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Keynote lecture

Designing climate resilient agricultural systems with some examples from India

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Climate variability is a major source of risk in food production in the semi-arid tropics that are home to almost 2.5 billion people. With other biophysical, socio-economic and political factors, climate risk contributes enormously to food insecurity, economic losses, and poverty. This situation is likely to be exacerbated by the projected changes in climate. Past and ongoing work has enabled us to understand the impacts of climate variability and change on smallholder agriculture and the perceptions and coping strategies being adopted by farmers. Research has also identified a number of potential options that can contribute to improved management of agricultural systems under variable climatic conditions. Agricultural productivity and profitability under these high climate risk environments aretherefore dependent on: (i) the inherent resilience of the farming enterprises which is a function of farm design within the context of the agricultural innovation system (we term strategic); and (ii) how well the farm activities are planned and executedin the context of the climatic risks (we term tactical).

The concepts of climate-resilient agriculture or climate-smart agriculture (CSA) have also emerged in response to the need to manage a variable and changing climate and to a large extent, build on well-established agronomic principles and crop improvement. However, the objectives of CSA are much broader and encompass increasing productivity and incomes, adapting practices and technologies to a changing climate and minimising emissions from agriculture, including the capture of greenhouse gases into soils. According to FAO (2021), these objectives may not always be met simultaneously, and consequently, the CSA approach should attempt to reduce trade-offs and promote synergies in their application considering the context.

CSA is a broad catch-all term and encompasses actions at all levels from farm through to country and regions, implemented by farmers, the private sector, community organisations and governments. For example, a study by FAO (2021) found that the Climate-Smart Agriculture Investment Plan (CSAIP) for Mali, developed by the Ministry of Agriculture, proposed eight climate-smart crop and livestock investments (value chains for non-timber forest products, flood recession agriculture, livestock, the integration of millet, sorghum and legumes, vegetables, the restoration of degraded lands, sustainable rice intensification and wheat).

For the purposes of this short review, we will focus on CSA as it relates to decisions made at the farm level and may encompass single technological innovations (e.g., a more heat or drought tolerant crop variety), packages of innovations (e.g., a bundle of agronomic practices with climate information for decision-making) through to the design of farms and farming systems to cope with climate variability and extreme events. Examples from semi-arid farming systems in India are used.

Strategic design of farming systems

The longer-term perspective, where a farming system is redesigned or adjusted to be more resilient to the current and future climate patterns, can be termed 'strategic' planning, which is also an example of transformational adaptation (Vermeulen *et al*., 2018). Farm design should consider what mix of enterprises, crop types and farming systems are most resilient to current and future climate also considering market and socioeconomic factors. This requires significant analytical efforts to understand historical and projected climate, model-based scenario analysis, co-design of farming systems that are more resilient to extreme events and reduce the damage of such events on the natural resource base. In some landscapes and environments, this may suggest transformational changes in landscape designare required, which are best achieved through a participative process with stakeholders and government (Vermeulen *et al.,* 2018). Strategic planning is required to manage the risks posed by climate change and variability and achieve sustainable crop productivity increases without compromising environmental sustainability. It involves evaluating several promising potential technological, institutional and policy options using rigorous quantitative methods to support decision-making and prioritization of research investment decisions and policy formulations at the regional, national, and global scale.

The following are examples from the Indian states of Telangana (2.1) and Andhra Pradesh (2.2) where simulation frameworks and multiple levels of government and industry have been engaged to consider the scaling of CSA investments.

Participatively prioritizing CSA practices and investments, Telangana, India

In line with the National Mission on Sustainable Agriculture launched in 2010 by the Government of India, State Governments, in varying degrees, have given policy focus that address likely risks arising from climate variability (Padhee, 2018). To address the growing problems of food security and climate change, multiple institutions and programs have demonstrated evidence for developing climate-smart villages (CSVs) across regions that can act as a sustainable model for adapting to changing climate and improve farmers' welfare. However, it remains a major challenge to upscale the CSV approach. An attempt to address this scaling challenge was the development of a unified approach in Telangana, India by Kumar et al. (2018). The key steps of this unified approach included:

i. Climate risk and vulnerability mapping at disaggregated (lowest administrative boundary of Mandal) level and the generation of geospatial maps for major crops under vertisols and light soils (Kadiyala et al. 2020).
ii. Inventory of CSA practices and respective technical coefficients.
iii. Multi-criteria analysis for participatory prioritization of location-specific CSA practices and identification of barriers and incentives.
iv. Ex-ante impact analysis of potential adoption and investment and infrastructure needs to implement CSA practices at local level and strategy for CSA integration into district level plans.
v. Local level vulnerability assessments and participatory prioritization based on an index calculated for climate smartness and ease of adoption for each proposed CSA practice formed the basis of prioritizing CSA interventions suitable for a particular location.

Based on participatory prioritization, six CSA practices were considered: (i) Tillage practice, broad bed and furrow for soil and moisture conservation and drainage; (ii) Farm pond for critical/supplemental irrigation; (iii) Crop residue management system for cotton; (iv) Drip irrigation system. (vi) Unpuddled mechanical transplanting of rice.

The proposed framework and tools enabled the district-wise potential for the promotion of CSA practices and technologies, public and private investment needs, economic impacts of the interventions to enable informed decision-making. Stakeholder consultations during different stages of this process were important for widely integrating different perspectives and creating ownership.

This meso-scale (district and Mandal) level analysis was also informed by farm household level quantification of vulnerability and resilience by accounting for a smallholder household's ability to adapt and respond to climatic risk (Kumar *et al.,* 2020). The unified framework helped to understand the district wise potential for promotion of CSA practices and technologies, public and private investment needs, potential economic impacts of the interventions to enable informed decision making for CSA. This evidence based scientific framework and approach is there to guide investments and policy making decisions on scaling up CSA in Telangana state.As a next step, this analysis is being used to develop district-level climate resilient action and investment plans to be mainstreamed into development planning of the Telangana state.

Integrated assessment approaches in Andhra Pradesh

Strategic planning to enhance farming system resilience requires *ex-ante* impact assessment of climate change impacts and co-design of various adaption strategies with stakeholders using interdisciplinary approaches under plausible climatic and socioeconomic scenarios. Besides, multi-stakeholder involvement will also ensure the alignment of regional agricultural policies with national agrarian policy. The integrated assessments can aid policymakers and development practitioners understand the farming systems' sensitivities and the potential benefits of climate change adaptation to current and future climate scenarios.

The Agricultural Model Intercomparison and Improvement Project (AGMIP, https://agmip.org/), an international network of multi-disciplinary researchers, has developed the Regional Integrated Assessment (RIA) framework to assess the impacts of climate variability and climate change on the different farming systems of the developing countries, particularly in South Asia and sub-Saharan Africa.The RIA framework was applied to assess the impacts of climate-smart adaptation strategies on rainfed chickpea fallow cropping systems in the Kurnool district of Andhra Pradesh, India. The adaptation strategies (drought-tolerant varieties, optimal fertilizer application, life-saving irrigation, mechanical harvesting, etc.) co-developed with key stakeholders (e.g., researchers, NARES, policymakers and farmers) have the potential of increasing the resilience of these farming systems to both current and future climate variability and change. Overall, the assessment showed that these adaptation practices help reduce the productivity losses and generate net economic gains for the households, reducing the region's poverty levels and increasing their annual household income (Nedumaran *et al.,* 2021). The integrated model links climate, biophysical, hydrology, and economic models as a structural modeling framework. The approach used to understand the tradeoffs between the biophysical and economic impacts (market effects) of potential climate adaptation strategies and their implications to global and national food systems in the context of changing environmental, biophysical, and a range of non-climatic factors under a combination of plausible future climatic and shared socioeconomic pathways (SSPs) scenarios. The International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT) developed by IFPRI is widely used for such assessments. Kadiyala *et al.,* (2021) used the integrated modeling framework and evaluated the spatial impact of climate change on groundnut production systems in India, further developing adaptation strategies and the potential implications for the global groundnut economy (Jalloh *et al.,*2013). This combination of climate, crop and economic models allowed the estimation of changes in yields, production, price and trade parameters. As a result, the final groundnut yields capture the interactions between soil, climate, crop management, markets, and the impact of socioeconomic (population and GDP) drivers. This approach allowed adaptation options to be compared, therefore enabling policymakers to better understand the consequences of targeted actions in their priority setting exercises.

Tactical management

To remain profitable and food secure, farmers must cope effectively with current climate variability as a first step while adjusting their farming systems to cope better with future climates. For near term and current decision-making, this can be termed 'tactical' where a flexible risk management strategy is adopted that uses multiple information sources to make decisions. This may include pre-season enterprise planning guided by seasonal climate forecasts, a set of criteria or 'triggers' for sowing and variety selection and a range of in-season responses to the prevailing weather, market signals or other factors. Pilot studies have clearly established the usefulness of climate information for smallholder decision-making, but the operational delivery, at scale, of actionable information products requires context-specific granularity, timeliness, formatting and, importantly, feedback loops for continuous learning.

Recent developments in climate science have led to significant improvements in the predictability of climate and weather at scales that are useful in planning and managing agricultural systems. These predictions, when linked to the systems information and scenario analyses through simulation models, provide an opportunity to critically evaluate and identify alternative soil, crop and management options that minimize the risks and improve productivity and profitability. Since seasonal production outcomes are uncertain, even with the best climate information, farmers have limited flexibility in applying management with confidence. In risky environments, farmers most often respond by adapting a risk-averse strategy and are reluctant to invest in risk reducing measures. In the SAT agro-ecologies, there are a limited range of CSA options to consider and adoption may be influenced by a multitude of factors related to the biophysical, socioeconomic or enabling environment.

Scaling climate information services is now of the highest priority. This will include enhancing the reliability, resolution and utility of national meteorological services to deliver increasingly location and system specific data made available for public consumption and to support thedevelopment of climate informed agro-advisories. An important aspect, in the context of resource poor farmers, will be equity i.e., making sure access to information and inputs are socially inclusive and gender sensitive, particularly in poorer SAT regions (Gumucio *et al.,*2020). The building of capacity in multiple stakeholders as a pre-requisite for effective climate risk management in semi-arid regions, especially around information translation into action (i.e., access to seeds, fertiliser, labour etc.), to take advantage of the climate information. Meinke *et al.,* (2006) concluded that climate risk management requires holistic solutions derived from cross disciplinary and participatory, user-oriented research – this implies that the multiple institutions / agencies present in India or any other country are required to better integrate their efforts for the benefit of smallholder farmers. We present 2 examples of enhancing the use of agro meteorology through (3.1) Next-gen agro advisories; and (3.2) Digital Agriculture. This work was initiated by the Ministry of Earth Sciences (MoES), India through the Monsoon Mission programs demonstrates a great example of multi –agency co-operation leading to a pan India impacts.

Next-gen agro advisories

The productivity and profitability of smallholder agriculture, especially the one practised under highly variable climatic conditions, depends on how well farm activities are planned and executed. Reaching farmers, considering the users (gender, age, literacy, resource endowment, attitude to risk etc.) with actionable climate information is crucial in supporting effective decision-making. This requires appropriate engagement to produce information that facilitates and guide early action and preparedness (Tall and Njinga, 2013). Recent research suggests that co-production of knowledge by scientists and users, results in better uptake of climate information supporting management decisions (Lemos and Morehouse, 2005, Cash et al., 2006, Sarewitz and Pielke, 2007, O' Mahony and Bechky, 2008, McKinley *et al.,*2012, Briley *et al.,*2015; Meadow *et al.,* 2015;). Efforts aimed at narrowing down the 'usability gap' (Lemos *et al.,* 2012), also requires effective access and delivery mechanisms that enable a better response to user needs.

While dissemination of weather information in India goes back to 1945, it was in 1976 that IMD launched a more robust forecast-based agrometeoro-logical advisory service (AAS) in collaboration with state governments. AAS enables the application of meteorological information to agriculture, thereby supporting farmers in making the best use of available natural resources (Ahmad *et al.,* 2017). The development of the 'next generation' of advisories system which aresignificantly improved in scale, content, context and timeliness to reach the 95.4 million farming households in the countryis now possible through the advances in climate science, big data analytics, digital communication and agriculture. Additionally, the adoption of ICTs has proven its importance to improving agriculture productivity and food production (Barakabitze *et al.,* 2015). To address these needs and to take advantage of the ICT innovations, ICRISAT in collaboration with Microsoft-India, the Indian Meteorological Department (IMD) and the Acharya NG Ranga Agricultural University (ANGRAU) developed the Intelligent Agricultural Systems Advisory Tool (ISAT) through a multi-stakeholder participatory approach. ISAT is a decision support guide underpinned by decision tree that use various data sources, climate analytics, forecasts and the local 'soil, crop and management realities.' The scalable methodology can potentially provide semi-automated farm advisories to millions of farmers on their phones at key decision points in a cropping cycle. By influencing pre-season and in-season decisions, the tool helped farmers to reduce risk and increase crop yield (Ramaraj *et al.,*2021; Rao *et al.* 2019). An evaluation of ISAT for groundnutin Anantapur, Andhra Pradesh, India for the past 3 years revealed an increase in yields at three out of four locations, averaging 16% across the locations. In one location, 56 % increase was observed. Evidence suggests that the benefits resulted from improved planting and tactical farm management decisions. Overall, 80 % of the farmers used the information for making decisions on harvesting, 79 % for sowing while 65 % of farmers used it for land preparation. Advisory information has impacted crop productivity positively (Rao *et al.,*2019).

Meghdoot – a Pan-India APP for accessing agromet information

India has an institutional framework called the District-level Agrometeorological Advisory Service (DAAS) that aims to foster a collaboration between various national and regional institutions to translate climate and weather information into actionable advisories for farmers. DAAS has been operational since 2008 and is the largest integrated agrometeorological information programs in the world (Rathore *et al.,* 2011). The practise of disseminating weather information in India commenced in 1945. In 1976, India Meteorological Department (IMD) launched a more robust forecast-based agrometeorological advisory service (AAS) in collaboration with state governments. By blending of climate science with agriculture, AAS could become a key to support farmers in putting the available natural resources (Ahmad *et al.,* 2017) to best use as well as facilitate technology transfer on climate change information (Ramachandrappa *et al.,*2018). In 1988, the National Centre for Medium-Range Weather Forecasting (NCMRWF) piloted agrometeorological advisories based on five-day, medium-range weather forecasts. This program was upgraded to the current DAAS program in 2008 to provide district-level weather information and crop management advisories across India. DAAS is operational through multidisciplinary teams called Agro-Met Field Units (AMFUs) which draws on expertise from the Indian Institute of Tropical Meteorology (IITM), the Indian Council for Agricultural Research (ICAR) and the State Agriculture Universities (SAUs). There are currently 130 AMFUs (one per agro-climatic zone) operational across India (Kumar 2020) catering to 680 districts. The AMFUs main responsibility to blend climate science and agronomy and create crop and district specific advisories. AMFUs are linked with IMD and its Regional Meteorological Centres to obtain local information and past and forecast weather data which is critical to issue district wise advisory bulletins (Dheebakaran *et al.,* 2020). These bulletins could enhance production and farmer income and reduce losses. The advisories are issued twice a week on every Tuesday and Friday. The AMFU network is poised to become District Agro-Met Units (DAMUs) network with IMD proposing to commission a DAMU at each of Krishi Vigyan Kendras (KVKs) in 530 districts in addition to the existing 130 AMFUs. In 2019, IMD in collaboration with ICRISAT conceptualized, designed, build, and deployed a mobile app called Meghdoot in order to improve the dissemination and uptake of advisories services rendered under the DAAS program. The need to support and enable farmers access district and crop specific advisories 24X7 and increasing smartphone penetration and mobile internet usage in rural communities stimulated a discussion on the need for a mobile app to link DAAS advisories to farmers. This effort was supported by a grant awarded to ICRISAT under the Monsoon Mission II initiative launched by India's Ministry of Earth Sciences and coordinated by IITM, Pune. The Meghdoot app and the backend platform can be a means to create a sustained engagement and dialogue between climate information producers, users and intermediaries and further the efforts to promote adaptation (Singh *et al.* 2016). Since its inception more than two years ago on Google Play (Google Play Store) as well as Apple App Store, Meghdoot has received a good response with 200,000+ downloads/installs and an average rating of 3.3/ 5.0 by 863 app users (as of July 26, 2021) on Google Play (Google Play Store) (Dhulipala *et al.,* 2021).

Supporting women farmers in a changing climate

It is well recognized that women and men are affected differently by the changing climate and or also climate variability. Women and men can also be powerful agents of innovation in response to climate change and may have different adaptive knowledge and capacities. Understanding this knowledge gap and engaging women and men in participatory, gender-responsive technology design and management can encourage changes in gender relations, improve community outcomes and strengthen community climate resilience. However, facilitating such transformation requires an enabling social, political, economic and institutional context (Huyer *et al*., 2016; Bantilan *et al.,* 2013).

CONCLUSION

In the semi-arid agroecology where the majority of livelihoods are dependent on agriculture, adaptation to climate change and extreme events is of paramount importance. This will be met through continuous on-farm adjustments through a mix of new technological options (e.g., heat and drought tolerant germplasm), enhanced decision support (e.g., next-gen agroadvisories) and redesign or 'transformation' of farming systems which are inherently more resilient to climate extremes. Given the cross-sectoral nature of climate change impacts, improving the adaptive capacity of people requires an inter-disciplinary and gender sensitive approach to implementing climate-smart technologies, policies and institutions. Science–policy engagement efforts to accelerate climate action in agricultural systems are therefore key to enabling the sector to contribute to climate and food security goals.Increased cooperation and partnership between farming communities, researchers, extension, the public and private sectors are the basis for real advances in adapting to these enormous challenges. The three thirds principle, i.e. allocating resources for research, engagement and communications,as suggested by Dinesh et al., (2018), may help the research agenda to link with the information needsof decision makers at all levels from local governments to State, Central (federal) government in such as way that climate-resilient and climate-smart approaches are mainstreamed in their policy strategies, plans and programmes.

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