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A Review

Empowering Indian dryland agriculture in the face of climate change

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SUMMARY : It is well known that due to impending climate change, there will drastic effects to agricultural productivity. In order to increase food production with demand from an ever increasing population, integration of multiple sources to combat climate change will be necessary. Those effected the most by these changes will be underdeveloped and developing countries. In the face of global climate change, India, the second most populous country, must utilize all resources whether genetic, technical, or agronomic to ensure adequate food and water production for the projected increase in population. Preparing for global climate change is possible through collective efforts on a national and global level and will help alleviate any problems we encounter in the future.

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BACKGROUND AND OBJECTIVES

Rainfed agricultural production in India is several hundred million acres comprises nearly 75 per cent of the arable land in the country. Approximately half of that land consists of dryland agriculture. In the semi-arid and arid regions of this land there is unpredictable distribution of rainfall across this region. As climate change creates a severe impact on agriculture, there will be drastic changes in precipitation patterns resulting in reduced and uneven spatial distribution but over the landscape, harnessing the power of adapted crops will become ever more important as agronomic practices that might act to conserve or collect water become ever more difficult. One of several innovations to combat these problems is the potential to exploit the genetic variation as it is currently partitioned within the genomes of the dryland legume crops. The exploitation of this potential is India's best chance at empowering dryland agriculture to alleviate and adapt to the impending climate change.

Land, water and vegetation are the natural resources, which provide food, feed, fiber, and fuel needs. The sustainable management of natural resources is the key for sustenance for humans world-wide. Water is one of our most precious finite resources, however, it is becoming scarce due to its overexploitation satisfy the need of an increasing population size. Agriculture is a major consumer of water for food production globally and especially for India being the second populous nation. For meeting this food demand several thousand cubic kilometers of water will be required. Therefore, an integrated approached to water management is necessary. Watershed development is a very effective way to manage water and land resources effectively especially for drought prone semi-arid regions in rainfed and dryland agricultural production systems.

Due to the negative effect of climate change, improving the agricultural crops and practices has become more vital in order to have adequate food supply. The improvement could be either through modifying existing crops for the harsher conditions or by introducing other important crops which are tolerant to harsher conditions inherently. In order to enhance food security there should be another green revolution to improve orphan crops like millets. This will best utilize the dryland areas with higher yield and thus acts as a support to other major grain crops and also generate income for dryland farmers.

The global concerns for food without any contamination have also introduced the concept of organic methods of cultivation. Organic farming has to be understood as part of a sustainable farming system and a viable alternative to the more traditional approach to agriculture.

Preparing dryland legumes for climate change : Reflections on the potential for genetic improvement through transgressive segregation:

Not to belabor the points made already in the introduction of this paper, it bears repeating that throughout the evolutionary history of settled human communities it has been hypothesized that dramatic shifts in climatic patterns have served to form the basis for adaptation and migration. The east-west Mesopotamian diaspora is widely hypothesized to have been driven by drought conditions in the Middle East. Changes in rainfall and temperature patterns across North and South America contributed to the demise of the Olmec and Mayan civilizations. Indeed even the recession of what is known as the 'mini ice age' paved the way for the advent of settled agriculture in much of the Northern hemisphere. And today, regardless of the extensively debated mechanism of climate change, changing patterns of rainfall, fluctuating oceanic temperatures, and increasingly unpredictable weather patterns are clearly characterizing a modern day climate change that stands to change the way we think about our activities on the planet. This is particularly a problem in parts of the world where poverty and lack of economic development already limit the magnitude of people's livelihood. India in particular is one place that stands to benefit the most from buffering the effects of climate change. This is true particularly because as a single nation, India harbors nearly fifteen per cent of the world's population and her geography is characterized by dramatic environmental extremes. Nowhere is this more obvious than in the dryland areas of southern India. Many of the people there already live under conditions hallmarked by severe drought, calcareous saline soils, lack of proper infrastructure, poor market access, and malnutrition. This fact became quite pointed in my mind as we visited ICRISAT and began to get a feeling for many of the constraints facing subsistence farmers in the drylands.

Dryland agriculture in India:

While as a class we visited ICRISAT and the Kotapali village we learned a tremendous amount about the constraints of the subsistence farmers living in this rain-starved area. We learned that India's rainfed agricultural production consists of more than 100 million hecatares of land and comprises nearly 75 per cent of the arable land in the country. Approximately half of that land consists of dryland agriculture, which is characterized by less than 500mm of rainfall a year. Compounding that fact is the erratic and unpredictable distribution of rainfall across this region. Indeed some fields consistently receive less than 300mm of rainfall every year. This is further complicated by complex and unfortunate soil chemistry consisting of heavy clays that make the land difficult and nearly unmanageable (Fig. 1). These soils must be worked three or four times before producing a bed of topsoil sufficient to plant seeds. These soils are often quite alkaline in nature, and due in part to natural geographic processes can be quite saline and/or sodic.

Source: Photographed by Prasann Kumar on 11 Jan, 2012 at Kothapally village, Hyderabad

Fig. 1 : An example of the compact, heavy clods of soil that must be worked several times with a plow before becoming arable

Many efforts have been made to try and optimize both the use of water on the drylands as well as to collect more of the rainwater and groundwater resources. These efforts are a tremendous challenge given the available infrastructure, but will be essential in order for a village to have any kind of reservoir of water available when periods of drought come at critical times such as flowering or grain filling. One of the most impressive efforts we witnessed while in India were the efforts to capture and manage the watersheds in the village of Kothapally. The tremendous engineering effort that was required to build the wells that served to both delay the run off of rain water as well as collect it were truly impressive (Fig. 2). Despite these efforts, reduced and erratic rainfall combined with poor soil fertility still plague much of the region. Such conditions make it very difficult to grow high yielding modern cultivars of mainstream crops such as wheat, maize, or upland rice. Such crops characterized the green revolution which contributed substantially to India's becoming self-sufficient in the last decades of the 20th century. Unfortunately for the dryland areas, high input, good yielding dwarf varieties of modern cereals simply don't produce the same amount of food stuffs as they do under irrigated conditions. Even as efforts to recapture water become increasingly difficult, many growers in the drylands have turned to certain 'orphaned' crops that are more adapted to their agroecology.

Source: Photographed by Prasann Kumar on 11 Jan, 2012 at Kothapally village, Hyderabad

Fig. 2 : A well from the kotapali watershed management project

Such crops include sorghum, millet, pigeonpea, chickpea, and groundnut. Millets and sorghum fill the majority of their diet, but dryland legumes fill an important niche in providing both a potent source of nutritional protein but also serving to nitrify the largely infertile soil. These crops are particularly valuable because they are already adapted to growing under harsh water scarce environments. As climate change forces the rainfall patterns to not only decrease but to become increasingly erratic over the landscape, harnessing the power of adapted crops will become ever more important as agronomic practices that might act to conserve or collect water become ever more difficult.

The implications for population structure in legumes:

While sorghum and millet have distinct advantages when being grown under water scarcity, dryland legumes really compromise the target for improving the livelihoods of those who subsist off of such little rainfall. The dryland legumes, however, possess an 'ace in the hole' as it were that (if properly exploited) has the potential to fuel adaptation to the climate change. ICRISAT houses the international germplasm collection for groundnut,, chickpea, and pigeonpea. With more than 20,000 varieties of chickpea, 13,000 varieties of pigeonpea, and 15,000 varieties of groundnut the germplasm collection is the master repository of genetic variation for each of these crops collected from around the world. In order to make such an extensive collection of germplasm approachable, curators have developed what are called 'core collections' which are designed to capture the majority of the diversity of the entire genebank in a more manageable number of lines. When these core collections of dryland legumes are analyzed genetically (even with relatively few markers) a very interesting pattern emerges (Fig. 3). What we see emerging is a principle known as population structure. Formally population structure can be defined as differential relatedness between individuals. Functionally what that means is that different varieties are more similar to each other than they are to other varieties, so groups (or sub-populations) begin to emerge. The concept of sub-populations is really quite intuitive when you think about it in terms of humans.

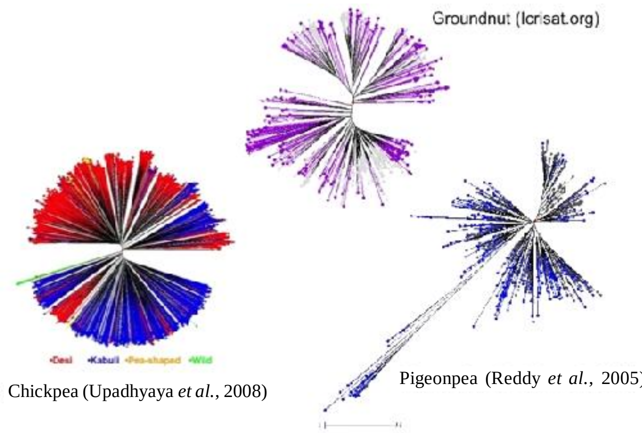


Fig. 3 : Population structure in dryland legumes

It is clear to even the most illiterate individual that someone of Korean decent is different from another person from Indian decent or American decent. It stands to reason that since our DNA is the basis of physical appearance, then the DNA between two Americans is likely more similar than it would be between an American and Korean. And there are alleles (gene variants) that then are common in some populations, but not in others. The same principle holds true for the germplasm collection. Varieties of chickpea that have been collected from Africa are very different than those collected from India or China. These sub-populations, however, sometimes run even much deeper than that. Using rice as a model, we gain some interesting insights. Rice (like dryland legumes) is deeply divided by population structure as well, but this structure goes back beyond modern cultivation of rice all the way to the origins of agriculture (Fig. 4).

One prevailing hypothesis is that rice in China was domesticated independently from rice in Southeast Asia. These two independent domestication events are now the origin of the two major clades of rice germplasm (Indica and Japonica). What's even more interesting is that over the millennia these two groups of rice have proliferated and in rare instances crossed and actually exchanged DNA. To the point now where in varieties that historically and culturally are indica (Thai Jasmine for example) harbor introgressions from the japonica subgroup at key loci (*i.e.* the gene controlling fragrance).

Even more interesting than the targeted introgression of

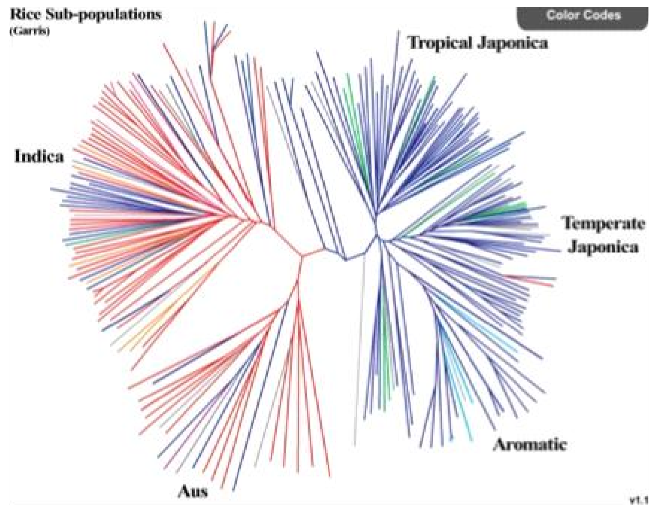


Fig. 4 : Genetic sub-population structure of domestic Asian rice (Garris *et al.*, 2003)

traits from one sub-population to another is the fact that alleles from an inferior subpopulation (for a given trait) can be used to enhance the performance of the superior subpopulation for the same trait. Such a phenomenon is known as transgressive variation, and it is the one of the most important principles for the genetic improvement of all crop plants worldwide. Again, rice serves as a convenient model since it too harbors deep population structure, but also has the advantage of being able to command the funding necessary for exploring that population structure. While working for the West African Rice Development Agency (WARDA) Monty Jones had an interesting idea to improve the performance of rice varieties grown in Cote d'Ivoire (Ivory Coast). He decided to cross an African variety of rice (well adapted to African climates, but poor yielding) with an Asian rice variety (high yielding but poorly adapted to African growing conditions). To his great surprise he ended up with progeny from that cross that significantly out yielded even the improved Asian cultivar. What Dr. Jones had presumed he had done was to introgress key genes controlling yield into the genetic background of African rice (rendering it both high yielding and adapted to the growing conditions). These new varieties (dubbed NERICA or New Rice for Africa) were distributed among many African rice growers and earned Dr. Jones the World Food Prize in 2004. Fascinatingly, later genetic analysis of the NERICA varieties revealed that they are indeed only 6 per cent African and 94 per cent Asian in their DNA. Meaning that a few targeted introgressions from the lower yielding parent (African rice in this case) substantially increased the productivity of the higher yielding parent (the improved Asian variety). This is a remarkable, but not isolated case of transgressive variation. A colleague of mine right here at Cornell demonstrated something similar when he showed that for Aluminum toxicity tolerance, targeted introgressions from Indica (the susceptible sub-population) had the ability to enhance the tolerance of even the most tolerant japonica varieties (Famoso *et al*., 2011). If such a widespread phenomenon like transgressive variation is so prevalent for yield and aluminum tolerance in rice, it bets the hypothesis that it might stand to reason for other traits in other crops. In order to adequately prepare for climate change transgressive variation would be needed to improve water use efficiency, yield, nodulation and symbiosis, nutrient use efficiency, and disease resistance in each of the dryland legumes for which we have adequate genetic resources.

In order to accomplish this however, several tools need to be developed in order to create and effective roadmap of the genetic variation of these important crops so that breeders know what crosses to make to leverage a comparative advantage. Most breeders make crosses only within sub-populations (not across) because to do otherwise would be to introduce all sorts of unadapted and undesirable alleles into the germplasm they are trying to improve. However if introgressions from other sub-populations can be done in a targeted way, it will empower breeders to take advantage of transgressive sergeants. The first tool that needs to be developed would be adequate SNP (single nucleotide polymorphism) genotyping platforms. In order to really see a complete picture of the genome for any of the dryland legumes, more than a few hundred markers need to be screened. This is really only practical with the advent of genotyping by next-generation DNA sequencing. But even once adequate marker resources are in place so we can fully survey the genome of each accession in the core collection, that information does relatively little good until we know what the different variants we see are capable of. In order to know this, high-throughput and meaningful phenotyping platforms should be developed that allow the collection of accurate and precise data regarding performance for the traits we are interested in targeting to combat climate change. Here's the real challenge though. To be totally honest, with the right sort of funding getting the genotype and phenotype information for each of the lines in the core collection is relatively simple. Even the bioinformatics and statistical analysis of that data to associate gene variants with phenotypic performance can be done with relative ease. The real challenge is effectively databasing this information in ways that make the data both approachable and queryable so that breeders can use the information in deciding which crosses to make. In order to do this, not only does the data need to be curated in some web-accessible format, but ontologies (or standardized controlled vocabularies) need to be developed to index that database. Without such ontologies, it would be impossible to know if two groups each submitting phenotype data were even measuring the same thing. Beauty, it appears, really is in the eye of the beholder.

In conclusion, there is tremendous potential to exploit the genetic variation as it is currently partitioned within the genomes of the dryland legume crops. The exploitation of this potential is India's best chance at empowering dryland agriculture to mitigate and adapt to the impending climate change. In order for this to occur however, significant funding will need to come to bear on the genetic characterization of the germplasm bank maintained at ICRISAT. For now at least, we can be grateful that such a resource even exists considering the widely varied and politically charged world all of us find ourselves navigating.

Improving yield of millets in dryland agriculture-Key to food security:

Indian has 108 million hectares of land which are rain fed and out of which 47 million hectares of land are drylands. These drylands are used to cultivate crops like sorghum, pigeon pea and millets. Millets are tolerant to many abiotic and biotic stresses, have high nutritional quality and can grow in hotter and drier conditions. The idea is to compare the yields of millet to other major irrigated crops like rice, wheat and maize and figure out the reasons for their lower yields. Based on these reasons, the issues that need to be focused on in order to improve yield are discussed. The improved yield will provide the world with more grains and also generate more income for the dryland farmers. Population growth is becoming a serious problem for the future world especially in developing countries like India and China. In order to feed the people the food production figures should go higher but with the same or even less land resource as available now. To alleviate this problem the productivity of crops should be increased significantly specifically the grain crops like rice, wheat, maize, etc. as these crops are the staple food in most of the countries. Tremendous research has and is being done on these crops to obtain higher yields and other desirable traits. Since the green revolution, wheat and rice have been receiving the most attention and thus resulting in superior varieties with high yields. But the millets and other grain crops had less focus till now.

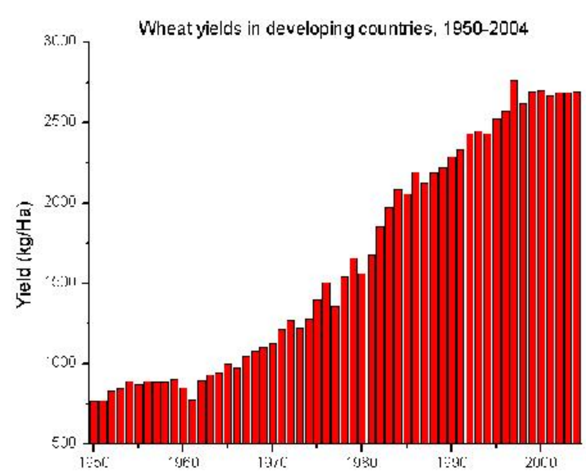
The green revolution has of course created a vent to the food crisis at that point of time by improving major crops but the problem is not eradicated completely. Currently, both the population coupled with climate change is posing a serious threat to the food security. The population directly increases the demand for more food production and the climate change is diminishing the yields of the major crops under cultivation. Rice and wheat cannot perform to their potential in dryland or semi-arid conditions and hence we need to focus on crops like millets which are well adapted to such environments. Improving these crops for better yield will provide livelihood for the dryland farmers and also generate additional grain yield to feed the world (Taylor, 2003).

When we compare the yield of millets to that of other major crops, the values are significantly lower (Table 1). The lower yields have been the major issue for farmers to avoid cultivating millets. But it is noteworthy to mention that millets are not cultivated in the same environment conditions like other major crops. Instead they are grown mainly in rainfed dryands with limited resources where major grain crops would perform very poorly. The yield increase in rice, wheat and maize did not happen overnight but rather was a gradual improvement through constant research and promising discoveries. In the case of rice and wheat, discovery of dwarfing genes enhanced the yield many folds. In maize, the yield increase was mainly due to the crosses made to produce hybrids. Prior to these findings the yields of major crops were very much comparable to the yields of millets as now.

Table 1 : Gives the average yields and species type of different grain crops in India

Crop	Average yield (t/ha)	Species type
Rice	3.26 (FAOSTAT, 2010)	C3
Wheat	2.82 (FAOSTAT, 2010)	C3
Maize	1.9 (FAOSTAT, 2010)	C4
Pearl Millet	0.85 (Khairwal, 2007)	C4
Finger Millet	1.48 (Khairwal, 2007)	C4
Foxtail Millet	0.8 (Channappagoudar *et al*.., 2008)	C4

Since the green revolution (1960s) there has been a constant increase of wheat's yield in the developing nations (Fig. 5). The graph shows a steep increase in yield from 1960 to 2000 but after that the trend slows down with only a meager increase or none. The steep increase of yield is due to the direct consequence of the improvement programs. Also, the yield increase was majorly due to the improvement in harvest



Source : FOASTAT, 2010

Fig. 5 : Shows the trend of yield increase for yield from 1950 – 2004 in developing countries

index. Looking at the tail end of the graph, one of the possible reasons for trend flattening after 2000 might be due to the crop reaching its yield potential. So in order to increase the yield further we might have to follow other strategies like improving biomass as a whole. Somewhat similar trend of plateauing of yield is also observed in rice and maize.

From FAO data the yield rise during 1960 -2000 was 208 per cent in wheat, 109 per cent in rice and 157 per cent in maize in the developing countries (FAOSTAT, 2010). These figures are encouraging when we compare millet crops in which the yield increase is not so significant thus far.

Pearl millet:

Pearl millet is a cross pollinated crop and the most widely cultivated crop among millets. The average pearl millet's yield will generally be low as 0.85 t/ha (Khairwal, 2007) with a harvest index as low as less than 20 per cent but it is definitely not the potential yield. Grain yields around 3.5 t/ha has been recorded way back in 1997 in the state of Gujarat, India (Rai *et al*., 1997) with harvest index around 40 per cent. The higher yield was achieved because of development of hybrid cultivars with higher harvest index and early maturity.

Finger millet :

Finger Millet is a self-pollinated crop but different from other millets as it grows best in moist conditions rather than dry environment. Average yield of finger millet in India is 1.48 t/ha (Mishra *et al*., 2010) which is very low when compared to rest of the world. Finger millet has high yield potential greater than 10 t/ha under optimum conditions.

Foxtail millet :

Foxtail millet is self-pollinated crop and can grow in any conditions and have average yield around 0.8 t/ha in India. Surprisingly, the yield records in China are hitting 10 t/ha which indicates the amount of scope to increase yield in India (Jiaju, 1986).

Advantages of millets:

Millets can perform in the unfavorable conditions which are unsuitable for any other grain crop and this is the reason to discuss millets under the topic of climate change and food security. Being C4 plants, millets have sophisticated photosynthetic capacity and thus their yield potential will be higher. Also C4 plants can tolerate high temperature and low moisture conditions. Probably this physiology gives the advantage to perform well in the semi-arid conditions. Interestingly maize is a C4 crop among major grains and the maximum yield values of maize are astoundingly higher and this gives us hope that millets also could have the same potential. Soil type is not an issue for growing millets as they perform over wide range of soils. The high yielding major grains are all grown in favorable conditions and comparing those yields to the millets grown in drylands in not logical.

Water is one of the most limiting factors in agriculture and now water itself has become limited. So crops with high water use efficiency (WUE) are required for the future to overcome the climate change scenario. Unfortunately crops like rice needs huge amounts of water for their production and this increases the demand for fresh water. Also it is really not easy and economical to get water in drylands and so improving crops which are already adaptable to drier conditions will be a better choice. Millets have high WUE and have the real advantage to tackle drier conditions.

When we compare the nutrient status of millet with other major grains it is clearly evident that millets are far more nutritious than rice and wheat. Pearl millet has almost 20 fold higher iron content and three times more calcium than rice. This is very important as India has a serious problem of malnutrition problems like iron and calcium deficiency. Finger millet is said to have around 300 mg/g of calcium which is super high than any other crop. Diabetes is a becoming another serious problem and this is mainly attributed to the consumption of rice and rice products almost every meal of a day. Thus adding millets in everyday diet is very important from the nutrition perspective (Table 2).

Table 2 : Nutrient status of millets, rice and wheat

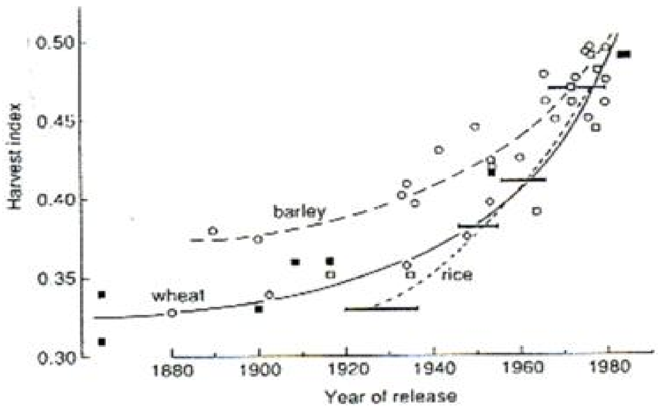
Crop / Nutrient	Protein(g)	Fiber(g)	Minerals(g)	Iron(mg)	Calcium(mg)
Pearl millet	10.6	1.3	2.3	16.9	38
Finger millet	7.3	3.6	2.7	3.9	344
Foxtail millet	12.3	8	3.3	2.8	31
Proso millet	12.5	2.2	1.9	0.8	14
Kodo millet	8.3	9	2.6	0.5	27
Little millet	7.7	7.6	1.5	9.3	17
Barnyard millet	11.2	10.1	4.4	15.2	11
Rice	6.8	0.2	0.6	0.7	10
Wheat	11.8	1.2	1.5	5.3	41

Source Millet network of India (MINI)

Millets have relatively shorter duration for growth which enables us to grow them in between cropping cycles of major crops when there is a drought or unfavorable condition. This will provide farmer with additional income rather than leaving the land barren and also ensure grain supply to the market. The incidents of disease and pest are also much lower compared to other major crops.

Issues for improving yield:

Improving harvest index (HI) of the crop is very important and this will increase the yield with any increase in biomass. Selecting varieties with bigger panicle and other breeding methods can be employed to achieve high HI. At present the major crops are in the range of 50 per cent HI and millets have very lower HI around 20 per cent (Fig. 6).



Source: Evans L.T. 1993. Physiological aspects of crop improvement

Fig. 6 : Increase in harvest index of crop rice, wheat and barley

Given that they are C4 plants and still yielding low more physiological studies could be carried out like photosynthetic rates of leaves, canopy, etc. Not many of these studies have been carried out and learning about physiology of millets will help us in the selection criteria of breeding for yield.

Harvesting is a real problem with millets as they have small seed size and no mechanization is available. So farmers mainly depend upon the laborers during harvest and post processing, and as we all know labor shortage is real issue in countries like India. Tools for harvest and processing are to be developed and then large scale planting is feasible.

Identification of short term varieties with higher yield will be really beneficial. Identification of crops that can withstand both high and low moisture conditions are helpful in places where the soil is poor and rainfall is unpredictable.

All these are possible only when we explore the genetic diversity of millets and search for different traits. There are germplasms and seeds collected at ICRISAT which exhibits huge phenotypic variation which I personally feel is not utilized in breeding programs (Fig. 7).

Source: Photographed by Prasann Kumar on 13 Jan, 2012 at ICRISAT, Hyderabad

Fig. 7 : Pear Millet diversity in their panicle displayed in ICRISAT

Conclusion:

India started taken steps to improve the dryland agriculture by modifying the agronomic practices like deep ploughing, lower seed rate, use of farm yard manure, etc. as early as 1923. The objective was to increase the yield of dryland crops and they managed to obtain yield increases of 15 – 20 per cent. During the green revolution a little progress was made by developing hybrids and high yielding cultivars. Now centers like International Institute for Semi-Arid tropic (ICRISAT, India) established in 1979 and Central Research Institute for Dryland Agriculture established in 1985 are carrying out research dryland agriculture. Having said all these millets are still considered as orphan crops compared to other major grain crops. In order to enhance food security there should be another green revolution to improve orphan crops like millets. This will best utilize the dryland areas with higher yield and thus acts as a support to other major grain crops and also generate income for dryland farmers.

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