

Dryland Agriculture: Coping with Climate Change

B. Venkateswarlu

Central Research Institute for Dryland Agriculture, Hyderabad 500 059, India

Received: December 2012

Abstract: Climate change impacts on agriculture are being witnessed all over the world. There are reports of negative impacts of increasing temperature and water stress on crop yields in India. The projected climate change is likely to further aggravate yield variations of many crops, particularly in rainfed situations. For successful adaptation to climate change we need to document the indigenous practices adopted by farmers for coping with climate variability, adaptation and mitigation potential of the existing best bet practices and a long term research plan to evolve new tools and techniques that help in adaptation. Selection of crops and varieties that fit into changed rainfall and temperature scenario, development of varieties for heat, drought and submergence tolerance and evolving varieties responsive to high CO₂ concentrations with high fertilizer and radiation use efficiency should receive high priority for adaptation research. Germplasm of wild relatives and local land races could prove valuable source of climate ready traits. Agroforestry systems like agri-silviculture, silvi-pasture and agri-horticulture offer both adaptation and mitigation opportunities. A large number of technological options are available for soil, water and nutrient management that may contribute to both adaptation and mitigation. Some important examples include in- and ex-situ moisture conservation, rainwater harvesting and recycling, efficient use of irrigation water, use of poor quality water, conservation agriculture, integrated and site-specific nutrient management and energy efficiency in agriculture. Watershed management is an accepted approach for development of rainfed agriculture. Integration of national development policies into a sustainable development framework that complement adaptation will be required to accompany the available technological options.

Key words: Climate change, rainfall, temperature, dryland agriculture.

Climate change impacts on agriculture are being witnessed all over the world, but countries like India are more vulnerable in view of the high population depending on agriculture and excessive pressure on natural resources. The warming trend in India over the past 100 years (1901 to 2007) was observed to be 0.51°C with accelerated warming of 0.21°C per decade since 1970 (Krishna Kumar, 2009). The projected impacts are likely to further aggravate yield fluctuations of many crops with adverse impact on food security and prices. Cereal productivity is projected to decrease by 10-40% by 2100 and greater loss is expected in rabi. There are already evidences of negative impacts on yields of wheat and paddy in parts of India due to increased temperature, increasing water stress and reduction in number of rainy days. Modeling studies project a significant decrease in cereal production by the end of this century (Majumdar, 2008). Climate change impacts are likely to vary in different parts of the country.

Parts of western Rajasthan, southern Gujarat, Madhya Pradesh, Maharashtra, northern Karnataka, northern Andhra Pradesh, and southern Bihar are likely to be more vulnerable in terms of extreme events (Mall *et al.*, 2006). For every one degree increase in temperature, yields of wheat, soybean, mustard, groundnut and potato are expected to decline by 3-7% (Agarwal, 2009a). Similarly, rice yields may decline by 6% for every one degree increase in temperature (Saseendran *et al.*, 2000). Water requirement of crops is also likely to go up with projected warming, and extreme events are likely to increase.

Greater Vulnerability of Rainfed Agriculture

While climate change impacts agriculture sector in general, rainfed agriculture is likely to be more vulnerable in view of its high dependency on monsoon, the likelihood of increased extreme weather events due to aberrant behavior of south-west monsoon.

*E-mail: vbandi_1953@yahoo.com

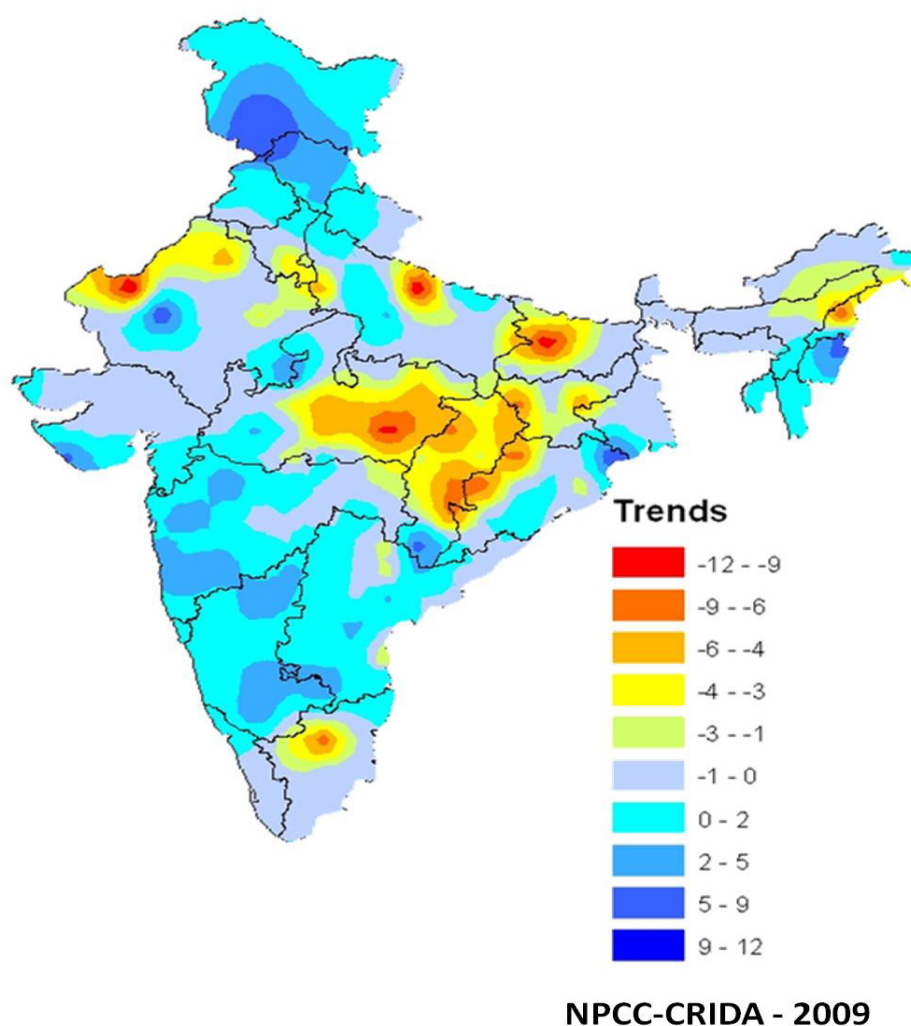


Fig. 1. Rainfall trends over India from 1901 to 2004 (Source: NPCC Annual Report, CRIDA, 2009-10).

Nearly 85 Mha of India's 141 Mha net sown area is rainfed. Rainfed farming area falls mainly in arid, semi-arid and dry sub-humid zones. About 74% of the annual rainfall occurs during south-west monsoon (June to September). This rainfall exhibits high coefficient of variation particularly in arid and dry semi-arid regions. Skewed distribution has now become more common with reduction on number of rainy days. Aberrations in south-west monsoon which include delay in onset, long dry spells and early withdrawal, all of which affect the crops, strongly influence the productivity levels (Lal, 2001). These aberrations are likely to further increase in future. The risk of crop failure and poor yields always influence farmers' decision on investing on new technologies and level of input use (Pandey *et al.*, 2000). Numerous technological (e.g. cropping patterns, crop

diversification, and shifts to drought-/salt-resistant varieties) and socio-economic (e.g. ownership of assets, access to services, and infrastructural support) factors will come into play in enhancing or constraining the current capacity of rainfed farmers to cope with climate change.

Trends in Key Weather Parameters and Crop Impacts

Rainfall is the key variable influencing crop productivity in rainfed farming. Intermittent and prolonged droughts are a major cause of yield reduction in most crops. Long term data for India indicates that rainfed areas witness 3-4 drought years in every 10-year period. Of these, 2-3 are in moderate and one may be of severe intensity. However, so far no definite trend is seen on the frequency of droughts as

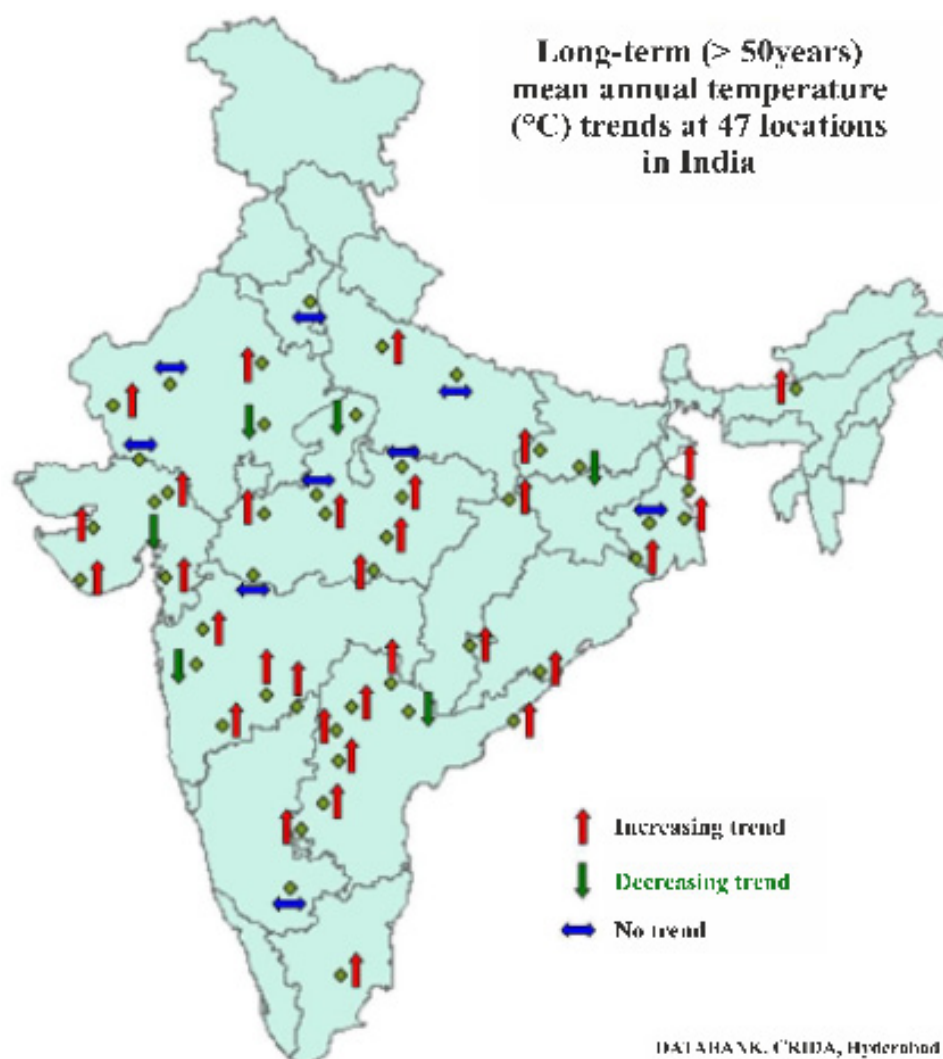


Fig. 2. Trends in mean temperature over different parts of India.

a result of climate change. For any R&D and policy initiatives, it is important to know the spatial distribution of drought events in the country. A long term analysis of rainfall trends in India (1901 to 2004) using Mann Kendall test of significance by AICRPAM, CRIDA indicate significant increase in rainfall trends in West Bengal, Central India, coastal regions, south western Andhra Pradesh and central Tamil Nadu. Significant decreasing trend was observed in central part of Jammu and Kashmir, northern MP, central and western part of UP, northern and central part of Chattisgarh (Fig. 1). Analysis of number of rainy days based on the IMD grid data from 1957 to 2007 showed declining trends in Chattisgarh, Madhya Pradesh, and Jammu and Kashmir. In Chattisgarh and eastern Madhya Pradesh, both rainfall and number of rainy days are declining,

which is a cause of concern as this is a rainfed rice production system supporting large tribal population who have poor capabilities.

Temperature is another important variable influencing crop production particularly during rabi season. A general warming trend has been predicted for India, but knowing temporal and spatial distribution of the trend it is of equal importance. An analysis carried out by AICPRAM, CRIDA using maximum and minimum temperature data for 47 stations across India (DARE, 2009) showed that 9 out of 12 locations in south zone showed an increasing trend for maximum temperature, where as in the north, only 20% locations showed increasing trend (Fig. 2). For minimum temperature most of the stations in India are showing increasing trend. This is a cause of concern for agriculture

Table 1. Estimated crop water requirement (mm) of four crops in major growing districts of the country under climate change scenario

District (State)	1990	2020	2050	% change over 1990 in	
				2020	2050
Groundnut					
Tiruvanamalai (TN)	506.0	515.2	544.0	1.8	7.5
Rajkot (Gujarat)	559.3	562.3	582.2	0.5	4.1
Junagadh (Gujarat)	522.6	528.5	550.2	1.1	5.3
Belgaum (Karnataka)	354.9	366.3	386.0	3.2	8.7
Anantapur (AP)	517.6	567.1	650.3	9.6	25.6
Bangalore (Karnataka)	490.9	510.9	559.3	4.1	13.9
Mustard					
Agra (UP)	276.4	284.0	295.5	2.7	6.9
Bharatpur (Raj)	276.2	283.8	295.1	2.8	6.8
Hisar(Haryana)	357.0	369.6	380.8	3.5	6.7
Nadia (WB)	483.2	491.5	508.8	1.7	5.3
Morena (MP)	263.4	269.0	282.5	2.1	7.2
Wheat					
Sirsa (Haryana)	281.8	293.1	301.4	4.0	7.0
Ahmedabad (Gujarat)	523.0	536.8	551.0	2.6	5.4
Ahemedanagar (Mah)	485.8	496.1	509.5	2.1	4.9
Ganganagar (Raj)	278.9	290.3	298.2	4.1	6.9
Hardoi (UP)	475.0	488.2	502.2	2.8	5.7
Kangra (HP)	367.7	380.7	391.2	3.5	6.4
Vidisha (MP)	437.1	446.9	460.4	2.3	5.3
Sangrur (Punjab)	391.1	405.4	416.3	3.7	6.4
Maize					
Udaipur (Raj)	388.8	392.4	400.9	0.9	3.1
Karimnagar (AP)	424.7	433.4	440.0	2.0	3.6
Jhabua (MP)	424.5	430.6	441.9	1.4	4.1
Begusarai (Bihar)	370.0	374.7	388.9	1.3	5.1
Bahraich (UP)	407.4	412.1	426.5	1.1	4.7
Godhra (Gujarat)	426.3	432.3	444.0	1.4	4.2
Khargaon (MP)	354.3	365.0	381.0	3.0	7.6
Aurangabad (Mah)	413.4	423.1	435.7	2.3	5.4

as increased night temperatures accelerate respiration, hasten crop maturity and reduce yields. The increasing trend is more evident in central and eastern zones where rainfall is also showing a declining trend, which is an area of concern and requires high attention for adaptation research.

Besides hastening crop maturity and reducing crop yields, increased temperatures will also increase the crop water requirement. A study carried out by CRIDA (unpublished) on the major crop growing districts in the country for four crops, viz., groundnut, mustard, wheat

and maize indicated a 3% increase in crop water requirement by 2020 and 7% by 2050 across all the crops/locations. The climate scenarios for 2020 and 2050 were obtained from HadCM3 model outputs using 1960-1990 as base line weather data (Table 1).

Adaptation and Mitigation Strategies

Successful adaptation to climate change requires long term investments in strategic research and new policy initiatives that mainstream climate change adaptation into development planning. As a first step, we

Table 2. Soil organic carbon sequestration potential through restoration of degraded soils

Degradation process	Area (Mha)	SOC sequestration rate (kg ha ⁻¹ y ⁻¹)	Total SOC sequestration potential (Tg C/y)
Water erosion	32.8	80-120	2.62-3.94
Wind erosion	10.8	40-60	0.43-0.65
Soil fertility decline	29.4	120-150	3.53-4.41
Waterlogging	3.1	40-60	0.12-0.19
Salinization	4.1	120-150	0.49-0.62
Lowering of water table	0.2	40-60	0.01-0.012
Total			7.20-9.82

need to document all the indigenous practices farmers have been following over time for coping with climate change. Secondly, we need to quantify the adaptation and mitigation potential of the existing best bet practices for different crop and livestock production systems in different agro-ecological regions of the country. Thirdly, a long term strategic research planning is required to evolve new tools and techniques including crop varieties and management practices that help in adaptation.

The Indian Council of Agricultural Research (ICAR) has initiated a Network Project on Climate Change (NPCC) in X Five Year Plan with 15 centers, which has been expanded in the XI Plan covering 23 centers. The initial results of the project through crop modeling have helped in understanding the impacts of changes in rainfall and temperature regimes on important crops and livestock (Agarwal, 2009b). Currently, the focus is on evolving cost effective adaptation strategies. More recently during 2010, ICAR has launched the National Initiative on Climate Resilient Agriculture (NICRA) as a comprehensive project covering strategic research, technology demonstration and capacity building. Targeted research on adaptation and mitigation is at nascent stage in India, but based on knowledge already generated, some options for adaptation to climate variability induced effects like droughts, high temperatures, floods and sea water inundation can be suggested. These strategies fall into two broad categories viz., (i) crop based and (ii) resource management based approaches.

Crop based Strategies

Crop based approaches include growing crops and varieties that fit into changed rainfall and seasons, development of varieties with changed duration that can over winter the transient effects of change, development of varieties for heat stress, drought and submergence tolerance; evolving varieties which respond positively in terms of growth and yield under high CO₂. In addition, varieties with high fertilizer and radiation use efficiency and also novel crops and varieties that can tolerate coastal salinity and sea water inundation are needed. Intercropping is a time tested practice to cope with climate variability and climate change if one crop fails due to floods or droughts second crop gives some minimum assured returns for livelihood security. Germplasm of wild relatives and local land races could prove valuable source of climate ready traits. We need to revisit the germplasm collected so far which has tolerance to heat and cold stresses, but not made use in the past due to low yield potential. A detailed account of crop based approaches is beyond the scope of this paper. Susheel Kumar (2006) provides a succinct account of breeding objectives under climate change in India.

Strategies based on Resource Conservation and Management

There are large number of options in soil, water and nutrient management technologies which contribute to both adaptation and mitigation. Much of the research done in rainfed agriculture in India relates to conservation of soil and rainwater and drought proofing which is an ideal strategy for adaptation to climate change (Venkateswarlu *et al.*, 2009). Important technologies include *in situ* moisture conservation, rainwater harvesting and recycling, efficient use of irrigation water, conservation agriculture, energy efficiency in agriculture and use of poor quality water. Watershed management is now considered an accepted strategy for development of rainfed agriculture. Watershed approach has many elements which help both in adaptation and mitigation. For example, soil and water conservation works, farm ponds, check dams, etc., moderate the runoff and minimize floods during high intensity rainfall. The plantation of multi-purpose trees in degraded lands helps in carbon sequestration. The crop and

soil management practices can be tailored for both adaptation and mitigation at the landscape level. Some of the most important adaptation and mitigation approaches with high potential are described below:

Rainwater conservation and harvesting

These are based on *in-situ* and *ex-situ* conservation of rainwater for recycling to rainfed crops. The arresting of soil loss contributes to reduced carbon losses. Lal (2004) estimates that if water and wind erosion are arrested, it can contribute to 3 to 4.6 Tg year⁻¹ of carbon in India. Increased groundwater utilization and pumping water from deep tube wells is the largest contributor to GHG emissions in agriculture. If surface storage of rainwater in dug out ponds is encouraged and low lift pumps are used to lift that water for supplemental irrigation, it can reduce dependence on groundwater. Sharma et al. estimated that about 28 Mha of rainfed area in eastern and central states has the maximum potential to generate runoff of 114 billion cubic meters which can be used to provide one supplemental irrigation in about 25 Mha of rainfed area. For storing such quantum of rainwater about 50 million farm ponds are required. This is one of the most important strategies not only to control runoff and soil loss but also contribute to climate change mitigation. Conjunctive use of surface and groundwater is an important strategy to mitigate climate change. Innovative approaches in groundwater sharing can also contribute to equitable distribution of water and reduced energy use in pumping.

Soil carbon sequestration

Soil carbon sequestration is yet another strategy towards mitigation of climate change. Although, tropical regions have limitation of sequestering carbon in soil due to high temperatures, adoption of appropriate management practices helps in sequestering reasonable quantities of carbon in some cropping systems particularly in high rainfall regions. The potential of cropping systems can be divided into that of soil carbon sequestration and sequestration in vegetation. Tree based systems can sequester substantial quantities of carbon in biomass in a short period. Total potential of soil C sequestration in India is 39 to 49 Tg year⁻¹ (Lal, 2004). This is inclusive of the potential of the restoration of degraded

soils and ecosystems which is estimated at 7 to 10 Tg C year⁻¹ (Table 2). The potential of adoption of recommended package of practices on agricultural soils 6 to 7 Tg year⁻¹. In addition, there is also a potential of soil inorganic carbon sequestration estimated at 21.8 to 25.6 Tg C year⁻¹. Long term manurial trials conducted in arid regions of Andhra Pradesh (at Anantapur) under rainfed conditions indicate that the rate of carbon sequestration in groundnut production system varied from 0.08 to 0.45 t ha⁻¹ year⁻¹ with different nutrient management systems (Srinivasarao *et al.*, 2009). Under semi-arid conditions in Alfisol region of Karnataka, the rate of carbon sequestration was 0.04 to 0.38 t ha⁻¹ year⁻¹ in finger millet system under diverse management practices. Under rabi sorghum production system in Vertisol region of Maharashtra (semi-arid) the sequestration rate ranged from 0.10 to 0.29 t ha⁻¹ year⁻¹ with different integrated management options. In soybean production system in black soils of Madhya Pradesh (semi-arid) the potential rate of carbon sequestration is up to 0.33 t ha⁻¹ year⁻¹ in top 20 cm soil depth.

Site specific nutrient management

Integrated nutrient management (INM) and Site-specific nutrient management (SSNM) is another approach with potential to mitigate effects of climate change. Demonstrated benefits of these technologies are; increased rice yields and thereby increased CO₂ net assimilation and 30-40% increase in nitrogen-use efficiency. This offers important prospect for decreasing GHG emissions linked with N fertilizer use in rice systems. It is critical to note here that higher CO₂ concentrations in the future will result in temperature stress for many rice production systems, but will also offer a chance to obtain higher yield levels in environments where temperatures are not reaching critical levels. This effect can only be tapped under integrated and site directed nutrient supply, particularly N. Phosphorus (P) deficiency, for example, not only decreases yields, but also triggers high root exudation and increases CH₄ emissions. Judicious fertilizer application, a principal component of SSNM approach, thus has two-fold benefit, i.e. reducing greenhouse gas emissions; at the same time improving yields under high CO₂ levels. The application of a urease inhibitor, hydroquinone (HQ), and a nitrification inhibitor, dicyandiamide

(DCD) together with urea also is an effective technology for reducing N_2O and CH_4 emissions from paddy fields. Very little information is available on the potential of SSNM in reducing GHG emissions in rainfed crops.

Conservation agriculture (CA)

In irrigated areas, zero tillage (ZT) in particular has effectively reduced the demand for water in rice-wheat cropping system of Indo-Gangetic plains and is now considered as a viable option to combat climate change. ZT has some mitigation effect in terms of enhancing soil carbon, reducing energy requirement and improving water and nutrient use efficiency, but actual potential has to be quantified from long term experiments. The scope of CA in rainfed agriculture has been reviewed by Singh and Venkateswarlu (2009). While reduced tillage is possible in few production systems in high rainfall regions in eastern and northern India, non-availability of crop residue for surface application is a major constraint, particularly in peninsular and western India where it is mainly used as fodder.

Bio-mass energy and waste recycling

A large amount of energy is used in cultivation and processing of crops like sugarcane, food grains, vegetables and fruits, which can be recovered by utilizing residues for energy production. This can be a major strategy of climate change mitigation by avoiding burning of fossil fuels and recycling crop residues. The integration of biomass-fuelled gasifiers and coal-fired energy generation would be advantageous in terms of improved flexibility in response to fluctuations in biomass availability with lower investment costs. Waste-to-energy plants offer twin benefits of environmentally sound waste management and disposal, as well as the generation of clean energy.

Livestock production has been an integral part of agriculture in India. Livestock provides an excellent recycling arrangement for most of crop residue. Most by-products of cereals, pulses and oilseeds are useful as feed and fodder for livestock, while that of other crops like cotton, maize, pigeonpea, castor and sunflower and sugarcane are used as low calorie fuel or burnt to ashes or left in open to decompose over time. Ideally such residue

is incorporated into soil to enhance physical properties of the soil and its water holding capacity. Lack of availability of proper chipping and soil incorporation equipment is one of the major reasons for the colossal wastage of agricultural biomass in India. Increased cost of labor and transport is another reason for lack of interest in utilizing the biomass. This is one area where little or no effort has gone in despite availability of opportunities for reasons such as aggregation, transport and investment in residue processing facilities. Many technologies like briquetting, anaerobic digestion vermin-composting and bio-char, etc. exist, but they have not been commercially exploited. This area is gradually receiving attention now as a means to producing clean energy by substituting forest biomass for domestic needs. Modest investments in decentralized facilities for anaerobic digestion of agricultural residue through vermin-composting and biogas generation can meet the needs of energy-deficit rural areas and simultaneously contribute to climate change mitigation.

Biomass based biogas production

There is a renewed interest in the use of anaerobic digestion processes for efficient management and conversion of cattle dung and other agro industrial wastes (livestock, paper and pulp, brewery and distillery) into clean renewable energy and organic fertilizer source. The biogas captured could not only mitigate the potential local and global pollution, but could either be combusted for electricity generation using combined heat and power generator in large to medium enterprises or used for cooking and lighting for small households. A 2 m³ digester can generate up to 4.93 t CO₂e year⁻¹ of certified emission reduction (CER). Animal wastes are generally used as feedstock in biogas plants. But, the availability of these substrates is one of the major problems hindering the successful operation of biogas digesters. Khandelwal (1990) reported that the availability of cattle waste could support only 12–30 million family-size biogas plants against the requirement of 100 million plants. A significant portion of 70–88 million biogas plants can be run with fresh/dry biomass residues. Of the available 1,150 billion tons of biomass, a fifth would be sufficient to meet this demand.

Table 3. Carbon storage ($\text{Mg ha}^{-1} \text{ year}^{-1}$) in different agrisilvicultural systems

Location	System	Carbon sequestration ($\text{Mg ha}^{-1} \text{ year}^{-1}$)	Reference
Raipur	Gmelina based system	2.96*	Swami and Puri, 2005
Chandigarh	Leucaena based system	0.87	Mittal and Singh, 1989
Jhansi	Anogeissus based system	1.36	Rai <i>et al.</i> , 2002
Coimbatore	Casuarina based system	1.45	Viswanath <i>et al.</i> , 2004

*Includes soil carbon storage of $0.42 \text{ Mg ha}^{-1} \text{ year}^{-1}$ (up to 60 cm depth).

Biochar

When biomass is exposed to moderate temperatures, between about 400 and 500°C (a kind of low-temperature pyrolysis), under complete or partial exclusion of oxygen, biomass undergoes exothermic processes and releases a multitude of gases in addition to heat along with biochar (Czernik and Bridgwater, 2004). Pyrolysis produces biochar, a carbon-rich, fine-grained, porous substance and solid byproduct, similar in its appearance to charcoal, which when returned to soil, produces a range of environmental benefits, such as enhanced soil carbon sequestration and soil fertility improvement (Lehmann, 2007). Both heat and gases can be captured to produce energy carriers such as electricity, hydrogen or bio-oil which can be used as a fuel for various purposes in the process of manufacturing biochar. In addition to energy, certain valuable co-products, including wood preservative, food flavoring, adhesives etc. can be obtained (Czernik and Bridgwater, 2004).

This is a novel approach to sequester carbon in terrestrial ecosystems which has several associated products in the process of its manufacture and also the end product. In India, it has been projected that about 309 Mt of biochar could be produced annually, the application of which might offset about 50% of carbon emission ($292 \text{ Tg C year}^{-1}$) from fossil fuel (Lal, 2005). Rice-wheat cropping system in the Indo-Gangetic plains of India produces substantial quantities of crop residues, and if these residues can be pyrolyzed, 50% of the carbon in biomass is returned to the soil as biochar, increasing soil fertility and crop yields, while sequestering carbon. Addition of biochar to soil has also been associated with enhanced nutrient use efficiency, water holding capacity and microbial activity. At CRIDA, research on biochar use in rainfed crops has been initiated. Biochar from castor, cotton and maize stalks was produced by using a portable kiln and

used as an amendment for pigeonpea during kharif 2010. The crop growth was significantly superior in biochar applied plots from all three sources (Venkatesh, 2010).

Agroforestry

Agroforestry systems like agrisilviculture, silvipasture and agrihorticulture offer both adaptation and mitigation opportunities. Agroforestry systems buffer farmers against climate variability, and reduce atmospheric loads of greenhouse gases. Agroforestry can both sequester carbon and produce a range of economic, environmental, and socio-economic benefits; the extent of sequestration can be up to $10 \text{ t ha}^{-1} \text{ year}^{-1}$ in short rotation *Eucalyptus*, leucaena plantations (Table 3). Agrisilviculture systems with moderate tree density with intercrops have however lower potential.

Policy Issues

Apart from the use of technological advances to combat climate change, there has to be sound and supportive policy framework. The framework should address the issues of redesigning social sector with focus on vulnerable areas/populations, introduction of new credit instruments with deferred repayment liabilities during extreme weather events, weather insurance as a major vehicle to risk transfer. Governmental initiatives should be undertaken to identify and prioritize adaptation options in key sectors (storm warning systems, water storage and diversion, health planning and infrastructure needs). Focus on integrating national development policies into a sustainable development framework that complements adaptation should accompany technological adaptation methods.

In addition, the role of local institutions in strengthening capacities e.g., SHGs, banks and agricultural credit societies should be promoted. Role of community institutions and private sector in relation to agriculture

should be a matter of policy concern. There should be political will to implement economic diversification in terms of risk spreading, diverse livelihood strategies, migrations and financial mechanisms. Policy initiatives in relation to access to banking, micro-credit/insurance services before, during and after a disaster event, access to communication and information services is imperative in the envisaged climate change scenario. Some of the key policy initiatives that are to be considered are: Mainstreaming adaptations by considering impacts in all major development initiatives Facilitate greater adoption of scientific and economic pricing policies, especially for water, land, energy and other natural resources. Consider financial incentives and package for improved land management and explore CDM benefits for mitigation strategies. Establish a "Green Research Fund" for strengthening research on adaption, mitigation and impact assessment. (Venkateswarlu and Shanker, 2009).

Conclusions

Even though climate change in India is now a reality, a more certain assessment of the impacts and vulnerabilities of rainfed agriculture sector and a comprehensive understanding of adaptation options across the full range of warming scenarios and regions would go a long way in preparing the nation for climate change. A multi pronged strategy of using indigenous coping mechanisms, wider adoption of the existing technologies and or concerted R&D efforts for evolving new technologies are needed for adaptation and mitigation. Policy incentives will play crucial role in adoption of climate ready technologies in rainfed agriculture too as in other sectors. The state agricultural universities and regional research centers will have to play major role in adaptation research which is more region and location specific while national level efforts are required to come up with cost effective mitigation options, new policy initiatives and global cooperation.

References

- Agarwal, P.K. 2009a. *Global Climate Change and Indian Agriculture*; Case studies from ICAR network project, Indian Council of Agricultural Research, 148 p.
- Agarwal, P.K. 2009b. Vulnerability of Indian agriculture to climate change: Current stage of knowledge. Paper presented at the National Workshop - Review of Implementation of Work Program Towards Indian Network of Climate Change Assessment, 14 October, Ministry of Environment and Forests, New Delhi.
- CRIDA 2009. *Annual Report*. Central Research Institute for Dryland Agriculture, Indian Council of Agricultural Research, New Delhi
- Czernik, S. and Bridgwater, A.V. 2004. Overview of applications of biomass fast pyrolysis oil. *Energy Fuels* 18: 590-598.
- DARE 2009. *Annual Report*. Department of Agricultural Research and Education, 2008-09, 137 p.
- Khandelwal, K.C. 1990. Biogas Technology development implementation strategies: Indian experience. In *Proceedings of the International Conference on Biogas Technology, Implementation Strategies* (Ed. Borda Bremen). Pune, India, 10-15 January 1990.
- Krishna Kumar 2009. Impact of climate change on India's monsoon climate and development of high resolution climate change scenarios for India. Presented at MoEF, New Delhi on October 14, 2009 (<http://moef.nic.in>)
- Lal, R. 2001. Future climate change: Implications for India summer monsoon and its variability *Current Science* 81: 1205-1207
- Lal, R. 2004. Soil carbon sequestration in India. *Climatic Change* 65: 277-296.
- Lal, R. 2005. Carbon sequestration and climate change with special reference to India. In *Proceedings of the International Conference on Soil, Water and Environmental Quality - Issues and Strategies*, pp. 295-302. Indian Society of Soil Science, IARI, New Delhi, India.
- Lehmann, J. 2007. A handful of carbon. *Nature* 447: 143-144.
- Mall, R., Singh, Ranjeet, Gupta, Akhilesh, Srinivasan, G. and Rathore, L. 2006. Impact of climate change on Indian agriculture: A review. *Climatic Change* 78: 445-478
- Mittal, S.P. and Singh, P. 1989. Intercropping field crops between rows of *Leucaena leucocephala* under rainfed conditions in northern India. *Agroforestry Systems* 8: 165-172.
- Mujumdar, P.P. 2008. Implications of climate change for sustainable water resources management in India, *Physics and Chemistry of the Earth, Parts A/B/C*, 33: 354-358.
- Pandey, S., Behura, D., Villano, R. and Naik, D. 2000. Economic cost of drought and farmers coping mechanisms: A study of rainfed rice systems in eastern India Discussion Paper series IRRI Laguna Philippines.

- Rai, A.K., Solanki, K.R. and Rai, P. 2002. Performance of *Anogeissus pendula* genotypes under agrisilvicultural system. *Indian Journal of Agroforestry* 4: 71-74.
- Saseendran, A.S.K., Singh, K.K., Rathore, L.S., Singh, S.V. and Sinha, S.K. 2000. Effects of climate change on rice production in the tropical humid climate of Kerala, India. *Climate Change* 44: 495-514.
- Sharma, B.R., Rao, K.V., Vittal, K.P.R., Ramakrishna, Y.S. and Amarasinghe, U. 2010. Estimating the potential of rainfed agriculture in India. Prospects for water productivity improvements. *Agricultural Water Management* 97: 23-30.
- Singh, A.K. and Venkateswarlu, B. 2009. Conservation agriculture in arid and semi-arid regions: Opportunities and constraints. *Indian Farming* (Special Issue), pp. 3-8.
- Srinivasarao, Ch. Ravindra Chary, G., Venkateswarlu, B., Vittal, K.P.R., Prasad, J.V.N.S., Sumanta, Kundu, Singh, S.R., Gajanan, G.N., Sharma, R.A., Deshpande, A.N., Patel, J.J. and Balaguravaiah, G. 2009. *Carbon Sequestration Strategies under Rainfed Production Systems of India*. Central Research Institute for Dryland Agriculture, Hyderabad (ICAR), 102 p.
- Susheel Kumar 2006. Climate change and crop breeding objectives in the twenty first century *Current Science* 90: 1053-1054.
- Swamy, S.L. and Puri, S. 2005. Biomass production and C-sequestration of *Gmelina arborea* in plantation and agroforestry system in India. *Agroforestry Systems* 64: 181-195.
- Venkatesh, G. 2010. Biochar for carbon sequestration. *News Letter*. Central Research Institute for Dryland Agriculture, Hyderabad, January-June 2010, 12 p.
- Venkateswarlu, B., Shankar, Arun Kumar and Gogoi, A.K. 2009. Climate change adaptation and mitigation in Indian agriculture. In *Proceedings of the National Seminar on Climate Change Adaptation Strategies in Agriculture and Allied Sectors*, pp. 109-121. KAU, Trissur, December 2008.
- Venkateswarlu, B. and Shankar, A.K. 2009. Climate change and agriculture adaptation and mitigation strategies. *Indian Journal of Agronomy* 54: 226-230
- Viswanath, S., Peddappaiah, R.S., Subramoniam, V., Manivachakam, P. and George, M. 2004. Management of *Casuarina equisetifolia* in wide-row intercropping systems for enhanced productivity. *Indian Journal of Agroforestry* 6: 19-25.