REVIEW ARTICLE

Climate change and resilient dryland systems: experiences of ICRISAT in Asia and Africa

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The article reviews and summarizes the climate change mitigation and adaptation work undertaken by ICRISAT. The effects of climate change are already being experienced in several parts of the world. Even though the effects of climate change will be felt over all kinds of agricultural production systems, they will be more pronounced in dryland areas where agriculture is totally dependent on rainfall. Simulation output analyses reveal that crop yield will decrease due to climate change and variability in drylands, but this can be mitigated in large parts by the application of existing knowledge on crop, soil and water management, and by re-targeting and re-deployment of the existing germplasms of the crops in the medium term (2010–2050). Integrated watershed management is an important tool to mitigate the climate change effects through soil conservation, improved water availability and other secondary benefits. Similarly, conservation agriculture practices under the integrated genetic and natural resources management strategy can help minimize the adverse effects of climate change on dryland agricultural productivity.

Keywords: Climate change, drylands, resilience, watershed management.

CLIMATE change is real and its effects are already being experienced in several parts of the world, as is evident from the increase in average maximum temperature all over the world. A recent study by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) found that maize and sorghum yields in Nalgonda District, Andhra Pradesh and Parbhani District, Maharashtra have declined during the last few years due to rise in temperatures[1]. The length of the growing period (LGP; defined as the number of days in any given period when there is sufficient water stored in the soil profile to support plant growth) has been reduced by 15 days in Nalgonda District, leading to moisture stress to the crops and ultimately reduction in yield[2]. Also, the analysis of long-term climatic data of Nalgonda District revealed that the climate here has turned arid from its semi-arid status over a period of time (Figure 1). The farmers faced losses in three out of the last five years in Nalgonda District. Cooper *et al.*[3] have predicted that in the Makindu area of Kenya, average LGP might decrease from 5% to 10% by 2050, when temperatures may increase between 1°C and 2°C. The other glaring example of climate change may be seen in the south Gujarat region of India. Navsari in south Gujarat receives average annual rainfall of 1650 mm, but during 2011 it received merely 350 mm rainfall by the end of first fortnight of July as against an average of 600 mm rainfall during this period (A. Nihlani, pers. commun., 2011). This region is experiencing abnormal temperature regimes over the past few years, more particularly during the winter season coinciding with the flowering and fruit-setting in mango, thus affecting the mango production in the region, which is famous for its delicious 'hapus' and 'kesar' cultivars of mango. According to the experts, this is the result of climate change[4]. At the ICRISAT farm in Patancheru, as against average annual rainfall of 800 mm, the total rainfall received during 2010 was about 1206 mm, whereas during 2011 total rainfall received was only 535 mm. Similarly, many other examples of climate change effects on agriculture can be seen all over the world. Some experts relate the recent famine in eastern Africa covering Somalia, Kenya and Ethiopia to climate change[5]. The insufficient rainfall has led to crop failures for a consecutive third season in these countries, leading to famine and large-scale migration of people to neighbouring countries. Evidence of change in climate, in particular with regard to temperature, is also emerging in southern and West Africa[6].

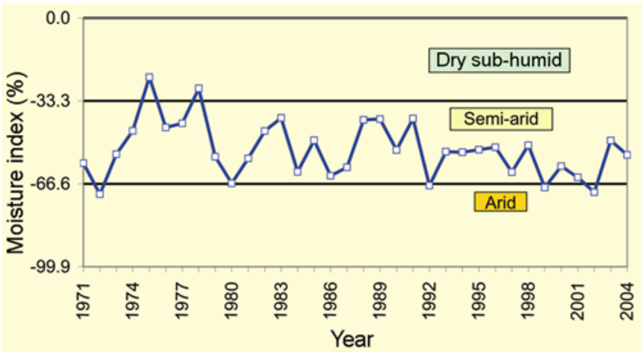

Figure 1. An illustration of climate change in Nalgonda District, Andhra Pradesh, India (source: Rao and Wani[2]).

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Table 1. IPCC projected climate change for India

		Increase in temperature (°C)		Change in rainfall (%)	
Year	Season	Lowest	Highest	Lowest	Highest
2020s	Rabi	1.08	1.54	–1.95	4.36
	Kharif	0.87	1.12	1.81	5.10
2050s	Rabi	2.54	3.18	–9.22	3.82
	Kharif	1.81	2.37	7.18	10.52
2080s	Rabi	4.14	6.31	–24.83	–4.50
	Kharif	2.91	4.62	10.10	15.18

Source: Lal *et al.*[29].

In India, the changes in temperature and rainfall are predicted to vary from 0.87°C to 6.31°C and –24.83% to +15.18% respectively, by 2080s (Table 1).

Even though the exact nature and extent of climate change remain uncertain, it is widely believed that it is the poor who will be hit hard due to climate change. This is especially true for those communities who live in the dryland areas and who rely largely or totally on dryland agriculture for their livelihoods. They are also the most vulnerable to the existing rainfall variability and climatic shocks. This necessitates farmers and farming practices in dryland areas to adapt to the predicted climate change.

Rainfed agriculture is pivotal to the economy and food security of India. About 60% of the total cultivated area is rainfed, supporting 40% of India's food demand of 1.2 billion people. Moreover, rainfed agriculture also supports 60% of livestock population. Likewise, coarse cereals (87.5%), pulses (87.5%), oilseeds (77%), rice (48%) and cotton (65.7%) are predominantly grown in rainfed areas[7]. Thus, drylands make significant contribution to the food and nutritional security of the country. In future, the significance of drylands in national food security will further increase due to growing population pressure and competition for land for non-agricultural uses. Drylands are being projected as the cradle of the next green revolution in India. In the sub-Saharan Africa (SSA), nearly 90% of staple food and feed production comes from, and will continue to come from, rainfed agriculture[8]. But crop production in the drylands in both Asia and Africa is presently plagued with numerous problems like insufficient and erratic rainfall, land degradation and low soil fertility, poor supply of agri-inputs, weak technology dissemination system, low investment capacity of farmers, etc. Further, it is strongly believed that climate change will further exacerbate the problems of dryland agriculture. The vulnerability of drylands to climate change and variability has been exposed by the devastating effects of recent flooding and prolonged droughts during the 20th century and the first decade of the 21st century in different parts of Asia and Africa. This highlights the need to develop climate change mitigation and adaptation strategies for the dryland regions.

Considering the above, ICRISAT has been continuously engaged over the past several years to study the effects of climate change on dryland agriculture and to develop mitigation and adaptation strategies to minimize the adverse effects of climate change on the livelihoods of poor farmers of these areas.

Effects of climate change on crop growth and development

ICRISAT studied the effects of climate change on crop growth, development and productivity using crop models (DSSAT and APSIM) under different climate change scenarios. The simulation outputs indicate that climate change in the dryland regions characterized by existing high temperature, will reduce crop productivity by reducing LGP and crop duration (faster crop development, thereby using less natural resources; Table 2), radiation interception, harvest index, biomass accumulation and increasing water stress in plants as a result of increased evapotranspiration demand due to high temperature[9]. Unless the change in rainfall is substantial, a slight increase or decrease will only have a marginal effect on the crop yields (Table 3). However, increase in CO_2 concentration will have beneficial effects on crops, especially the legumes (C3 species) by increasing the photosynthesis rate. Based on simulation (DSSAT) results, Wani *et al.*[10] reported that a temperature increase of 3.3°C, which is expected to take place by the end of this century, will on an average reduce the crop yield under good management by 27% at Parbhani (Figure 2). At the same time, the effect of 11% increase in rainfall will be marginal. They also simulated climate change effects on groundnut yield at Anantapur, Andhra Pradesh using DSSAT and reported that despite a variable response across seasons to increase in temperature, an average yield reduction of groundnut crop will be about 38% and an increase in rainfall will benefit the crop marginally (Figure 3). Considering the impacts of increase in temperature and CO_2 concentration, the simulated yield reduction of the rainfed crops across a few select

Table 2. Simulated impact of temperature increase on the mean rate of development and yield of sorghum (var. CSV 15) at Aurangabad, Maharashtra based on historical daily climatic data (1955–1983)

Climate scenario	Mean seasonal temperature	Time to maturity	Percentage of reduction from current	Crop yield (kg/ha)	Percentage of reduction from current
Current	27.6	105	–	2941	–
Current + 1°C	28.6	100	4.8	2628	10.6
Current + 3°C	30.6	91	13.3	1913	34.9
Current + 5°C	32.6	85	19.0	1285	56.3

Source: Adapted from Cooper *et al.*[3].

Table 3. Simulated effect of a factorial combination of temperature and rainfall changes on mean sorghum yield (kg/ha) at Parbhani, Maharashtra

Mean rainfall change from current level	Current yield	Mean temperature increase above current level (°C)		
		1	3	5
+10%	–	3972	3318	2733
0	4221	3915	3252	2673
–10%	–	3788	3118	2547

Source: Adapted from Cooper *et al.*[3].

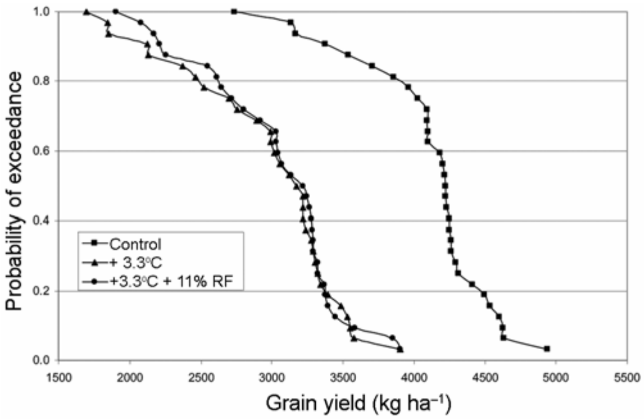

Figure 2. Probability distribution of the kharif sorghum yield under climate change at Parbhani, Maharashtra (source: Wani *et al.*[10]).

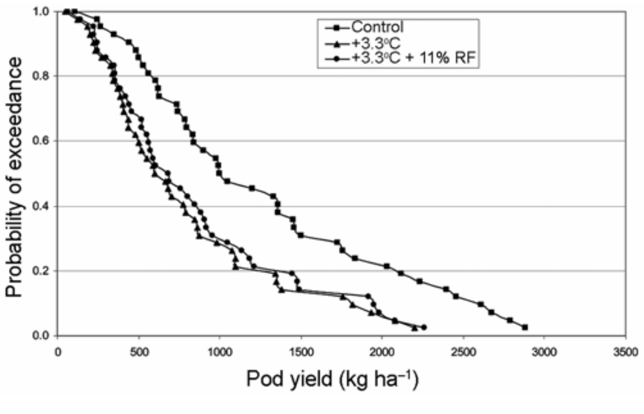

Figure 3. Probability distribution of groundnut yield under climate change at Anantapur, Andhra Pradesh (source: Wani *et al.*[10]).

locations in India range from 22% to 50% for kharif sorghum, 33% to 51% for pearl millet, 23% to 29% for groundnut, 8% to 11% for pigeon pea and 7% for chickpea at Nandyal, Andhra Pradesh and Akola, Maharashtra sites[10]. They also reported that because of the current low temperatures during the post-rainy season at Guna, Madhya Pradesh, climate change is expected to increase the chickpea yield by about 9%. However, it is important to note that the climate change impact at the current low levels of management of crops would be marginal. This means that as we improve the management of crops to get higher yields to achieve food security, the impact of climate change will become more and more significant.

Thus, it is clear that climate change is going to affect crop productivity and consequently food security. Besides the impact of climate change on crop growth and development, LGP, water availability, etc., there is a strong possibility of further soil degradation due to loss of soil organic matter as influenced by increased temperature regimes. This may lead to greater yield reduction than what is being predicted currently. Adaptation to climate change is therefore no longer a secondary and long-term response option, but it is now prevalent and imperative, and for those communities already vulnerable to the impacts of present day climatic hazards, an urgent imperative[11].

There is need to work on a holistic approach so as to minimize the impact of climate change on crop productivity, soil health and water availability.

Mitigation and adaptation strategies for resilience against climate change-related variabilities

In the changing climate scenario along with the need to feed the burgeoning population and a highly degraded resource base (land and water), the current practice of crop production in drylands is no longer an option. To ensure food security for a vast population on a sustainable basis, suitable long-term coping strategies need to be developed for dryland agriculture in the near future. Farmers in particular and the society in general have always attempted to adopt to climatic stresses by resorting to practices like mixed cropping, changing varieties and planting times and by diversifying their sources of income. In future, such adaptation strategies would need to be considered along with new innovations to cope with climate change.

'Given the constraints of both current climate-induced production risk and the predicted change in nature of that risk in the future, it is now widely accepted that a two-pronged approach, sometimes referred to as the "twin pillars" of adaptation to climate change, is needed'[12]. Such an approach recognizes short- and medium-term adaptation strategies. According to Cooper and Coe[12] in the shorter term, since rainfed farmers are already vulnerable to current weather variability and associated shocks, it is essential to help them build their livelihood resilience through coping better with current weather-induced risk as a pre-requisite to adapting to future climate change. Even though it was stated in the context of Africa, it is equally applicable to India also, where the adoption of improved production technology remains low, particularly in dryland agriculture. Secondly, however, it is accepted that in the medium to longer term, farmers need to adapt their farming practices to a new set of weather-induced risks and opportunities.

Growing resilient crops and adapted/improved cultivars

For dryland agriculture to successfully adopt to climate changes and variability, there is need to identify climate-resilient crops and cultivars for different regions. Through simulation studies using APSIM, Dimes *et al*.[9] found that in the semi-arid regions of Zimbabwe, pigeon pea and sorghum were more resilient to the climate change shocks compared to maize and groundnut, mainly due to improved harvest index and water-use efficiency respectively. Under the current unimodal rainfall conditions (and latitude) in semi-arid tropics of Zimbabwe, pigeon pea has a very long duration and grain-filling takes place under declining rainfall and increasing water stress. But higher temperatures under climate change will shorten the crop duration of pigeon pea so that it matures when the wet season is still active. Sorghum, on the other hand, experiences greater shortening of the vegetative phase (18%) relative to the grain-filling phase (14%), resulting in increased harvest index[9]. One easy and readily available adaptation strategy to climate change, therefore, is to retarget the current long-duration germplasms to regions which are likely to experience increase in temperature, because the increase in temperature will reduce crop duration due to hastening of crop development[9]. Early maturity due to hastening of crop development will lead to yield losses because of the reduced use of solar radiation, low biomass accumulation and low grain-filling, but retargeting the current long-duration germplasms will help minimize such yield losses. The simulation studies for groundnut done at ICRISAT showed that in the warmer regions of India (northern, western and some parts of southern India), where in spite of increase in CO_2 and rainfall, the detrimental effects of increase in temperature are large, there is a need for cultivars that are temperature-tolerant, and fit well according to LGP (ICRISAT, unpublished results). Whereas in the relatively cooler regions where the beneficial effects of increase in CO_2 and rainfall are greater in terms of biomass production, there is a need for cultivars having even greater harvest index to take advantage of climate change. For climate change adaptation, ICRISAT already has on hand climate-ready cultivars that are adapted to heat stress and high soil temperature. Knowledge and understanding of photoperiod sensitivity, information on the genetic variation for transpiration efficiency, short-duration varieties that escape the terminal drought and high-yielding, disease-resistant varieties will help dryland agriculture adopt to climate change. ICRISAT has been continuously working to identify short duration, heat stress and drought-tolerant lines of its mandate crops of chickpea, groundnut, pigeon pea, pearl millet and sorghum for use in crop improvement with impressive success[13–16]. In chickpea, genotypes ICCV 96029 (super early 75–80 days), ICCV 2 (extra early 85–90 days) and KAK 2 (early 90–95 days; Figure 4) have been identified for cultivation in semi-arid regions with short growing period. ICCV 92944 has been identified as one of the best available heat-tolerant sources, but as this genotype is early, it is also thought to escape the heat stress[15]. Similarly, genotype ICC 14778 is found to be stable and heat-tolerant besides being the top drought-tolerant accession[14]. The ICRISAT–NARS-developed improved groundnut variety ICGV 91114 is more drought-tolerant, having larger seeds, uniform maturity, disease tolerance and better palatability of its straw for livestock, and produced 23% higher yield over the popular variety in Anantapur District[17]. Hybrid pigeon pea variety ICPH 2671 produced 48% more yield over its popular counterpart, Maruti.

ICRISAT in collaboration with private and public sector seed companies, has commercialized hybrid pigeon pea variety ICPH 2671 for its wider cultivation by the farmers. Another notable work at ICRISAT in the field of crop improvement is the pearl millet hybrid 'HHB 67 Improved', which is India's first public marker-assisted cultivar, resistant to downy mildew, which also helps save US$ 8 million. The improvement of HHB 67 remains the greatest landmark in developing early-maturing and disease-resistant pearl millet cultivars. Further, ICRISAT is engaged in crop improvement work for

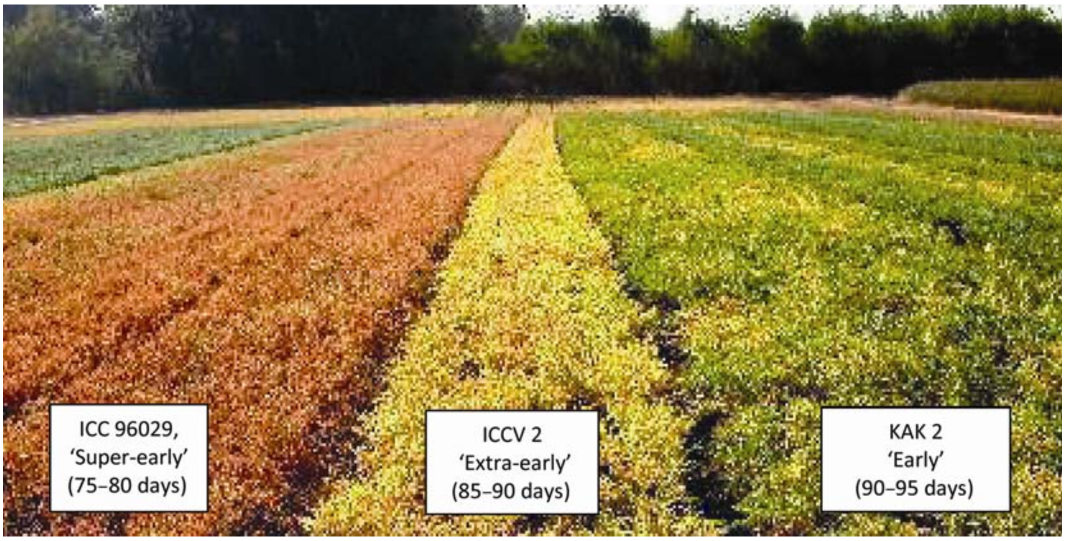

Figure 4. Short-duration chickpea cultivars that can withstand high temperatures. Courtesy: The ICRISAT farm in RP3 field.

developing cultivars resistant to abiotic and biotic stresses, keeping in view the threats to dryland agriculture due to current and future climate change.

Responsive agronomic practices to cope with climate change and variability

Under the climate change scenarios, many of the conventional cultivation practices and strategies may no longer be relevant. Therefore, there is a need to recommend technologies to the farmers which respond well to climate change effects and give greater resilience against such shocks. Growing early maturing, photo-insensitive, high-tillering cultivars with optimal root traits and tolerant to abiotic and biotic stresses; mulching with crop residues; planting more seedling per hill for heat stress; better soil nutrient and water management, moisture conservation for late onset of monsoon and life-saving irrigation with stored rainwater for mid-season drought to harvest positive effects of the increased CO_2 level are a few strategies recommended by ICRISAT to cope with the effects of climate change and variability on dryland agriculture[11]. As the dryland soils are critically low in soil organic matter, there should be more emphasis on improving soil organic matter status, which is an important driving force for biological activities in the soil, the source of food for soil flora and fauna. Besides, enriching soils with organic matter can minimize the climate change-induced water stress effects on crops by improving water-holding capacity of the soils and consequently enhancing LGP. Therefore, management practices that augment soil organic matter and maintain it at a threshold level are needed. Farm bunds could be productively used for growing nitrogen-fixing shrubs and trees to generate nitrogen-rich lopping. For example, growing *Glyricidia sepium* at a close spacing of 75 cm on farm bunds could provide 28–30 kg nitrogen per ha in addition to valuable organic matter. Also, large quantities of farm residues and other organic wastes could be converted into valuable source of plant nutrients and organic matter through vermicomposting[18].

Conservation agriculture, which basically consists of zero/minimum tillage, soil cover through crop residues or cover crops and suitable crop rotations is being promoted as another strategy for climate change mitigation and adaptation as well as sustainable crop production through soil and water conservation and other associated ecological benefits. In Zimbabwe, precision conservation agriculture has consistently increased average cereal yields by 50–200% in more than 40,000 farm households (with the yield increase varying with rainfall regime, soil type and fertility, and market access)[19]. At ICRISAT, we have observed encouraging results of conservation agriculture on crop productivity and soil quality along with considerable reduction in run-off, peak run-off rate and soil loss. Cooper *et al.*[3] evaluated the potential use of mulching with crop residues in mitigating the temperature-induced reduction in LGP. They simulated LGP at Makindu, Kenya under three scenarios: (i) current climate with no water conservation (blue line, Figure 5), (ii) current climate + 3°C with no water conservation (green line, Figure 5) and (iii) current climate + 3°C + mulching for water conservation (red line, Figure 5). The average LGP at Makindu under current climate and current soil management was 110 days, but it reduced to 101 days with a 3°C rise in temperature. However, the application of maize residue mulch under the climate change scenario raised the average LGP to 113 days, three days longer than under the current climate conditions. Thus mulching has a beneficial effect on moisture storage in the soil profile and hence on LGP not only under the current climate conditions, but it can also play a major role in helping to manage and ameliorate the impact of future climate change on LGP.

Crop diversification options by including crops, multipurpose tree species, medicinal and aromatic plants, etc. may help dryland agriculture adapt to climate change and variability. Crop intensification and diversification with high-value crops helped households achieve production of basic staples and surplus for modest incomes in model watersheds adopted by ICRISAT[20]. With technical support from the watershed consortium, the farming system was intensified from rice and rape seed to tending livestock (pig-raising) and growing horticultural crops (fruit trees like *Ziziphus*; vegetables like beans, peas and sweet potato) and groundnut[10]. Further, there is a need to identify and test different locally suitable crop diversification options for different agro-ecological regions. ICRISAT along with its consortium partners is engaged in identifying resilient crops and cropping systems through its watershed programme in different parts of the country. Our experience at ICRISAT shows that intercropping systems are more resilient to climatic shocks and drought than growing sole crops.

It is hypothesized that the adoption of available improved practices by farmers and retargeting adapted cultivars can help mitigate the climate change effects in the medium term (2010–2050)[3]. To support this hypothesis, Cooper *et al.*[3] performed simulation studies using DSSAT to know the effect of improved management and adapted cultivars under current climate and climate change scenarios on the productivity of groundnut and sorghum at Kasungu, Malawi and Aurangabad, Maharashtra, India respectively. A model framework and simulation outputs for sorghum done at Aurangabad, are as follows:

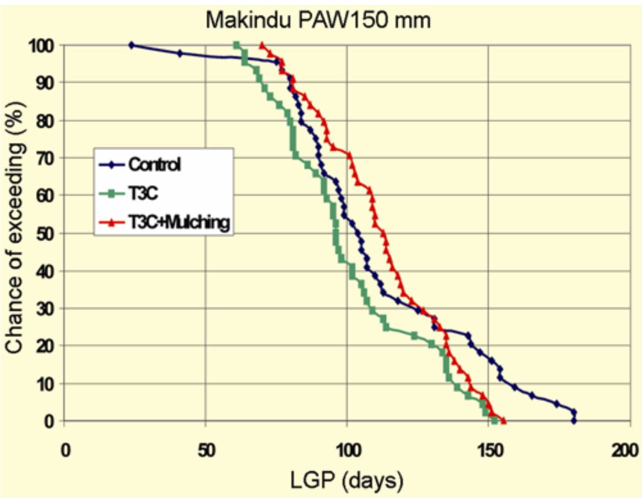

Figure 5. The effects of mulching on ameliorating the impact of climate change on LGP at Makindu, Kenya (source: Cooper *et al.*[3]).

Sorghum is a widely grown crop in the dryland areas of India, but currently yields remain low due to application of lower than recommended dose of nitrogen and phosphorus fertilizers besides many other reasons. Sorghum (var. CSV15) matures in about 105 days after emergence in Aurangabad. Based on the above, the following scenarios were simulated using DSSAT and long-term (1955–1983) daily climate data from Aurangabad.

- ‘Column 1: Sorghum (var. CSV15) planted between 1 June and 20 July with 18 kg N + 20 kg P ha^{-1} as DAP at sowing and 15 kg N ha^{-1} as urea at 40 days after sowing. This represents the current low-input farming.
- Column 2: Low-input agriculture as above, but under a climate change scenario of an increase in temperature of 3°C.
- Column 5: Improved practice under current climate comprised sowing CSV15 within the same planting window, but with the recommended application of fertilizer, namely 40 kg N + 40 kg P ha^{-1} as DAP at sowing and 40 kg N ha^{-1} as urea at 40 days after sowing.
- Column 3: Improved practice as above, under an increased temperature of +3°C.
- Column 4: Improved practice under climate change as above, but with an adapted longer-duration sorghum variety that matures in 119 days under current conditions at Aurangabad (such as Brandes, taken from the DSSAT sorghum database), but which matures in 103 days under the warmer climate change scenario simulated’ (Cooper *et al.*[3], reproduced with permission).

The results of these simulation studies are presented in Figure 6.

A temperature increase of +3°C had very little impact (145 kg/ha reduction) on the sorghum yield under low-input fertilizer use as nutrient limitation remained a major limiting factor. Adoption of improved fertilizer use

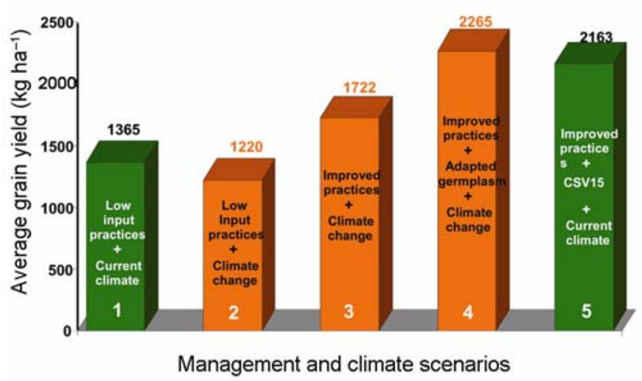

Figure 6. Simulated (DSSAT) sorghum yield (kg/ha) at Aurangabad, Maharashtra, 1955–1983 (source: Cooper *et al.*[3]).

(column 3) resulted in yield gain of 357 kg/ha even under climate change over what farmers are currently getting with low fertilizer use practices under current climatic conditions (column 1). Perhaps the most notable result in this case was that growing a longer-duration variety (Brandes), better suited for a warmer region (column 4), helped achieve 5% higher yields than what farmers could achieve by growing cultivar CSV 15 with improved practices under current climate (column 5). This illustrates the significance of retargeting the adapted long-duration cultivars in higher temperature environments due to climate change.

Similarly, simulation outputs for groundnut at Kasungu, Malawi indicated that even under the climate change scenarios, improved production practices [growing a shorter duration variety (121 days to maturity) planted early (mid November to 15 December) at a row spacing of 0.75 m] resulted in yields 28% above those being currently obtained under low-input systems [cultivar Chalimbana which matures in 150 days planted late (mid December to 15 January) at a row spacing of 1.2 m][3]. Again, under changing climatic conditions, growing an adapted cultivar (that matures in 138 days under the current conditions, but which matures in 119 days under the warmer climate change scenario simulated) better suited to a warmer region together with improved practices, resulted in 880 kg/ha higher yield than that currently obtained by the farmers under low input practices, and only 245 kg/ha lower than the yield that could be achieved with improved practices under the current climate.

Thus the outputs from the above simulation studies support the hypothesis that through the application of existing knowledge on crop, soil and water management innovations, and the redeployment and retargeting of the existing germplasm of its mandate crops, ICRISAT is in a good position to help farmers mitigate and adapt to the climate change effects in the medium term (2010–2050). However, Cooper *et al.*[3] stressed that this simulation test and those done for other locations hardly scratch the surface of the work that remains to be done, both in simulation work and the more pragmatic testing of our hypothesis in the field. There is need to enhance and expand the value of crop growth simulation work with the APSIM and DSSAT through undertaking an extensive field-based exercise that results in the proper phenological and physiological characterization of the sub-sets of our germplasm, so that we can fully exploit the genetic diversity we have at hand through the development of new and the re-deployment of existing cultivars, both in under simulated and field-condition research[3]. The above 'genetic-based' field research should be complemented by elaborate calibration of DSSAT and APSIM for a wide range of soil, water and crop management practices that we believe hold hope both in the present as well as for the future.

Watershed management: a growth engine for drylands

It has been predicted that most of the rainfall will now occur in the form of high-intensity short-duration rain events due to global climate change[21]. It is imperative to harvest the run-off water to protect the crops against moisture stress as well as to avoid floods in downstream areas. Therefore, integrated watershed management will play an important role in soil and water conservation, efficient use of rainwater, improved crop and livestock productivity and improved living standard of people at large, especially in dry and marginally fertile land areas.

A consortium model proposed by ICRISAT for community watershed management espouses the principles of collective action, convergence, cooperation and capacity building (4Cs) with technical backstopping by a consortium of institutions to address the issues of equity, efficiency, economics and environment (4Es)[10]. The new integrated community watershed model provides technological options for management of run-off water, *ex situ* water harvesting for lifesaving irrigation, *in situ* conservation of rainwater for improved soil moisture content, (Figure 7), groundwater recharging, developing grassed waterway systems, appropriate nutrient and soil management practices, and improved crop production technology and appropriate farming systems with income-generating micro-enterprises for improving livelihoods, while protecting the environment[22–24]. As water alone cannot improve the productivity of crops in the dryland areas, promotion of proper soil, crop, nutrient, and pest and disease management practices are essential to improve crop productivity and impart climate change resilience to dryland systems.

The ICRISAT experience on watershed management in India is one such example. As illustrated in the Adarsha watershed at Kothapally, the combined effects of enhanced crop tolerance to drought, integrated management of land and water resources and improved water productivity have reduced the vulnerability to climate shocks and also improved productivity (Figure 8). Integrated watershed management has contributed to improving the resilience of agricultural incomes despite the high incidence of drought during 2002. While drought-induced shocks reduced the average share of agricultural income (as percentage of the total household income) in a nearby non-project village from 44% to 12%, this share remained unchanged at about 36% in the Adarsha watershed project village of Kothapally[25]. Because of the diversification of sources of income by undertaking more off-farm activities, the farmers' resilience to external shocks has improved. Moreover, the watershed interventions have reduced the inherent risks in agriculture in the semi-arid zone posed by high rainfall variability and frequent dry spells, thereby strengthening the resilience to drought. The implementation of the watershed management

Figure 7. *Ex situ* (***a***, ***b***) and *in situ* (***c***) harvesting of rainwater for successful crop cultivation (***d***) in drylands.

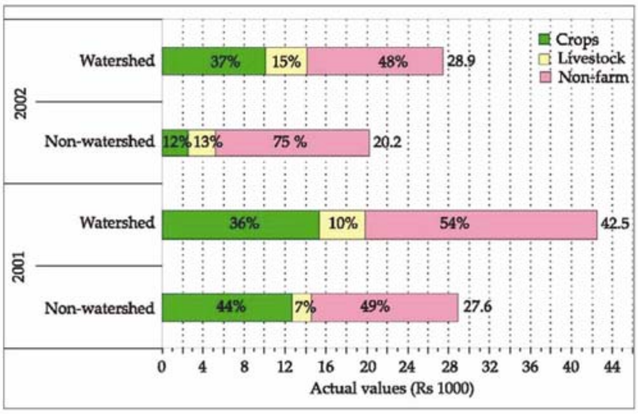

Figure 8. Effect of the watershed programme on income enhancement and resilience during normal (2001) and drought year (2002) at Adarsha watershed, Kothapally, Andhra Pradesh (source: ICRISAT).

programme by including *in situ* water harvesting and check dams has significantly changed the water resource availability in the watershed[26]. *In situ* water management practices improved the infiltration capacity and water-holding capacity of the soil, which resulted in higher crop-water availability. This was particularly important during the drier years, when yields were low. Rainwater harvesting through various *ex situ* structures has led to improved groundwater level, which *inter alia* led to improved water availability for supplementary irrigation of crops at several sites in India (for details, see refs 20 and 27). Increased water supply due to rainwater harvesting has also led to crop diversification with high-value crops like vegetables and *Bt* cotton in Kothapally village. Garg *et al.*[27] reported approximately 15–35% improvement in cotton yield due to various soil and water conservation interventions compared to no watershed intervention conditions.

Supplemental irrigation with harvested rainwater, one of the climate change adaptation strategies, can play an important role in reducing the risk of crop failures and in optimizing the productivity in the dryland areas.

Meta-analysis of 311 watershed case studies from different agro-ecological regions in India has revealed that watershed programmes have benefited farmers through enhanced irrigated areas by 33.5%, increased cropping intensity by 63%, reducing soil loss to 0.8 t ha^{-1} and run-off to 13%, and also improved groundwater availability[11]. Economically, the watershed programmes were beneficial and viable with a benefit–cost ratio of 1 : 2.14 and the internal rate of return of 22% (ref. 28). However, about 65% of the case studies showed below-average performance. Better performance of watersheds was realized in the rainfall regime of 700–1000 mm. There is need to develop new technologies for the areas falling in the rainfall regime of < 700 mm and > 1000 mm.

The effectiveness of improved watershed technologies was evident in reducing run-off volume, peak run-off rate and soil loss, and improving groundwater recharge. This was particularly significant in the Tad Fa, Thailand watershed, where interventions such as contour cultivation at the mid-slopes, field bunds planted with vetiver, fruit trees grown on steep slopes and relay cropping with rice bean reduced the seasonal run-off to less than half (194 mm) and soil loss to less than one-seventh (4.21 t ha^{-1}) compared to the conventional system (473 mm run-off and 31.2 t ha^{-1} soil loss). This holds true for peak run-off rate, where the reduction is approximately one-third due to watershed interventions. Thus it is evident that watershed-based interventions improve the resilience of agricultural systems against climate change and variability mainly through soil and water conservation, and improved water availability, leading to crop intensification and diversification.

As the drylands will become increasingly important to ensure the food security of the nations in the future, there is need to develop climate change mitigation and adaptation strategies along with restoring the natural resource base, which at present is critically degraded in the drylands. This is also important for the livelihood security of millions of the poor people who live in the arid and semi-arid regions. ICRISAT believes that in the medium term (2010–2050), it is well placed to help the dryland farmers cope with climate change effects by retargeting and redeploying its current long-duration varieties and soil, water and crop management techniques developed at the institute over the years. Integrated watershed management holds great promise to minimize the climate change effects on dryland agriculture through soil and water conservation, productivity enhancement, promotion of agroforestry, and income-generation activities through value-addition and other off-farm activities.

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