to recover the genome of the recurrent parent in pearl millet (Jangra et al., 2019).

Genetic dissection of drought tolerance in grain legumes has been primarily driven by the analysis of biparental populations. Several studies have detected QTL controlling traits that are important in tolerance against drought in grain legumes. For more details, the reader may refer to other reviews (i.e., Jha et al., 2019). Notable among these examples is a study by Varshney et al. (2014). The authors reported a QTL cluster on LG 4, referred to as "*QTL-hotspot*" that harboured QTLs for 12 traits and explained about 58.20 % phenotypic variation. This QTL region was identified by the analysis of two RIL populations viz. ICC 4958 × ICC 1882 and ICC 283 × ICC 8261, which segregated for a variety of drought tolerance-related traits. Similarly, analysis of a RIL population (VC2917 × ZL) under irrigation and drought conditions in mung bean led authors to identify 58 QTLs for several drought tolerance-related traits including maximum leaf area, relative water content and yield (Liu et al., 2017). Consistent QTL explained up to 20.1 of the phenotypic variation observed in the population. The genome-wide association studies (GWAS) have also emerged as a popular technique to dissect the genetic architecture of drought tolerance traits in grain legumes. Li et al. (2018) measured yield and yield-related traits of 132 Australian chickpea varieties under drought stress and implemented GWAS and genomic selection (GS). The study examined drought response of these 132 lines by analysing the phenotypic and whole genome resequencing (WGRS) data. Advances in DNA sequencing technologies have facilitated the identification of candidate genomic regions/causative loci that can be exploited in legume breeding programmes to improve genotypes for their tolerance level against drought stress. For instance, the functional genomics approach in pigeon pea uncovered a set of drought-responsive candidate genes including *CcHyPRP, CcCDR, CcCYP, CcMT1, DLP, APB*, and *LTP1* under drought response (Deeplanaik et al., 2013). Among the various expressed sequence tags (ESTs) identified, three of the selected stress-responsive genes, viz. CcHyPRP, CcCDR, and CcCYP showed remarkable tolerance against multiple abiotic stresses in transgenic Arabidopsis (Mir et al., 2014). Analysis of whole genome re-sequencing (WGRS) data of 292 pigeon pea genotypes superior haplotypes for 10 drought-responsive genes (Sinha et al., 2020). The study led to the identification of a total of 83, 132 and 60 haplotypes specific to breeding lines, landraces, and wild species, respectively. Candidate gene-based association analysis using these ten genes in a set of 137 accessions revealed significant associations of five genes with seven drought-tolerance-related features. Furthermore, haplo-pheno analysis for the strongly associated genes resulted in the identification of most promising haplotypes for three genes regulating five component drought traits. The haplotypes such as C. cajan_23080-H2, C. cajan_30211-H6, C. cajan_26230-H11, C. cajan_26230-H5 were identified as superior haplotypes which could be targeted for assembly in future pigeon pea cultivars for improved response to drought stress.

Drought tolerance is a complex quantitative trait regulated by coordinated effects of many genes or several quantitative trait loci (QTLs). Millets being a drought-tolerant species, QTL mapping in millets might provide some novel genomic locus or alleles controlling drought response and could be employed in future crop improvement programmemes. An interspecific hybridization between *S. italica* cv. Yugu 1 and its wild relative *S. viridis* cv. W53 leads to the generation of a mapping population which is further employed in the detection of 18 QTLs associated with drought and dehydration stress (Qie et al., 2014). Similarly, recombinant inbred lines (RILs) developed following a cross between 863B and ICMB 841 were utilized as mapping population to harness water use-related QTLs in pearl millet (Aparna et al., 2015). The study identified four major QTLs associated with water use in which a QTL mapped on linkage group 6 was found to control plant growth, transpiration, and drought responses. Six more drought-associated QTLs were identified in a fine mapping population of pearl millet which also related to tiller contribution and plant biomass under low water conditions (Tharanya et al., 2018). A functional synonymous SNP (A/G transition) of *SiDREB2* at 558th position was found to be linked with dehydration tolerance in foxtail millet. This SNP serves as a potential marker to distinguish drought-responsive genotypes and was validated in 170 foxtail millet accessions (Lata et al., 2011; Lata and Prasad, 2013). Likewise, many SNPs were identified through genotyping-by-sequencing (GBS) strategies in diverse accessions of pearl- and finger millet (Hu et al., 2015; Gimode et al., 2016; Kumar et al., 2016). These genetic variations can be employed to determine population diversity and offspring selection during marker assisted breeding for the development of drought-tolerant verities.

2.3.3.3.2 Marker-Assisted Selection

Several studies have reported molecular markers-based analysis of drought stress tolerance in maize, including various secondary traits associated with grain yield under drought-stressed environments in the tropics (Prasanna et al., 2021). Though, the genetic dissection of drought tolerance in maize has provided good insight on this challenging trait, so far a few applications have emerged in practical maize breeding programmes. The key factors behind this include the complex genetic basis of the traits, crop stage for drought stress in field, significant effect of genetic background, cost of fine mapping of QTLs, and QTL×environment effects (Tuberosa et al., 2002). Most of the QTLs are often genetic background-specific and applying MAS for several small effects QTLs may be more expensive than conventional breeding methods for improving drought tolerance (Xu et al., 2009). MAS for any trait, including drought tolerance, needs major QTLs with large effects, and stable across genetic backgrounds and environments. Unfortunately, no QTLs with sufficiently large effects are found to be effectively used in MAS programmes for drought tolerance in maize. Therefore, the lack of consistent and major phenotypic effects of the QTL in diverse recipient genetic backgrounds suggests that QTL-based marker-assisted selection is unlikely to play a major role in breeding for drought tolerance in maize.

Of the stay-green genotypes (B35, SC56, and E36-1) studied, B35 (BTx642) is a useful source of stay-green for research and development of sorghum hybrids (Jordan et al., 2012). Stay-green QTL individually reduced leaf senescence in introgression lines and contributed significantly towards breeding drought tolerance (Harris et al., 2007; Kassahun et al., 2010). More recently, the potential use of Stay-green QTL in improving transpiration efficiency and water extraction capacity in sorghum for terminal drought tolerance (Vadez et al., 2011) and grain yield particularly under low yield environments has been demonstrated (Jordan et al., 2012). Marker-assisted breeding is a better approach to enhance post-drought tolerance in sorghum (Kassahun et al., 2010). Therefore, efforts have also been initiated to transfer this trait through marker-assisted backcrossing (MAB) into elite cultivars and study their expression in different backgrounds (Ngugi et al., 2013; Kassahun et al., 2010; Isaac et al., 2019). Current studies at ICAR-IIMR, Hyderabad on marker-assisted introgression of stay-green QTL, Stg3a and Stg3b from B35 to Indian post-rainy sorghum lines, M35-1, CSv-29R, CSV-26, CRS4 and RSLG262 have shown promise in imparting terminal drought tolerance. The introgression lines had higher green leaf area retention at maturity, and improved stover yield and seed size along with grain yield under both stress and no-stress conditions.

Three major QTLs related to grain yield with low quantitative trait loci and environmental (QTL×E) interactions were detected across different post-flowering water stresses in pearl millet (Bidinger et al., 2007). One of the major QTLs explained ~32% of the phenotypic variation for grain yield under water deficit conditions. The impacts of these dominant QTLs have been validated in the marker-assisted back cross (MABC) programmes wherein 30% enhancement of the general combining ability for grain yield is anticipated from this QTL under terminal drought stress. It was recovered in introgression lines using informative data generated with markers flanking the QTL (Yadav et al., 2011). This QTL has been fine-mapped using the LG2 QTL NIL-derived F2 mapping population with ddRAD SNPs (Srivastava et al., 2017). Out of 52,028 SNPs that were identified between the NILs, a total of ten SNPs were anchored to the QTL interval and are being used in the forward breeding programmes using the HTPG platform.

Many potential marker-assisted backcrossing (MABC) methods have been employed in QTLs introgression from a donor to an elite recurrent parent in pearl millet. Several validated QTLs have been introgressed into elite hybrid parental lines (A-/B-, R-) resulting in the improved version of the hybrids or (essentially derived varieties (EDVs).

One of the notable examples of genomics-assisted breeding for drought tolerance in legumes includes the transfer of 'QTL hotspot' region in chickpea. This has resulted in the development and release of *Pusa Chickpea* 10216 in India following genomics-guided transfer of genomic regions from ICC 4958 that control several component traits associated with drought tolerance (Bharadwaj et al., 2021).

2.3.3.3.3 Genomic Selection

Genomic selection (GS) is another marker-based strategy that incorporates all the available marker information simultaneously into a model to predict the genetic value of progenies for selection (Meuwissen et al., 2001; Lorenz, 2013). Each marker is considered a putative QTL, reducing the risk of missing small-effect QTLs (Guo et al., 2012). De los Campos et al. (2009) and Crossa et al. (2010) examined several statistical models for genomic selection in diverse panels of maize germplasm from the CIMMYT using a random cross-validation scheme that mimics the prediction of unobserved phenotypes based on markers and pedigrees. Beyene et al. (2015) implemented GS for drought tolerance on eight bi-parental maize populations and demonstrated the efficiency of GS in maize, with an average gain per cycle of 0.086 mg/ha under drought stress without significant changes in maturity and plant height. The study showed that overall gain in average grain yield using GS was two- to four folds higher than the previously reported gain in average GY under drought stress using conventional phenotypic selection. Vivek et al. (2017) used GS to enhance drought tolerance in Asian maize germplasm and suggested that a positive selection response can be obtained with the use of markers for GY under drought. Hence, the statistical model used to determine the effects of the markers works in practice and thus is validated. The use of GEBV allowed the selection of superior plant phenotypes, in the absence of the target stress, resulting in rapid genetic gains for DT in maize. Das et al. (2020, 2021) compared genetic gains with GS and conventional phenotypic selection for multiple stress tolerance, including drought and waterlogging stress and found that the gains with GS were relatively higher under drought, whereas PS showed *at par* or better response under waterlogging stress. The study concluded that the careful constitution of multiparent population involving trait donors for targeted stresses along with elite high-yielding parents and its improvement using GS is an effective breeding approach for building multiple stress tolerance without compromising on yields under optimal conditions.

2.4 FUTURE PERSPECTIVES

Modern agriculture involving digital tools for automated high-throughput and reliable phenotypic technologies is increasingly used to accelerate genetic gain in various crop breeding programmemes. Phenomics platforms employ simple and fast quantitative and qualitative methods to evaluate plant growth and development. This facilitates the detailed observation and measurement of the different traits resulting from the expression of genetic characteristics of plants, both physical and environmental factors. Of the several field-based plant phenomics approaches, aerial drones are highly promising for measuring traits like panicle emergence and its traits, plant height, biomass, biotic and abiotic stress incidence, canopy cover etc. Aerial drones can cover large areas quickly, allowing all genotypes in a study to be measured simultaneously, and are not impeded by plant height, which allows them to capture data throughout the entire growth season (Liebisch et al., 2015).