Food Security and Climate Change in the Asia-Pacific Region: Evaluating Mismatch between Crop Development and Water Availability

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Abstract

Phenological development is the single most important attribute of crop adaptation to shifting climates. Climate change may alter the rate of phenological development and the amount and distribution of rainfall during the growing season. These changes may in turn result in mismatch between water demand by crops and water availability from rainfall. This paper illustrates how an understanding of the impact of climate shifts on key crops will enable the Asia-Pacific farmers, community workers and policy agencies to better prepare and adapt to climate change. Strategies include changes to existing policy and practices, for example, timing of planting, managing rainwater resources, use of new varieties, disease management protocols, alternate crops and shift in geographic distribution of crops. An international project is described which combines a new analysis of realized changes in meteorological parameters, and use of estimates from published work on future climates to assess temporal shifts in crop phenology, likely shifts in the pattern of rain and water availability, mismatch between crop phenology and water availability, and the expected consequences of this mismatch for food security.

1. Introduction

Climate variability and climate change, and in particular the inability to predict or respond to growing season weather, are major threats to the profitability and even the viability of farming operations. This is the case in both developed and developing countries, although in developing countries the farmer's livelihood is more affected by individual crop failures.

In real-life situations, climate variability and climate change occur simultaneously, with long-term natural cycles or permanent changes being super-imposed on short-term variability. However, adaptation to climate variability and climate change involves different approaches for different stakeholders. Adaptation to climate variability requires a range of on-farm management practices to protect farmers from adverse consequences. Climate change has additional local implications such as time of planting and choice of crop type or variety, and Government policy implications regarding water availability and areas suitable for cropping.

Climate change may result in changes in the temporal distribution of meteorological variables during the crop growing season. One particular concern is that crop phenological development, which is largely determined by temperature and photoperiod, may be out of phase with rainfall and hence water availability during critical periods of grain yield determination. The possible mismatch between crop phenology and water availability poses the following questions:

1. What are the expected temporal shifts in crop phenology under future climates, and what are the driving forces behind these changes?
2. What are the likely shifts in the pattern of rain and water availability?
3. To what extent climate change will contribute to any mismatch between crop phenology and water availability?
4. What are the expected consequences of this mismatch for food security?

The paper describes case studies of past, existing and planned projects to address these questions. It concludes with a listing of strategies to adapt to the mismatch between crop phenology and meteorological variables.

2. Key Issues Related to Climate Change, Crop Phenology and Water Availability

Phenological development is the single most important attribute of crop adaptation to shifting environments (Anderson et al., 1978). Both season length and the relative duration of key phenophases are critical determinants of grain yield (Sadras and Connor, 1991). The relative duration of the pre- and post-flowering phases is critical for determinate species in rain-fed systems (Sadras and Connor, 1991). For example, genetic improvement of wheat in Australia has been associated with dramatic shifts in time to anthesis relative to the early germplasm introduced in the country. Similarly, adaptation of chickpeas to different environments of India is largely driven by the matching of phenology and environment. Phenological development is genetically controlled and environmentally modulated, chiefly by temperature and photoperiod. Indeed, temperature-driven phenological shifts constitute strong evidence of recent warming. Australian studies with wheat and grapevine suggest a week shift in maturity ^{o}C^{-1} change in ambient temperature (Petrie and Sadras, 2008; Sadras and Monzon, 2006).

Modelling studies on the effect of climate change on crops have often focused on grain yield under future climate scenarios (Asseng et al., 2004). In this paper we focus on temperature and rainfall changes in the past century in Australia and their effect on wheat phenological development, grain yield and hydrology. Two examples are given from different parts of the wheat growing areas of Australia- the north-east part of New South Wales in the east and the south-west region of Western Australia (Figure 1).

3. Temporal Shifts in Crop Phenology with Climate Change

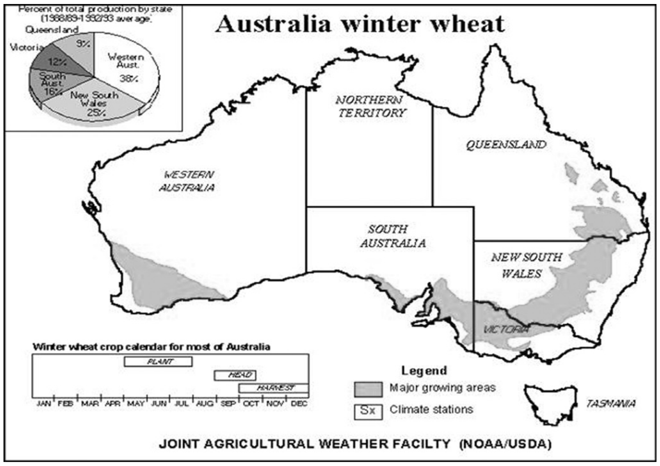

Figure 1: Wheat growing areas in Australia

As the wheat module in APSIM and CERES-Wheat both assume that crop phenology is driven by photoperiod and temperature (Jones et al., 2003; Keating et al., 2003), changes in duration of crop phenophases simulated with these models can be primarily attributed to changes in temperature. Thermal time models have been used to investigate the effects of climate change on phenology of woody perennials. The expectation is shortened season length associated with warmer climate in the last decades. The aim of simulation modelling was to quantify the actual magnitude of phenological changes, the relative changes in the duration of pre- and post-flowering phases, and the interaction between changing temperature and sowing date for wheat in eastern Australia.

Sadras and Monzon (2006) studied the changes to phenophases for wheat at Narrabri in northern NSW. Realized mean annual temperature changes over the period of simulation (1957-2000) were in the order of plus 0.2^{o}C 10-year^{-1} period (Hennessy et al., 2008). Simulated changes in phenophases are summarised below:

- Simulated time to maturity of crops sown in mid-May was reduced at a rate of 0.3- 0.054 days year^{-1} ($p<0.0001$) using a linear regression model. A non-linear model fitted to the data shows a sharper decline in time to maturity in the last two decades due to a more rapid increase in temperature over this period.
- Simulated time from sowing to flowering was reduced at 0.26-0.047 days year^{-1} ($p<0.0001$), accounted for most of the variation in time to maturity ($r^2=0.77$, $p<0.001$).
- Duration of the modelled post-flowering phase was unchanged ($p>0.21$). Shortened time to anthesis was associated with increased temperature in the pre-flowering phase, while the lack of change in the duration of the flowering-maturity phase corresponded with unchanged temperature in this phase. The lack of change in temperature during post-flowering resulted from earlier flowering, which shifted post-flowering development to relatively cooler conditions, thus neutralising the trend of increasing temperature detected for the average post-flowering phase.
- The rate of change in the duration of modelled wheat phenophases (sowing to flowering and sowing to maturity) declined with late sowing. Full graphical representation of these data is shown in Sadras and Monzon (2006).

In China, due to a shift of rainfall (Liu et al., 2009; Shao et al., 2006), and especially increases in temperature, the northern boundary of winter wheat has extended. There have also been changes in sowing date and length of phenophases compared with 20 years ago.

An analysis of trends in on-farm rice and wheat yields in the Indo-Gangetic Plains, starting from the 1980s using CERES models, revealed that reduced radiation and increased minimum temperatures have been associated with a decline in the simulated potential yields in several places. However, alternative interpretations of the link between increasing temperature and yield reductions are possible and correlative evidence needs to be interpreted with caution (Peng et al., 2004; Sheehy et al., 2006).

4. Recent Shifts in the Pattern of Rain, and Impacts on Crop Yield and Hydrology

Water availability is a world-wide constraint to agricultural productivity (Fereres and Gonzalez-Dugo, 2009). Shifts in rainfall patterns including amount and seasonality can have dramatic impacts on crop productivity and food security. Dore (2005) reviewed recent trends in precipitation, and concluded that the following general global pattern is emerging: (a) increased precipitation in high latitudes (Northern Hemisphere); (b) reductions in precipitation in China, Australia and the Small Island States in the Pacific; and (c) increased variance in equatorial regions. The changes in precipitation in Australia for two periods are shown in Figure 2a and 2b.

For the period 1950-2007 there are both large negative (-50 mm decade^{-1}) and positive (+50 mm decade^{-1}) changes in annual rainfall. Changes for the period 1900-2006 are much less extreme, ranging from -20 to +20 mm decade^{-1}. Also, geographical distributions of rainfall change do vary between the two periods. For example, started in 1950, a strong drying trend is observed for south-eastern Australia that is not evident for the 1900-2006 series. This is related to a wet cycle in the 1950s. This highlights the importance of not only the length of the time series for analysis but also its actual starting and end limits.

Since the mid-1970s a significant decline in winter rainfall has been experienced in the Mediterranean and the semi-arid region of Western Australia (Smith et al., 2000). This decline is apparent in Figure 2a, and is a continuation and amplification of the trend shown in Figure 2b. The decline in rainfall in the south-west of Western Australia was associated with, and probably caused by, a large-scale change in global atmospheric circulation during the mid-1970s with anthropogenic force contributing to about 50% of the observed rainfall decline (Cai and Cowan, 2006). The drop in rainfall by up to 20% has had significant negative impacts on the water sector in Western Australia. For example, the water inflow into dams surrounding Perth has declined by about 50% (Power et al., 2005). While the impact of the drying trend on the water sector is very clear, the impacts on the agricultural sector are less well understood. As most of the agriculture in Western Australia is rainfall limited, it has been assumed that a drying trend would also have a negative impact on crop production. However, despite reduced growing season rainfall, observed farmers' average wheat grain yield in the Western Australian wheat belt increased from 1 t ha^{-1} in 1970 to about 1.7 t ha^{-1} in 2000 (Turner and Asseng, 2005).

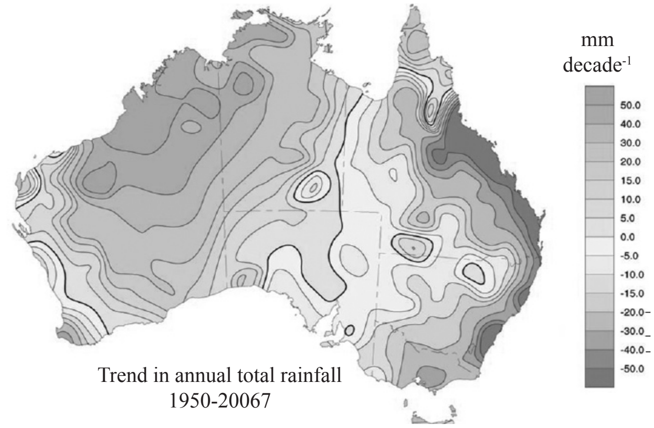

Figure 2a: Historical changes in mean annual rainfall for Australia over the period 1950-2007

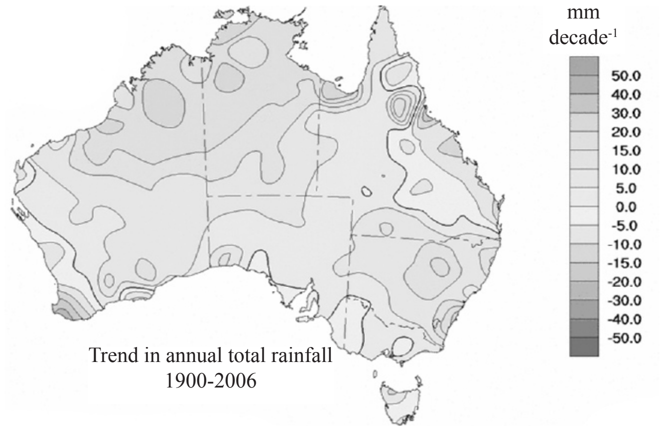

Figure 2b: Trends in mean annual rainfall for Australia over the period 1900-2006

When examining trends in historic grain yield data, it is difficult to separate the effect of climate change on crop production from the effects of changes in land use, crop varieties and crop management (Magrin et al., 2005). Such uncertainties can be overcome by using simulation models to assess the effects of changed climate on crop yield. Asseng et al. (2009) used the APSIM model in combination with historic weather data to study the impact of past rainfall reductions on wheat yield, deep drainage and nitrate leaching against a constant background of cultivars and management. Unexpectedly, this study revealed that despite the large decline in rainfall, simulated yields (Figure 3a) based on the actual weather data did not fall. However, simulated drainage (Figure 3b) and hence nitrogen leaching decreased by up to 95%. These results were due to the fact that rainfall reductions mainly occurred in June and July, a period when rainfall often exceeds crop demand, and when large amounts of water are normally lost by deep drainage. These simulated findings explain why climate change in this area has had little impact on crop yields but large impacts on deep drainage and stream flow. The results have significant implications for estimating future climate change impacts in this region, with rainfall reduction causing non-proportional impacts on production and externalities like deep drainage, where proportionality is often presumed (Asseng et al., 2009).

When changes in crop phenology and rainfall and water availability are considered collectively, it follows that the shifts in rainfall and temperature (minimum, maximum and average) patterns need to be considered against the framework of dynamic cropping systems where length of growing season and phenological shifts may be moving critical periods of yield determination in relation to patterns of water availability. Mismatches between crop phenology and water availability may develop, and the analysis of mismatches and strategic responses to maintain productivity are the subject of the projects discussed below.

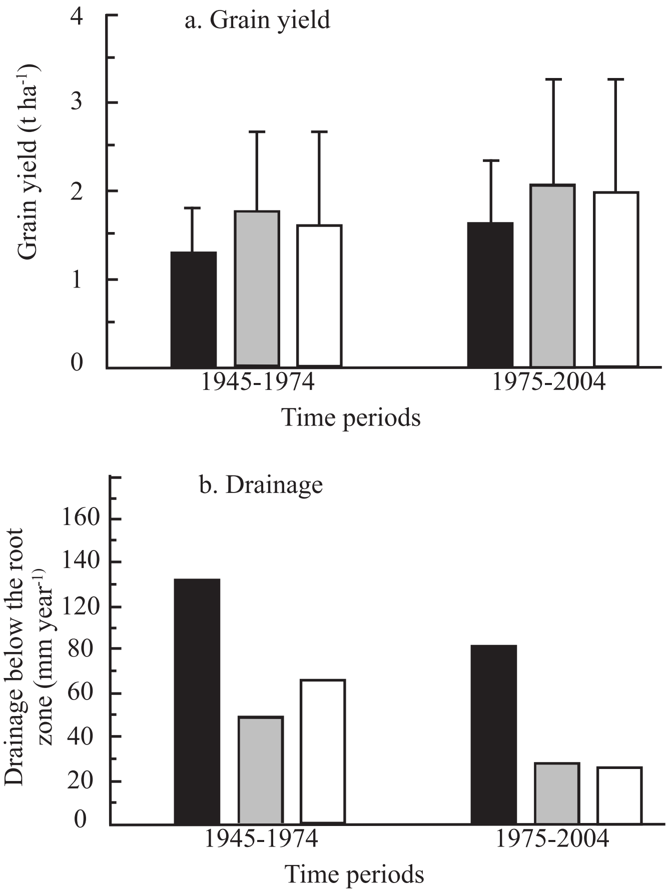

Figure 3: Simulated average a) wheat grain yield and b) annual deep drainage below potential root depth for a sand (filled bars), loamy sand (diagonal lines) and a duplex soil (cross bars) at Mingenew, Western Australia

5. A Catchment-scale Project on Integrated Genetic and Natural Resource Management (IGNRM) in India

This model watershed integrates a genetic and natural resource management (IGNRM) approach at a small catchment scale by adopting a 'consortium, collective action, capacity building and convergence' (4Cs) principle. It resulted in increased crop productivity by two to four folds, reduced runoff by 45%, and reduced soil loss from 2.6 to 1.1 t ha^{-1} year^{-1} (Table 1). Increased groundwater availability, diversification of cropping systems with high-value vegetables and improved livestock-based systems were important system components (Wani et al., 2003, 2008). This participatory research and development approach has built the resilience of the community and natural resources to cope with the impacts of drought and future challenges including climate change (Wani et al., 2008). This approach has provided the 'proof of concept' for the hypothesis that crop yield gaps between current farmers' yields and achievable yields can be bridged and productivity and incomes can be doubled in rain-fed areas through a science-led IGNRM community watershed approach.

The IGNRM approach involves:

- Understanding the probable impacts of climate change on crop production and water availability.
- Sharing the knowledge with small farm holders about the changing climate, its impact on agriculture and adaptation strategies.
- Identification and evaluation of soil, water, nutrient, crop, pests and ecosystem management practices as adaptation strategies. These include rainwater management through conservation, water harvesting and improved irrigation methods, and development of site-specific nutrient and land management practices to improve soil health at micro-watershed/catchment scale.
- Diversification of cropping and farming systems to increase family incomes of small farm holders.
- Identifying policies and institutions to enhance water and other inputs use efficiency and protecting the environment.

This project will be incorporated into the International Project on Adaptation to Climate Change described below.

6. An International Project on Climate Change and Adaptation to Mismatches in Crop Phenology

The co-authors of this paper have recently come together as Principal Investigators in an International Project entitled 'Food Security and Climate Change in the Asia-Pacific Region: Evaluating Mismatch between Crop Development and Water Availability'. Funds are being provided for two years by the Asia-Pacific Network for Global Change Research (APN) and the project aims to utilise current knowledge of the changes to

Table 1: Effect of integrated water management interventions on runoff and soil erosion from Adarsha Watershed, Andhra Pradesh, India

Year	Rainfall (mm)	Runoff (mm)		Peak runoff rate (m^3 s^{-1} ha^{-1})		Soil loss (t ha^{-1})	
		1	2	1	2	1	2
1999	584	16	NI	0.013	NI	NI	NI
2000	1161	118	65	0.235	0.230	4.17	1.46
2001	612	31	22	0.022	0.027	1.48	0.51
2002	464	13	Nil	0.011	Nil	0.18	Nil
2003	689	76	44	0.057	0.018	3.20	1.10
2004	667	126	39	0.072	0.014	3.53	0.53
2005	899	107	66	0.016	0.014	2.82	1.20
2006	715	110	75	0.003	0.001	2.47	1.56
Mean	724	75	44	0.054	0.051	2.55	1.06

NI=Not installed; Source: Sreedevi and Wani (2009); 1: Treated; 2: Untreated; *10.4%; **6.1%

the phenology, water availability and yield of selected crops under climate change.

The main activities include:

1. Collection of historical and current climate, crop and management data from selected sites in China, India and Australia to allow us to conduct scenario studies for target crops such as rice, sorghum, wheat, maize, chickpea and cotton.
2. Collection of key agronomic data including phenology, water availability period, and grain yield and biomass for selected field sites to encourage community participation.
3. Analysis of existing data on phenology, water availability and yield using the cropping systems simulation model APSIM and locally available models and by comparing with current farm practices to determine if there are any increased risks to crop production and food security in the study region.
4. Using the models to assess practices recommended for projected future climate change scenarios.
5. Developing and evaluating adaptation strategies to minimize the risk and maximize the opportunities related to the likely impact of climate change variables on current and future practices.

Studies on the likely shifts in the rainfall pattern involve analysis of both realized change over the climate record, and projections of future trajectories using GCM. Many authors have produced projections of climate change in Asia using GCM. Our approach therefore combines (a) new analysis of realized changes, and (b) use of existing and well accepted estimates from published work on future climates. Preliminary information on realized changes in rainfall pattern including timing of onset and withdrawal, amount and intensity of rain in the past few decades will be collated, depending on availability of climate records. One outcome using reliable long-term historical rainfall data is to identify locations in China, India and Australia where such shifts have occurred. Dore (2005) highlights approaches used in different institutions for rainfall pattern analysis. We will use a series of established methods to analyse rainfall shifts, including Walsh and Lawler seasonality index, Markham vectors for seasonality, and approach for size of event patterns. Time series analysis will also be used and indices may be modified as required.

Along with the analysis of historical information, published information on projected climate change scenarios will be matched with crop phenology, water availability and agronomic practices. Reference publications for climate projections and modelling tools to link climate, phenology and agronomy include Huda (1988), Huda (1994), Huda and Virmani (1987), Huda et al. (2007), Moghaddam and Huda (2007), Monteith et al. (1989), Sadras and Monzon (2006), and Moeller et al. (2009).

One major outcome of this project is to link together existing projects in three countries in the Asia Pacific region. In India, we will link with the Adarsha Watershed Project described earlier. The watershed project is an innovative program of water, soil, and land management enabling farmers to access water and grow crops not just in the rainy season, but all year round. In China, our project links with the national key project of mapping agro-climatic resources and adaptation of agriculture to climate change, particularly in water availability. The joint Center of Excellence for Dryland Agriculture, set up in China in 2009 with support from institutions including ICRISAT, is serving as a platform to sustain cooperation in the region. In Australia, it links with a national program co-funded by government and farmers aiming at improving farm water-use efficiency. Projects operate under the umbrella of 'Australia's Farming Future', a program run by the Federal Government Department of Agriculture, Fisheries and Forestry.

Participation of policy personnel from Australia, China and India, particularly in planning workshops, sets the direction of this work in accordance with their policy needs which helps to identify the issues including location and pattern of cropping; efficient use of water (rainfall and irrigation—green water and blue water), and land use policy. Appropriate maps of suitable areas for crop production now and in the future, information on changes on land use patterns, water availability and crop phenology are useful to them for making decisions.

7. Conclusions and Strategies for Adaptation to Climate Change

An understanding of the impact of climate shifts on key crops under climate change, as well as the risks and opportunities, will enable farmers, community workers and policy agencies to better prepare for and adapt to climate change, through changes to existing policy and practices. Sharma (2009) reviewed threats and opportunities in dry-land and irrigated cropping systems of Asia. He concluded that sustainable food production in Asia 'lies in scientific advancements that could alleviate a string of problems including climate change, shrinking availability of fertile land, marginal land under cereal cultivation, soil degradation, dwindling water availability for irrigation, biotic and abiotic stresses, yield gaps, genetic yield stagnation, localized labor shortages, and policy failures. Opportunities for sustainable increase in the productivity of cropping systems in Asia include:

- Advances in management practices—integrated and site-specific nutrient management, integrated pest management and integrated crop management collectively aiming at enhancing productivity, resource-use efficiency and conservation of the resource base.
- Rainwater harvesting and efficient use at small catchment scale with community involvement.
- Genetic improvement in cereals—new plant types in rice and wheat, expansion of chick-pea, pigeon-pea, groundnut and other dry-land legumes, maize hybrids, hybrid rice, improved disease tolerance and drought and heat tolerant cereals.
- Development of more diverse cropping systems in which new crop cultivars and management techniques are integrated.

From our studies of the mismatch of phenology and water availability, some specific strategies arise for climate change adaptation which include the following:

1. Changing time of planting.
2. Managing rain water resources through water harvesting and irrigation at times of high crop demand.
3. Development of new short duration high yielding, high temperature and water stress tolerant cultivars with matching phenology and anticipated changes in the growing season.
4. A shift in geographic distribution of crops to provide a better match between phrenology and climate.
5. Monitoring emerging new pests and diseases, and their management by adopting integrated pest/disease management options.
6. Use of alternate crops.

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