Food Production: Global Challenges to Mitigate Climate Change

Niaz Ali and Abdul Mujeeb-Kazi

Abstract There is no simple solution to sustainably feeding a global population as large as 9.6 billion by 2050 while we focus to diminish the emission of greenhouse gases (GHG) and other crop productivity constraints that cumulatively can penalize outputs. Moreover, strong drifts in global climate change have already been recorded, indicative that prospects of further deterioration are inevitable. Sustaining future food security poses a serious challenge in the face of mounting population, climatic instability, and emergence of new crop uses such as biofuels. Bread wheat (*Triticum aestivum* L., AABBDD) is a major source of calories and protein, providing 20% of the total calories in human diet, and the importance to increase wheat production is widely acknowledged. It is unequivocally recognized as the major conduit toward food security. Nevertheless, yields of all major cereals have stagnated at farm levels with wheat showing the lowest rate of increase due to the emergence of various biotic and abiotic stress constraints. With almost no opportunity to expand agriculture on existing land, increasing genetic gains for grain yield and associated traits could significantly influence the number of people at hunger risk. However, yield is a complex trait, and obtaining higher yields under any situation is unlikely to be addressed with a single or uniform approach. While improvements in agronomy could boost the yield potential in some regions, yield gains in many other areas could be achieved with genetic improvements only. We argue that achieving increased crop adaptation is likely to be the key component of future food security, and this must be well integrated into climate change-related issues and sustainable agriculture. Public investments in agri-food infrastructure and adaptation of innovative farming practices will be crucial in developing resilient crops. Development of crops with a wide genetic base and adaptation to limited agricultural inputs are warranted. Thus dietary preferences could significantly reduce the emissions of GHG and are likely be necessary components of transition toward a low-carbon society. Further, application of the recently evolved high-throughput genotyping and phenomic tools in con-

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N. Ali (✉)
Department of Botany, Hazara University, Mansehra, KP, Pakistan

A. Mujeeb-Kazi
Texas A&M University, College Station, TX, USA

S. H. Wani et al. (eds.), *Physiological, Molecular, and Genetic Perspectives of Wheat Improvement*, https://doi.org/10.1007/978-3-030-59577-7_1

junction with genome editing tools could enable plant breeders to use the untapped genetic variability in crops that may ensure agricultural resilience, thereby increasing crop productivity.

Keywords Climate change · Genetic diversity · Synthetic hexaploid wheats · Food security · Alien introgression

1 Introduction

Despite doubling of the total population, the past half-century has witnessed a remarkable growth in food production, resulting in a dramatic decrease in global hunger (Godfray et al. 2010; FAO 2018). With no exaggeration, the rate of worldwide poverty today is lower than it has ever been in recorded human history. However, meeting the targets of “zero hunger” is still not over and requires substantially greater efforts (Liu et al. 2018; Mujeeb-Kazi et al. 2019). Even today more than one in seven individuals do not get balanced food, and an even greater number suffer from various forms of malnutrition (Godfray et al. 2010; Hawkesford et al. 2013; Mundial 2018). Since human population will continue to rise, this means that the worldwide demands for food will surge. Therefore, production of high-quality food must be doubled in ways that are environmentally and socially sustainable (Borlaug 2002; Ramírez-González et al. 2018; Hickey et al. 2019).

Spikes in food prices are signs of the tendencies of food availability. Although gross food values have curtailed, the rise in food prices more recently was driven primarily by the increasing demands from developing countries and to an extent by biofuel synthesis (Godfray et al. 2010; FAO 2018). The average cereal yield has increased from 1.35 t/ha in 1961 to 3.35 t/ha in 2007 and is likely to reach 4.8 t/ha by 2040. This indicates to the remarkable success of plant breeders during the last 60–70 years in increasing the yield potential of our important crops for human livelihood. If this increase was not attained, nearly three times more land would have been required to sustain the needs of the existing population (Smith and Gregory 2013). Nonetheless, man is perhaps confronted with one of the greatest challenges of this civilization, to sustainably feed over nine billion people by 2050 in sustainable ways and that the world’s poorest people are no longer hungry (Borlaug 2002; Liu et al. 2018).

Recent studies have revealed that agricultural land is shrinking and areas that were once productive have been lost to urbanization. On the other hand, historical expansion of agriculture has significantly contributed to the loss of biodiversity (Mujeeb-Kazi et al. 2013; Hickey et al. 2019). Overarching is the major threat of climate adjustments where worries of how mitigation and adaptation procedures may affect food supply (Godfray et al. 2010). Slight changes in climate at the global level will impact plant distribution in both natural and managed ecosystems

(Coakley et al. 1999; Hawkesford et al. 2013). So while at the same time as we are to improve food production, we must take into account the needs to significantly decrease climatic impacts on agriculture as well as improve the resilience of our food production (Smith and Gregory 2013). The most probable scenario is that more food shall be required from the same or even less land and with fewer resources. Therefore, it is critical for us to identify approaches that integrate both the challenges of food security and climate change mitigation concerns while addressing the growing food demands set for 2050 (Godfray et al. 2010; Bevan et al. 2017).

Here we outline important strategies for addressing the challenge of feeding approximately 9.6 billion people and combat global challenges to mitigate climate change. Example of the wheat crop is explored because of its immense potential in feeding the global populace as well as of its being a major conduit toward future food security. Further, the prevalent current practices are unlikely to deliver the food and ecosystem services we require ahead; thus sustainable agriculture will require radical changes from sowing to harvesting supported by an astute dynamic policy approach for decades.

2 Global Climate Changes, Prospects, and Challenges for Sustainable Agriculture and Food Supply

Global food security is a major challenge of the twenty-first century to supply sufficient food while minimizing the climatic burdens of already stressed environment (Rasheed et al. 2017; Borrill et al. 2019). The recent visible changes in temperature and rainfall intensity have influenced agricultural production at the regional as well as global level and were associated with climate change phenomenon (Milus et al. 2009; Abberton et al. 2016). These changes have affected soil composition, living biota and agricultural production and threaten the household, national and global food securities (Nelson et al. 2009). Though contradictions exist in both causes as well as nature of climate changes, more recently the ecological consequences have been so evident that many of these disagreements have been resolved (Foley et al. 2011; Valizadeh et al. 2014).

Increasing efficiency of the agricultural system could galvanize sustainable agricultural production. Similarly, crop production is determined by optimum temperature and rainfall, therefore vulnerable to uneven climatic patterns (Milus et al. 2009; Campbell et al. 2016). Studies have shown that the average global temperature has increased and there would be considerable reduction in freshwater resources by the end of the twenty-first century. Likewise, variations in regional rainfall as well as snowfall have been reported, and these changes are likely to intensify in days ahead (Ewert et al. 2005; Stocker et al. 2013; Misra 2014).

Agriculture releases significant amounts of greenhouse gases (GHG) like CO_2, CH_4, N_2O, and halo-carbons to the atmosphere, playing an important role in absorbing the solar radiation (Valizadeh et al. 2014). Agriculture is responsible for the release of about 17–32% of all global anthropogenic GHG emissions (Bellarby et al. 2008). The potential to cut GHG released from agriculture and mitigate future climate changes offers a massive challenge while the focus is set for "zero hunger." Although climate change may benefit some crops in some regions (particularly the areas of the northern widths above 55°), the increased temperatures will eventually reduce crop yields at a large scale particularly in hot and dry areas (Milus et al. 2009; Smith and Gregory 2013; Valizadeh et al. 2014). Additionally, high temperatures will boost weed and pest attacks, thereby declining crop production (Ewert et al. 2005; Nelson et al. 2009).

Undoubtedly, the overall impacts of climate change on agriculture are expected to be harmful, will threaten global agricultural production systems, and ultimately influence food security. Food security is linked directly and indirectly to ecosystems through provisioning and supporting services; climate change will stretch this fine balance (Smith and Gregory 2013; Valizadeh et al. 2014). Although climate change will affect our overall ability to access food, marginalized populations in developing countries, like South and East Asia, are likely to be the worst affected by climate change (Misra 2014; Campbell et al. 2016). It is clear that from the food and ecosystem services, we anticipate that future demands offer more radical changes from production to consumption to policy making (Bellarby et al. 2008; Godfray et al. 2010; Bevan et al. 2017).

3 Strategies to Ensure Food Security and Mitigate Climate Change Impacts

Investments in Agri-Food Infrastructure and Adaptation of Innovative Farming Practices

Investments in advance technologies and relevant infrastructure in conjunction with other cost-effective measures could make agricultural sector more productive and sustainable (Hazell and Wood 2007; Bevan et al. 2017; Rasheed et al. 2018). Roughly 30–40% of food is spoiled mainly due to the non-existence of agricultural infrastructure and the scarcity of financing in storage facilities. Moreover, poor transport facilities increase the prices of agricultural inputs and delivery of the harvest into markets (Godfray et al. 2010; Foley et al. 2011). The last few decades have seen remarkable technological innovations in agri-food industry. Robots and unmanned aerial vehicles (UAV) have been developed for farming purposes. The UAVs that are equipped with hyperspectral cameras could analyze crop status from remote centers (Walter et al. 2017). Similarly, nano-technology has emerged with the potential to minimize the adverse effects of agricultural practices on ecosystems, thereby promoting sustainable food security. The nanodevices could confer benefits to the agri-food sector by minimizing leaching, while improving nutrient uptake by plants. Furthermore, it is noteworthy to mention that nanomaterial could also be exploited to improve soil and waste management practices. Nanomaterial could improve pesticide efficiency by providing a more specific release toward target organisms (Mishra and Singh 2015; Fraceto et al. 2016).

Technological advancements and its judicious application hold immense potential, but there are potential risks if the benefits are embroidered alone. Similarly, investments in genetic modification technology and transgenic crop development are valuable, although the "fors and againsts" needed to be rigorously defined before it may substantially contribute toward global food security (Godfray et al. 2010; Walter et al. 2017; Mujeeb-Kazi et al. 2019). There is also a potential role for large-scale agricultural investments in poor countries and that are open to debate. No doubt, fair returns on investment are due, the rise of intellectual property rights raises concerns over the investments of the private sector, particularly for poor countries. Although the external investments in agriculture of developing countries may transform and bring on one side major benefits to crop production and processing, such investments may also be associated with "poverty traps" (Godfray et al. 2010).

Crops Adaptation to Limited Agricultural Inputs, Soil Nutrients, and Water Management

Food production is carried out on almost 38% of earth's surface and having evident impacts on worldwide ecosystems. Still, food sufficiency can be satisfied by improvements in agriculture that is ecologically sustainable (Foley et al. 2011; Kitano et al. 2012). Climatic changes will modify temperature and soil moisture and increase CO_2 levels; therefore, agriculture is particularly vulnerable to climate change effects. Avoiding global hunger will require plant adaptation to the extreme conditions and land management to increase resilience of our agricultural systems (Borlaug 2002; Ogbonnaya et al. 2013). Best land management practices including judicious use of nutrients and multiple crops grown in rotation are a must to disrupt the life cycle of pests (Hawkesford et al. 2013; Borrill et al. 2019). Multiple cropping is an adjustment strategy to deal with rainfall, and it allows effective use of soil surface by reducing nutrient losses and erosion. The main objective of soil nutrient management is to enhance the yield and quality of crops and not compromising on environmental aspects (Agus et al. 2016; Walter et al. 2017).

Balance fertilizer applications are essential to increase crop yield as well as resilience to extreme events. Astonishingly, nitrogen production for agriculture accounts for 1.2% of global energy, and about 70% of freshwater supplies are used by agriculture (Foley et al. 2011; Kitano et al. 2012). The excessive use of chemicals is detrimental to crops, soil, and environment, and the ill impacts can be reduced if fertilizers are used in balance and in combination with organic matter to meet the crop needs (Misra 2014; Agus et al. 2016). Soil microbial communities carry out the bulk of decomposition and nutrient recycling activities. Further, changes in precipitation and temperature will modify soil microbial communities and thus the overall ecological niches. Also, plant endophytes (bacteria and fungi) have the potential to increase access of soil nutrients to plants and allow host plants to thrive on nutrient deficient soils, thus having a tremendous role in reducing the negative impacts of agriculture on environment (Ikram et al. 2018).

Similarly, freshwater supply is likely to be one of the main limiting factors for future agriculture; therefore, water efficient crops as well as investment in relevant infrastructure are required (Ogbonnaya et al. 2013; Misra 2014). Nonetheless, excessive amounts of water are also counterproductive and cause poor aeration, inhibiting plant growth. Exclusive of proper management, irrigated agriculture can be devastating to the environment and jeopardize agricultural sustainability. Breeding and selection for higher yield in stress-free conditions have indirectly improved yield in many water-limiting circumstances (Coakley et al. 1999; Godfray et al. 2010; Smith and Gregory 2013). Foremost pathways for enhancing water use efficiency in irrigated agriculture are to increase the output per unit of water. Moreover sprinkler irrigation is extremely useful and has shown promise in increasing the water use efficiency of crops (Ainsworth and Long 2005; Hawkesford et al. 2013; Walter et al. 2017). Yield potential of crops in water stress environments could be achieved by improving agronomy and plant physiology. The recent developments of traits affecting yield under drought have provided candidate genes to understand water use efficiency in much detail, thereby allowing to improve the quality and diversity of crops that are better adaptable to future human needs (Mujeeb-Kazi et al. 2013; Agus et al. 2016; Rasheed et al. 2017). Therefore, large-scale adaptation of crop breeding is essential to ensure food security. Plant breeders have pyramid traits sustaining yield under water-deficient conditions into future genotypes without yield penalties. This strategy will result in smart and better-adapted cultivars with high yield potential and stability under future climatic conditions (Borlaug 2002; Cattivelli et al. 2008; Hawkesford et al. 2013).

Improving Agricultural Resilience by Increasing Crop Productivity

There is a wide range of variation in crop productivity, even across regions with similar agro-climates. To some extent, obtaining higher yields depends on the capacity of farmers to utilize the available resources (Godfray et al. 2010; Tariq et al. 2018). However, in comparing yields, it is important to also consider cropping systems, e.g., the highest wheat yields of over 15 t/ha are recorded for winter wheat (compared to the average of 3 t/ha) with a long growing season. In such cases, maximizing yield is not their sole objective; rather profitability is a more important criteria (Ainsworth and Long 2005; Hawkesford et al. 2013). Substantially more food could be produced with current crops if yield gaps are minimized. Similarly, trait stability, particularly yield and quality attributes, is essential that must be consistent across a range of environments (Masood et al. 2016; Rasheed et al. 2018; Borrill et al. 2019). Low yields may also occur due to technological constraints, for example, farmers may not have access to varieties or the technical skills required to maximize yields. Similarly, high costs to low returns ratio from increased production make it economically sub-optimal to raise production (Cattivelli et al. 2008; Hawkesford et al. 2013).

The tremendous success of the Green Revolution is attributed to the breeding efforts that resulted in the development of F1 maize hybrids and semi-dwarf varieties of wheat and rice with fungal resistance. These varieties were able to withstand more irrigation and fertilizer inputs without being vulnerable to lodging or disease epidemics (Borlaug 2002; Godfray et al. 2010; Mujeeb-Kazi et al. 2017). Augmented yield alone is although a major goal of food security, the importance of water and nutrient application, tolerance to stresses must be recognized. Indeed, ensuring sustainable food security is a multi-faceted challenge, involving much more than just increasing food production; it is also about protecting yield potential as well as increasing resource use efficiency (Hawkesford et al. 2013; Ali et al. 2016; Ikram et al. 2018).

The key to increased productivity is the ability of plants to harvest sunlight energy that regulates the ultimate yield (Hawkesford et al. 2013). The most productive crops like sugarcane convert solar energy into biomass with an efficiency of ~2% when grown in optimum conditions. Thus accelerating the rate of photosynthesis is the simplest way forward to increase yields (Ainsworth and Long 2005). Wheat converts 4.6% of the intercepted radiation into photosynthate where further improvement is at least theoretically possible (Zhu et al. 2010). Further, the CO_2-fixing enzyme Rubisco from different species has a good deal of variation in kinetic properties, and exploiting this pathway may deliver higher photosynthetic rates and in higher yields. Although theoretical yield limits for major crops vary greatly, there is clearly considerable scope for increasing production limits, and new models can predict more accurately these complex interactions (Godfray et al. 2010; Hawkesford et al. 2013; Agus et al. 2016).

Changing Lifestyles and Food Demand Patterns

The recent tendencies of healthy life have considerably modified eating behaviors and food preferences. In addition rural migration toward cities for jobs and the "so-called" better lifestyles is shaping urban landscaping (hard infrastructure) and is associated with extension of the urban boundaries (Foley et al. 2011; FAO 2018). In addition to pressures on food web and sustainable ecosystem services, the changing standard of lifestyle and priorities is deeply rooted with the recent shifts in global climatic changes. Besides drastic reduction in net primary productivity, these big urban centers influence emissions of GHG from the transport and other building facilities (Creutzig et al. 2016; Ali and Abdullah 2017). This trend is threatening the socioeconomic stability of regions, especially in mega cities for transportation, social services, and residential settlements. To mitigate the impacts of urbanization on GHG and climate change, urban designing must integrate walking and bicycle lanes and discourage private motorized transport (Ainsworth and Long 2005; Creutzig et al. 2016; Walter et al. 2017).

The conversion efficiency of plant matter into animal is ~10%; thus, it is believed that more vegetarian people could be supported from the same arable land than if they were eating meat. Such dietary shifts alone could reduce emissions of anthropogenic GHG by more than 70% (Godfray et al. 2010; Creutzig et al. 2016). Thus eating behavior alone could reshape urban environment and is likely be a necessary component of transition toward a low-carbon society (Ali and Abdullah 2017). Additionally, consumers in the developed world are purchasing foods of the highest cosmetic standards and litigation on edible products safety; food fit for consumption is thrown away (Smith and Gregory 2013). It may be perceived that hunger is more likely a problem of income distribution rather than that of food shortages. While the hungry cannot afford to buy food, the rich have excessive food intake and suffer from obesity. Thus the global efforts to increase plant productivity may not address this problem (Hazell and Wood 2007). Many solutions of food shortages to climate change mitigation are aligned to changing habits, norms, and behavior, having immense potential for reducing GHG emissions and climate change effects (Godfray et al. 2010; Hawkesford et al. 2013; Walter et al. 2017).

Application of the Untapped Genetic Variability and Accelerated Domestication

Modern agriculture is founded on the cultivation of only a few highly productive crop species that were domesticated from the wild (Mujeeb-Kazi et al. 1989; Tanksley and McCouch 1997; Tariq et al. 2018). Further, in almost all crop species including wheat, new varieties are virtually derived from crosses among genetically related modern varieties – excluding the ancestral species (Ali et al. 2016; Mujeeb-Kazi et al. 2019). Evidences suggest genetic diversity in all crop species has drastically declined during polyploid formation and domestication followed by intensive selection. This loss of useful genetic diversity has inspired maintenance of plant genetic resources in gene banks. International collections and gene banks provide precious repositories for alternative rare alleles of loci that have been exhaustively selected during domestication and modern breeding (Godfray et al. 2010; McCouch et al. 2013; FAO 2018). Virtually all crops including wheat need to be more tolerant to mitigate the impacts of future climate change hazards. Studies have suggested that each degree rise in temperature is associated with a 6% decrease in wheat production (Asseng et al. 2017; Borrill et al. 2019). Hence, it is appealing to increase the genetic base and breed stress-tolerant wheat genotypes deemed to address the

United Nations Millennium sustainability goals (Masood et al. 2016; Rasheed et al. 2017; Mujeeb-Kazi et al. 2019).

It is also documented that favorable introgressions from wild relatives could significantly improve grain yield, adaptability, end-use quality, and disease resistance of wheat as well as other important crops (Tanksley and McCouch 1997; Rasheed et al. 2018). Alien genes have long been recognized as excellent sources of allelic diversity against biotic and abiotic stresses, and high rates of alien introgressions in wheat cultivars indicate the global impact of wild relatives in farmer's fields (Ali et al. 2016). Successful gene transfers in wheat have been achieved from members of diverse genera including (but not limited to) *Triticum*, *Secale, Aegilops*, *Hordeum*, *Thinopyrum*, *Lophopyrum*, *Agropyrum*, *Psathyrostachys*, *Elymus*, *Leymus*, *Dasypyrum*, etc. (see Mujeeb-Kazi and Hettel 1995, Mujeeb-Kazi et al. 2017 for details). In addition to alien gene or chromosomal segments, introduction from related *Triticeae* species, the natural route of wheat polyploidization was exploited at CIMMYT, and synthetic hexaploid wheats (SHW's) were developed. D-genome synthetic wheats are prominent sources of unique and rare alleles for improving adaptation and yield potential in bread wheat. These SHW lines are distributed internationally for the introgression of suitable traits and represent one of the most effective breeding programs on the restoration of lost genetic diversity in wheat (Mujeeb-Kazi and Hettel 1995; Ali et al. 2016). In addition to bread making or end-use quality traits, SWHs undergo homologous pairing across all three genomes (ABD) to increase the genetic base of wheat (Mujeeb-Kazi et al. 1989; Ogbonnaya et al. 2013; Masood et al. 2016; Tariq et al. 2018).

Unlike when the first grain crops were domesticated 10,000 years ago, plant breeders today have an array of modern tools in their pursuit for crop improvement. The recent progress in high-throughput genotyping and phenotyping platforms and their affordability is instrumental to identification of genes in the quest of food security (Tanksley and McCouch 1997; Abberton et al. 2016; Mujeeb-Kazi et al. 2019). The development of high-throughput phenotyping enables appraisal of larger populations, thereby increasing selection accuracy. A key limiting factor in plant breeding was the long generation cycles of crops that has been reduced by "speed breeding," and this will significantly accelerate trait screening and discovery of favorable alleles (Rasheed et al. 2017, 2018).

Domestication has indeed resulted in the extensive appraisal of only a subset of useful genes available in ancestral species among crop cultivars (Ewert et al. 2005; Borrill et al. 2019). With the availability of the todays' inventions and remarkable biological developments, repeating the process of domestication through neo-domestication of wild species could be an alternative way to swiftly breed cultivars (Godfray et al. 2010; Bevan et al. 2017). Other routes to domestication of new species are possible via editing of known domestication genes with CRISPR–Cas9. The CRISPR system has major implications to produce climate-resilient crops (Abberton et al. 2016; Rasheed et al. 2017; Mujeeb-Kazi et al. 2019). Recently unbalanced expression and inheritance of the three wheat homoeologous genomes have been described; deciphering the mechanism may lead to breed improved wheat varieties (see Ramírez-González et al. 2018).

Persistent progresses in wheat and other important crops productivity will be ascertained by integrated approaches of combining genetic improvements supported by agronomy (McCouch et al. 2013; Hickey et al. 2019). Moreover, advances and cost-effectiveness of DNA sequencing and genomic prediction tools have shown incredible potential in plant breeding and improvement. Availability of reference genomes of wheat and other *Triticeae* species will allow insights into origin, evolution, and domestication of these species. Hence, it is likely that varieties of crop species with relevant phenotypic traits may be developed that will enable us to further capitalize on crop productivity and adaptation and address new challenges (King et al. 1997; Valizadeh et al. 2014; IWGSC 2018; Hickey et al. 2019).

4 Conclusions

Climate changes have started influencing agricultural production at the regional as well as global level. Preparing agricultural systems for climate change-related impacts would require more resilient agricultural system and investments in relevant infrastructure. Food security is already threatened, and yields of all major cereals have stagnated with wheat showing the lowest rate of increase. Increases in production will have an important part to play in food security; it will be constrained by the finite resources like land and freshwater availability. Noteworthy is to consider that there is no simple solution to sustainably feed ten billion people while aiming diminishing emission of GHGs at the same time. Sustainable food production is not simply to maximizing productivity but also is well connected to optimizing productivity across ecological landscape.

Addressing this challenge will require radical changes in the way food is produced, harvested, handled, and distributed. Unless urgent adaptive measures such as changes in crop growing patterns, eating habits, lifestyle, and innovative technologies are adopted, increases in global food production are likely to be non-sustainable and even counterproductive. Achieving increased crop productivity and adaptation are likely to be the key components of sustainable agriculture and food security. A multifaceted and well-integrated global strategy is demanded from producers to policy makers. The application of the recently evolved high-throughput platforms and genome editing as well as de novo domestication tools could enable plant breeders to identify and use the new genetic variations that may ensure future food security in ways that are environmentally and socially sustainable. We do need to be cognizant that to effectively combat the constraints that influence food productivity. The need is to carefully gauge the coverage on this treatise by the distinguished contributors, harness their conclusions in a well-integrated manner, and prioritize the best applicable modus operandi with an admixture blend of technologies that influences the multiple needs of a productive crop across diverse environments by recognizing the numerous micro- and macro-needs by establishing working teams that operate in unison, work in tandem, and make impacts that will deliver output gains in a timely manner that in recent years have fallen drastically below expectation targets.

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