ACIAR SDIP Foresight Program: Status Report

CLIMATE CHANGE IN SOUTH ASIA: PROJECTED TRENDS AND IMPACTS ON AGRICULTURE IN THE EASTERN GANGETIC PLAINS

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Executive summary

Climate change will adversely impact on agriculture in South Asia and jeopardise food security and rural livelihoods. This briefing note* provides a summary overview of the projected future changes to the region's climate and the likely impacts on agriculture in the Eastern Gangetic Plains (EGP).

Climate change trends

- There has already been observed changes to the EGP's climate over the past 50 years: annual mean temperatures have increased by around 1°C, the number of extreme heat days has increased and cold days decreased; rainfall intensity has risen, cropping season length and optimal planting times have changed, and there has been a slight decrease in annual precipitation;
- By mid-century average annual temperatures in the EGP are projected to be between 1°C-1.5°C higher than the 1980-2010 average (depending on the future emissions trajectory) and 2.5°C-4°C+ by 2100, with warming most pronounced in winter and for night time minimums;
- The number of extreme heat days is expected to rise 2-3 fold by mid-century and the number of cold days fall by a similar amount;
- Projected trends in annual average precipitation remain subject to some uncertainty but averaged across all models the EGP is expected to receive a small increase in total rainfall (up to 10% by mid-century) with most of the increase occurring during the summer monsoon months;
- There will be an increased risk of drier winters across most of Indo Gangetic Plains;
- Rainfall intensity will increase, especially during the summer monsoon;
- Evaporation and evapotranspiration are expected to rise in line with temperatures (5-7% by mid-century), potentially offsetting projected precipitation increases;
- Floods and droughts will increase in frequency and intensity, as will year-on-year climate variability, with wet years becoming wetter and dry years drier;
- River flows are likely to be lower in winter and late spring/early summer, and higher in early spring and late summer.

Impacts on EGP agriculture

- Increased annual mean temperatures will push many regions beyond optimal growing conditions and reduce growing season length, particularly during the Rabi season, and grain yields are expected to fall 10-15% by mid-century.
- By late century many areas of the EGP will be unsuitable for grain production.

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- Extreme weather events (extreme heat, higher risk of intense droughts/floods) pose the most immediate threat to EGP agriculture over the period to mid-century but underlying changes to average climate pose the most significant threat in the longer term.
- Elevated atmospheric CO_2 concentrations will boost crop growth rates and yields, primarily for C3 plants, but may result in negative effects (such as a lower nutritional content of crops).
- Pest and pollinator regimes will change but the net impact on crop yields remains uncertain.

Targeted research on the impact of climate change on EGP agriculture remains limited and needs to be significantly increased, especially in relation to crop heat resilience, changes to insect pest/pollinator regimes, and crop responses to elevated CO_2 concentrations.

1. Introduction

The objective of this briefing note is to provide a summary overview of:

- Observed changes to South Asia's climate over recent decades;
- How the region's climate is projected to change in the future; and
- Identify the potential impacts these changes could have on agricultural production and food security in the Indo-Gangetic Plains

1.1. Context

South Asia is among the world's most vulnerable regions to the impacts of climate change due to its: existing physical, geographic and climatic characteristics (some areas of South Asia are projected to warm above the average global rate); increasing water scarcity; and the high level of dependence of most of the region's population on agriculture as their primary livelihood. A recent 2018 report by the World Bank Group identified South Asia as one of the world's major climate change hotspots and highlights the projected impact on food, water and energy security, and in particular the impact on agricultural livelihoods[1]. Understanding how the climate is likely to change and the impacts these changes will have on physical and socioeconomic systems is essential for informed planning and decision making at all scales.

1.2. Observed changes in South Asia's climate to date

South Asia's climate has changed over the past 50 years. Observed changes include:

- Annual mean temperature has increased by approximately 1°C across most of the region (including the EGP), in line with average global trends, but warming has tended to be above the global average in the West/Northwest and the high mountain regions of South Asia. Some areas of the Hindu Kush Himalaya (HKH) have already warmed by 2°C – well above the global average.
- Warming has been most pronounced in winter and night time minimum temperatures - summer and day time maximum temperatures have increased but to a lesser extent.
- The frequency and intensity of extreme weather events has increased, especially the number of extreme heat days, rainfall intensity and flood severity, while the number of cold days has also decreased. For example. Pakistan has experienced a 5-fold increase in the number of extreme heat days since 1980.
- Rainfall intensity has increased for most of the HKH and Northern India but as yet there has been no significant change in intensity indicators for the EGP.
- There have been no statistically significant observed changes in annual average precipitation to date, but there has been an observed weakening of the Asian monsoon, a slight drying trend across parts of southern and western Pakistan and across the Indo Gangetic plains, while there has been increased precipitation in parts of Southern India and the HKH region.
- Changes in temperature and seasonal precipitation patterns have already altered growing seasons and optimal planting times, especially affecting the Rabi season, with a shortening of the season in most places, and a lengthening in the HKH region.
- Sea levels have risen around 20-25cm, broadly in line with the global average, resulting in observed increases in coastal erosion and saline intrusion in the low-lying delta regions.

[1] South Asia's Hot Spots: The impact of temperature and precipitation changes on living standards, World Bank Group, 2018

2. Modelling future climate change

Projections of how the climate will change in the future are subject to some uncertainty, especially in the long term (post 2050) as the amount and rate of climate change is heavily dependent on the future emissions trajectory.

Most projections contained in the literature are based on averaged results from an ensemble of global climate models (General Circulation Models – GCMs). Different models provide different outcomes but all models generally agree on the underlying direction of changes, they just vary in the estimates of the magnitude of change. At a global and aggregate regional level GCMs perform well and are being constantly improved and refined. However, at a local and sub-regional level GCM results remain relatively coarse and often mask specific sub-regional climate dynamics. This is particularly the case for South Asia due to its complex geography and topography (especially the Hindu Kush Himalaya) and the existence of meteorological data gaps.

To provide more granular and targeted information on potential changes at the regional and sub regional level specific regional downscaling techniques are often used. Some regionally specific modelling and downscaling work has been undertaken for South Asia but it still remains relatively limited – as consequence future climate change projections remain heavily dependent on GCM modelling results. Nonetheless, sufficient consistent information exists to provide a good indication of the direction and magnitude of change (especially for temperature, extreme weather events and sea level rise), although uncertainty surrounds potential annual and seasonal precipitation changes.

The Intergovernmental Panel on Climate Change (IPCC) has adopted four potential atmospheric concentration pathways up to 2100 (RCP 2.5, 4.5, 6.5 and 8.5) that are used as a basis for comparison of potential future climate change outcomes. RCP 2.5 is the lowest IPCC emissions pathway (consistent with keeping warming to 2°C or less), and would involve radical cuts in global emissions from present levels, while RCP 8.5 is the highest emissions scenario (business as usual but embodying expected technology and efficiency gains). The world's current emissions trajectory is closely tracking the RCP 8.5 trajectory and, if this persists, it is projected to deliver 4°C+ increase in global average mean temperature by 2100, and potentially 6-8°C+ at the poles and in high mountain regions.

While some assessments focus on RCP 2.5 it considered unlikely that the global community, based on the current level of international commitment and action, will be able to move to the RCP 2.5 pathway in a time frame sufficient to limit warming to less than 2°C[2]. As a result, RCP 4.5 (a mid-range scenario that still requires concerted mitigation action), and RCP 8.5 (depicting business as usual with little or no mitigation action) are the two most commonly used reference benchmark for future climate change projections.

The projections contained in this document relate specifically to South Asia, and where possible, the Indo Gangetic Plains (IGP) and Eastern Indo-Gangetic Plains (EGP). Greater emphasis is given to projected changes over the next 30-50 years, rather than likely outcomes by the end of the century, although reference is made to potential longer-term impacts. Projections up to 2050 are more robust and less dependent on the future global emissions trajectory, as much of the climate change over the next 20-30 years is already locked into the system, or soon to be committed. There is less than 0.5°C difference in temperature outcomes between the high and low emission trajectories by mid-century. It is beyond 2050 where the projected mean temperature changes under different emission pathways begin to diverge significantly, with more than 2°C difference in warming by 2100 between the low and high emission scenarios.

[2] All countries signatory to the Paris Accord have submitted Nationally Determined Commitment documents that outline their national mitigation targets and objectives will be to 2030. In aggregate if all countries deliver on their commitments, climate models suggest that it this emissions trajectory would result in a global temperature rise of 2.5°C -3°C by 2100 (broadly consistent with RCP 4.5).

3. Climate change projections for the EGP[3]

3.1. Projected temperature changes

There is a relatively high degree of confidence in temperature projections for South Asia and considerable consistency across different models.

- Average mean temperatures are projected to increase for all regions across South Asia over the coming decades, with more pronounced warming in the west (Pakistan, North-western India, Afghanistan) and across all of the HKH region - inland areas will experience greater warming than coastal areas;
- Mean temperatures for the EGP region are projected to rise by 1°C -1.5°C (relative to the 1980-2010 average) by mid-century;
  - In western South Asia and the HKH regions temperatures are projected to increase at a higher rate than the regional average (1.5°C -2.2°C+ by mid-century).
- Projected warming for the EGP by 2100 would be around 2.5°C under RCP 4.5 and 4°C-4.5°C under RCP 8.5;
  - The IGP is considered a mild to moderate climate change hotspot under RCP 4.5 but becomes a more severe hotspot over time under RCP 8.5;
  - Some areas of the HKH could potentially warm by more than 6°C by 2100 under RCP 8.5[4].
- Warming will be more pronounced in the winter (Dec-Feb) than summer (Jun-Aug);
- Night-time minimums are projected to rise faster than day time maximums (especially in winter);
- The number of above average extreme heat days is likely to triple by mid-century and the number of below average cold days will decrease.

[3] Projections of future changes in the South Asian contained in this section are sourced from: Krishnan, R., Shrestha. A., and Ren, G. Chapter 3: Climate Change, Comprehensive Assessment of the Hindu Kush Himalaya", ICIMOD, 2018.; IPCC Climate Change 5th Assessment Report 2013; "4°C - Turn Down the Heat: Climate Extremes Regional Impact and the Case for Resilience", World Bank 2013; South Asia's Hot Spots: The impact of temperature and precipitation changes on living standards, World Bank Group, 2018; Climate Change Profile of Pakistan, Asia Development Bank, 2017; and H Zheng, et al, "Future climate and runoff projections across South Asia from CMIP5 global climate models and hydrological modelling", Journal of Hydrology: Regional Studies, 2018.

[4] Krishnan, R., Shrestha. A., and Ren, G. Chapter 3: Climate Change, Comprehensive Assessment of the Hindu Kush Himalaya", ICIMOD, 2018

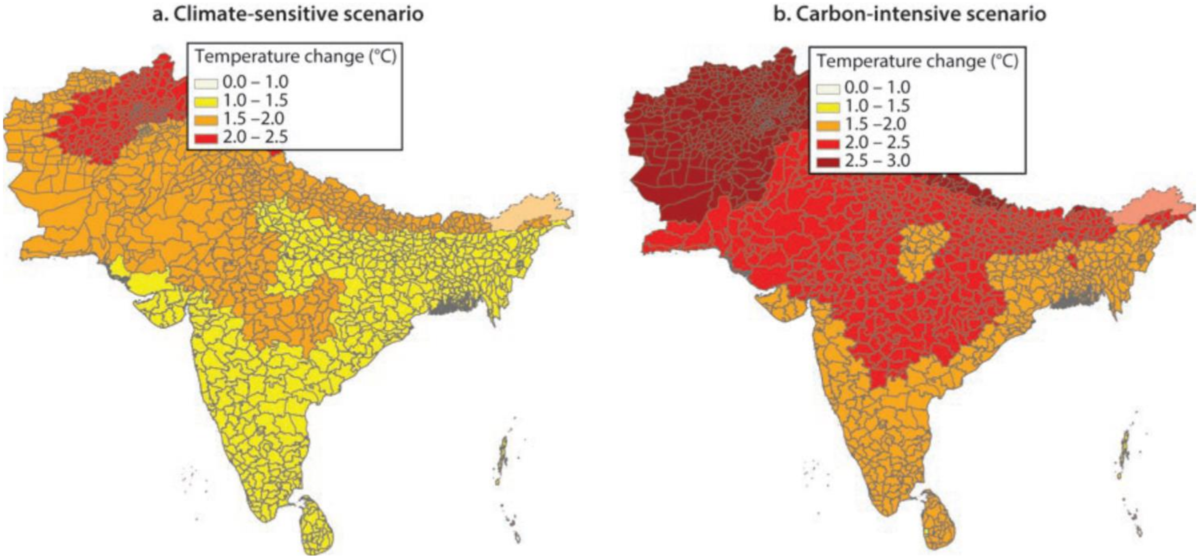

FIGURE 1: ANNUAL AVERAGE TEMPERATURE IS PROJECTED TO CONTINUE INCREASING DRAMATICALLY UNDER THE CLIMATE SENSITIVE AND CARBON-INTENSIVE SCENARIOS[5] (ORIGINAL SOURCE IS HARRIS AND OTHERS 2014 (CLIMATE RESEARCH UNIT TS 2.24). NOTE: CHANGES ARE BY 2050 (AVERAGE FOR 2036-2065) RELATIVE TO 1981-2010 AVERAGES (FIGURE 2.1).

3.2. Projected changes in precipitation and water availability

Annual precipitation projections are subject to much greater uncertainty than temperature projections. Some models predict a significant increase in precipitation while others a slight decrease. Considerable uncertainty also surrounds potential changes in the strength and length of the monsoon. The level of confidence on precipitation projections is considered only low-medium and considerable variation in projections exists across the different models.

- Averaged across all models there is projected to be a slight increase in annual precipitation in the EGP (5-10%) at 2°C and 15-30 % at 4°C, in contrast to the observed decline in average annual precipitation over the past 30 years;
    - In general, the higher the warming level the greater the projected increase in rainfall.
- The highest increase in rainfall is projected for the HKH region and the Southern/Western Indian Peninsula.
- All models predict a significant increase in climate variability in relation to precipitation with wet seasons becoming wetter and dry seasons drier.
- *Seasonal variation*: The probability of receiving less rainfall is highest during Rabi (drier winters) as all models predict an increase in summer monsoon rainfall across most of South Asia (though this is less pronounced in arid areas);
    - the EGP faces a lower risk of reduced Rabi rainfall compared to western South Asia (and some models predict a slight increase in Rabi precipitation);
    - North western India/Pakistan and Afghanistan face the greatest risk of reduced winter rainfall;
    - There is a higher level of consistency across models in relation to seasonal changes (as compared to average annual rainfall) but still with only a medium level of confidence.

[5] Mani, M., S. Bandyopadhyay, S. Chonabayashi, A. Markandya, and T. Mosier (2018). *South Asia's Hotspots: The Impact of Temperature and Precipitation Changes on Living Standards.* South Asia Development Matters. Washington, DC: World Bank.

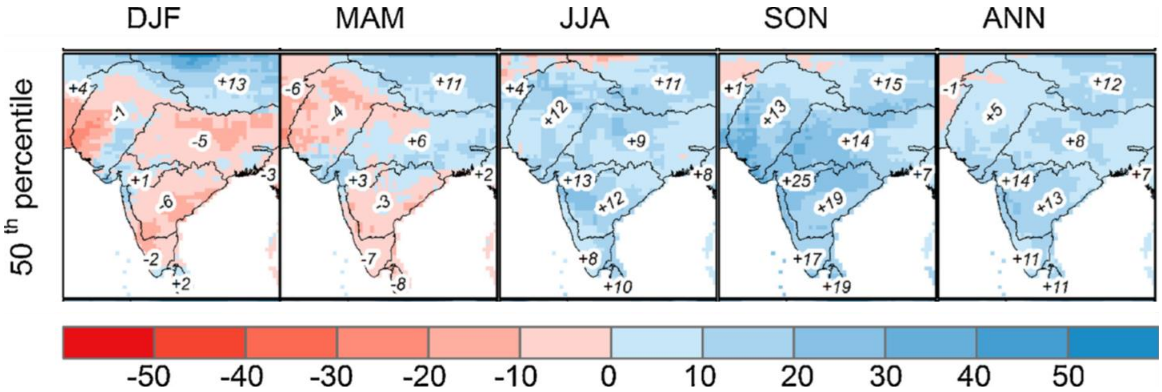

FIGURE 2: PROJECTED PERCENTAGE CHANGE IN PRECIPITATION (MEDIAN FROM THE 42 GCMS) FOR RCP8.5 FOR 2046-2075 RELATIVE TO PRESENT/BASELINE (1976-2005) FOR THE FOUR SEASONS AND THE ANNUAL SCALE (ZHENG ET AL, 2018; PP99).

Potential evaporation Potential evaporation and evapotranspiration are projected to increase across all of South Asia as temperatures rise.

- For the EGP, models predict a 5-7% increase in annual potential evaporation by mid-century, but higher levels during the winter months (8-10% increase);
- The most pronounced increase in evaporation potential is in the western regions of South Asia (in line with greater projected warming) where annual evaporation potential is expected to increase by 8-10% (10-12% in winter months);
    - As a general rule of thumb for each 1°C rise in average mean temperatures (across the range of 28 to 35°C) evaporation and evapotranspiration increases by 4 to 5%[6].
- Projected increases in evaporation and evapotranspiration are likely to accentuate water availability issues, irrespective of changes to precipitation, and could potentially outweigh projected precipitation increases, especially across the IGP and the western regions of South Asia.

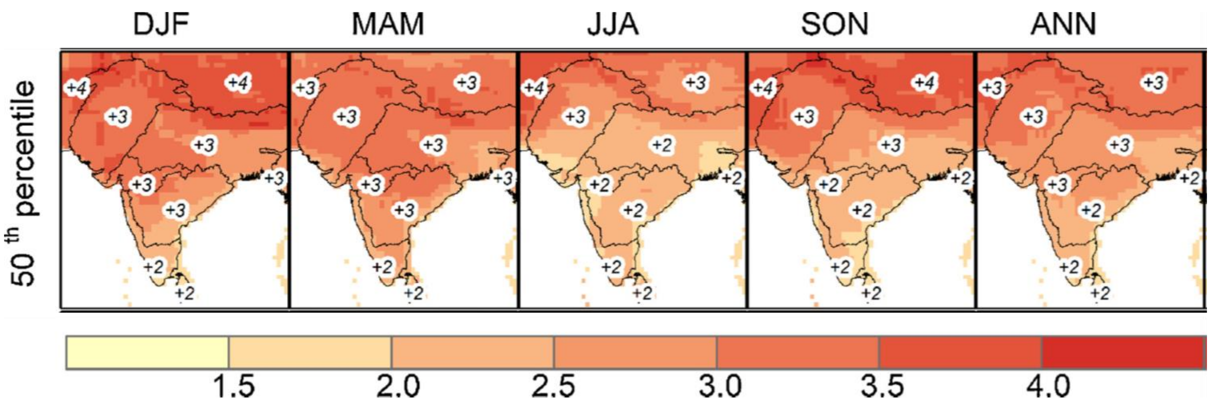

FIGURE 3: PROJECTED CHANGE IN DAILY AVERAGE TEMPERATURE (MEDIAN FROM THE 42 GCMS) FOR RCP8.5 FOR 2046–2075 RELATIVE TO PRESENT/BASELINE (1976–2005) FOR THE FOUR SEASONS AND ANNUAL SCALE (ZHENG ET AL., 2018; PP98)[7]

[7] H Zheng, et al, "Future climate and runoff projections across South Asia from CMIP5 global climate models and hydrological modelling", Journal of Hydrology: Regional Studies, 2018.

Rainfall intensity is projected to increase considerably over the coming decades and is likely to have subsequent flow on effects in terms of more rapid and severe flood events, increased soil loss and crop damage.

- Intensity increases are projected to be most apparent for summer monsoon rainfall, with little or no change expected for winter rain intensity (Rabi);
    - While there is expected to be an increase in the number of intense rainfall days, modelling suggesting that there may be fewer total wet days in summer over the coming decades (increases in rainfall intensity account for much of projected increase in summer rainfall).

Annual run-off is projected to increase across most of South Asia, especially during the summer monsoon - consistent with projections for precipitation and rainfall intensity[8].

- Annual run-off is expected to increase by 10-15% by mid-century in central and northern India, and 20-30% in south west India/Eastern Himalaya/Tibetan Plateau;
- Most models predict a decrease in annual run-off in the far western regions of South Asia (particularly Afghanistan);
- There is no significant expected change in annual run-off by mid-century for the EGP.

Seasonal river flow regimes are likely to experience considerable change over the next 30-40 years, especially in winter, potentially exacerbating existing water security issues and irrigation water availability in many areas of west South Asia, central India and the IGP. The rapid changes occurring in the cryosphere of the HKH (loss of glacial mass and higher early spring melt rates) has already resulted in changes to seasonal river flow regimes, especially in the Indus, and this trend is expected to continue. There is a medium-high confidence in projected changes to river flow regimes. Projected changes to mid-century (at 2°C) include:

- Lower winter flows for the Indus and Brahmaputra, and to some extent the Ganges;
- Increased flows in early spring but reduced flows in late spring and early summer, particularly for the Indus and Brahmaputra;
- Higher flows during the monsoon, but with greater inter annual variability.

3.3. Extreme weather events

Both the intensity and frequency of extreme weather events is projected to increase as temperatures rise and are considered the single largest threat to livelihoods and crop yields over the next 20-30 years. A significant increase in the number of extreme heat days, higher flood peaks, more intense dry periods (particularly short-term drought), and increased rainfall intensity are the key changes to extreme weather changes that will impact on the IGP/EGP, while in coastal regions projected increases in cyclone intensity and storm surges are also key threats.

- The incidence of *extreme heat days* is projected to increase 2-3 fold with 2°C of warming, and up to a 10 fold increase in a 4°C world[9].
    - By mid-century most areas of the IGP and central India are likely to experience an additional 30-40 extreme heat days a year and will continue to rise as warming intensifies;
    - Conversely the incidence of extreme cold days is projected to fall considerably.

[8]Krishnan, R., Shrestha. A., and Ren, G. Chapter 3: Climate Change, Comprehensive Assessment of the Hindu Kush Himalaya", ICIMOD, 2018

[8] H Zheng, et al, "Future climate and runoff projections across South Asia from CMIP5 global climate models and hydrological modelling", Journal of Hydrology: Regional Studies, 2018

[9] "4°C - Turn Down the Heat: Climate Extremes Regional Impact and the Case for Resilience", World Bank 2013

- *Flood frequency and severity* (peak flood levels) are projected to increase across most of South Asia (including the IGP/EGP) as temperatures rise, especially during the summer monsoon - increases in rainfall intensity and the greater variability in monsoon strength (wet years are likely to become wetter) are key contributors to increased flood risk (high confidence level).
- *Drought frequency and intensity* is also projected to increase across South Asia (especially in West South Asia, central India and IGP/EGP) over the coming decades, primarily due to the increased probability of extreme dry years, higher evaporation rates and the potentially reduced winter precipitation (high level of confidence).
- *Cyclones* are also projected to increase in intensity and destructive force (high level of confidence), and the Bay of Bengal is considered a *hotspot* in the region in terms of vulnerability to tropical cyclones, although uncertainty surrounds whether the frequency of cyclones will change (low confidence)
    - *Storm surge* levels are projected to increase in line with storm intensity increasing the land area subject to temporary inundation (and subsequent salinization).

3.4. Sea level rise

Some uncertainty surrounds potential future sea level rise (SLR), particularly in the long term, due to knowledge gaps that still exist in relation to cryosphere-climate dynamics and the sensitivity of the ice sheets (especially Greenland and Antarctica) to different levels of warming. There is a high level of confidence in projected sea level rise for the next 20-30 years but beyond mid-century the level of confidence declines.

SLR is a long slow process and the seas will continue to rise for centuries after global temperatures have been stabilised. The warming experienced to date has already locked in several metres of rise in the long term (over several centuries). The rate at which the sea levels increase in the future, and the final long-term sea level equilibrium point, depend on how much the planet warms. While stabilising at 2°C is likely to deliver several metres of rise over the very long term, with 3- 4°C of warming the seas are likely to eventually rise 20+ metres.

- Sea levels in South Asia have risen by around 20 -25cm over the past 100 years (in line with the global average) with some regional variations;
    - Melting of land-based ice sheets and glaciers presently contribute around 55% to SLR, while thermal expansion of the ocean accounts for the remainder.
- The average annual global rate of SLR is presently 3mm/year - most of South Asia is rising at a similar rate, although some areas are experiencing higher rates (for example, sea levels in the Maldives have been rising at a higher rate than the global average);
- By 2050 the IPCC projects an additional 8-12cm of SLR, and an additional 40-70cm by 2100, (although some studies suggest that rises of up to 100cm are possible by the turn of the century).

4. Climate change impacts on agricultural production in the EGP

The projected changes to South Asia's climate over the next 30-50 years are expected to present many challenges for agricultural productivity and food security. It is likely to compromise the ability of South Asian countries to maintain food security. Increases in climate variability, intensified weather extremes (especially extreme heat, drought and intense rainfall events), shifts in seasonal precipitation patterns, and changes to insect and pollinator regimes are all expected to impact on agricultural production. Many of South Asia's primary food production regions are already at or beyond optimum growing conditions for many crops, especially grains, and a warming climate will push many regions further beyond optimal growing conditions for existing crops[10]. The on-going rise in atmospheric CO_2 concentrations will also impact on agricultural productivity, with both positive and negative effects.

There is a clear consensus across the literature that the impact of projected climate change on agricultural productivity in South Asia will be overwhelmingly negative and crop yields (especially grains) are likely to fall, particularly if warming exceeds 2°C. This could have potentially serious repercussions for millions of rural livelihoods. For example, it estimated that changes to average mean temperatures will reduce living standards by up to 10-15% over the period to 2050 in India, Bangladesh, Sri Lanka and Pakistan, with agricultural livelihoods the most impacted[11].

Although the severity of climate change impacts in the eastern regions of the EGP are expected to be more moderate than other areas of South Asia (especially the western and northern regions) the projected changes are still expected to be significant, even if warming can be kept to 2°C[12]. As mentioned earlier, global emissions continue to track the RCP 8.5 trajectory which would deliver 4.0°C+. Even if all the 2030 emission reductions agreed through the Paris Accord commitments are delivered, the globe will still be on track for 2.5°C-3.0°C warming over the course of this century.

The extent to which crop yields and aggregate food production change in the coming decades depends on a complex interaction of climatic variables (temperature/precipitation/extreme weather/carbon dioxide fertilisation effect), natural ecosystems (the responses of plants, insects and soil organisms) and human adaptation efforts (for example the development of climate resilient cultivars, greater water use efficiency). As a result, predicting the actual magnitude of the impact on agricultural productivity over the period to 2050, and beyond, is challenging and subject to considerable uncertainty.

Over the past 20 years there has been an increase in targeted research on the potential response of different crops to climate change, and the knowledge base has improved. However, many knowledge gaps remain, especially for South Asia where targeted crop impact assessments have been relatively limited to date (although some have been undertaken)[13]. As a consequence, estimates of future impacts on yields and aggregate food production are often based on the results of global studies and research, many of which have been undertaken in temperate regions. Nonetheless, sufficient

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[10] Mani, M., S. Bandyopadhyay, S. Chonabayashi, A. Markandya, and T. Mosier (2018). *South Asia's Hotspots: The Impact of Temperature and Precipitation Changes on Living Standards.* South Asia Development Matters. Washington, DC: World Bank.

[11] Op cit

[12] See IPCC Special Report on the impact of 1.5°C of global warming, Intergovernmental Panel on Climate Change, 2018 for an overview of the additional impact of even 0.5°C increase in mean temperatures – the impacts are non-linear.

[13] For example: 'Assessment of impacts of climate change on rice and wheat in the Indo-Gangetic plains', M. Zacharias et al., Journal of Agrometeorology (2014) and 'Climate change impacts on rainfall and temperature in sugarcane growing Upper Gangetic Plains of India', R. Verma, T. Srivastava and P. Singh, Theoretical and Applied Climatology, 2018

understanding exists to indicate the likely direction (both positive and negative) of potential changes at different levels of warming.

The section provides a brief overview of the current understanding on how changes to key climatic variables and ecosystems may impact on agricultural productivity and food security in the EGP in the coming decades.

4.1. Changes to mean temperature and temperature extremes

The prevailing mean temperature regime is one of the most important variables influencing plant growth and productivity. Any change to mean temperatures (and to average minimum/maximums) can impact on crop yields, alter growing season length and optimum planting times, and determine types of crops that can be grown in a specific geographic location. The changes to average mean temperatures in South Asia over the past 50 years has already resulted in observed changes to growing seasons and optimal planting times. The projected increased warming of 1C – 1.5C by 2050, and possibly 3°C – 4.0°C+ by 2100, is expected to have more far reaching impacts.

- As a *general rule of thumb,* based on global assessments, for each 1°C rise above optimal growing conditions wheat yields decline by 6%, rice by 3%, maize 7% and soybean 3%;
    - Yield declines for South Asia are expected to be higher than the global average for wheat (9%) and rice (6%), but lower for maize (5%)[14].
    - However, some areas in South Asia that are currently 'cold limited' (for example parts of the HKH region) are likely to experience improved growing conditions in the short-to-medium term, although the area that will benefit is small compared to those that don't.
- *Higher average temperatures* reduce crop growth duration, shorten grain filling periods and reduce seed set.
    - Many of South Asia's current cropping areas are likely to become progressively unsuitable for certain crops over the coming decades, especially Rabi wheat but also rice.
- *Higher minimum temperatures and extreme temperature events* also adversely impact on yields, especially those that have a minimum chilling degree requirement, and if minimum temperatures exceed optimal thresholds (as is projected for the IGP), reducing pollen viability and fertilisation rates.
    - *Extreme temperature events* (which are projected to become more frequent and intense) at critical stages of the crop cycle are a major risk;
    - For example, above average minimum temperatures reduce rice spikelet fertilisation rates (increased sterility), and if temperatures exceed 34°C during grain filling periods yields fall considerably (a 10% decrease for each 1°C increase above the threshold);
    - For wheat if temperatures exceeding 31°C become prevalent just before anthesis pollen sterility increases, and if average temperatures exceed 26°C post anthesis yields decline considerably[15].
- Livestock are also susceptible to increased temperatures and extreme heat events (heat stress) – for example, poultry do not cope well with extreme temperatures, and mortality rates increase significantly in temperatures above 35°C and milk production from dairy cows tends to decline at high average temperatures.

[14] "Temperature increase reduces global yields of major food Temperature crops in four independent estimates". C. Zhao et al, Proceedings of the National Academy of Scientists, Vol 114, (2017)

[15] 'Assessment of impacts of climate change on rice and wheat in the Indo-Gangetic plains', M. Zacharias et al., Journal of Agrometeorology (2014).

- The productivity of freshwater fisheries is also affected by changes in water temperatures, water quality, salinity, seasonal flow regimes and the health of aquatic ecosystems (already degraded through a range of human impacts).
    - Although fish production is likely to be adversely affected by extreme climate events, especially in very dry years (low flows), the current scientific consensus is that the projected increased temperatures in South Asia's inland water ways will increase the productivity of freshwater fisheries, through enhanced growth and a lengthening of the fish breeding season[16].

4.2. Changes in rainfall and water availability

Maintaining adequate soil moisture is critical to achieving good yields and the projected changes to precipitation, evaporation and river flow regimes will adversely impact on crop yields in the EGP. Although models generally indicate that the EGP may experience an increase in average precipitation as global mean temperatures increase, the possibility of drier than average winters remains a real risk, especially where irrigation is limited.

    - The impact of increased temperatures on plant productivity is accentuated if soil moisture levels are low;
    - The projected increases in evaporation/evapotranspiration will reduce water availability and changes to seasonal flow regimes may mean that access to reliable water supplies for irrigation (especially during Rabi) could be more limited;
- The probability of more frequent and intense drought events (and the occurrence of ultra-dry years) will rise as the climate warms
    - This is likely to increase the risks of water scarcity and soil moisture deficits (especially for rainfed areas) – resulting in crop production losses
    - Measures to increase water use efficiency and more drought resilient cultivars will be important to maintaining production.
- More intense rainfall events, and increased flood frequency and severity, is likely to result in greater crop, livestock and farm infrastructure losses, and increase the risks of soil loss – having both immediate and longer-term impacts on yields
    - Soil conservation techniques and other flood impact reduction measures (including improved post flood recovery) will be important to reduce these risks.

4.3. Elevated CO_2 concentrations

In addition to the impacts of changes in temperature, precipitation and extreme weather on agricultural productivity and crop yields, the changes to atmospheric CO_2 concentrations will also impact on crop growth, nutritional levels, and plant-herbivore insect interactions. These are projected to have both positive and negative effects.

Atmospheric CO_2 concentrations have increased from 280 ppm in 1850 to reach 410 ppm today (nearly all of this increase has occurred since 1950), and concentrations continue to rise by 2.0-2.5 ppm/year but may accelerate if aggregate emission levels continue to rise. Based on current trends, CO_2

[16] 'Inland Fisheries and Climate Change: Vulnerability and Adaptation Options', A.P.Sharma et al, ICAR – Inland Fisheries Research Institute, 2015.

concentrations are expected to reach 480- 500 ppm by mid-century, and 550 by 2070 (excluding any climate change feedback effects).

While the impacts of elevated CO_2 concentrations on crop productivity and yields are more a medium to long term issue, the research on projected concentration levels by the 2050-2070 period has revealed several potential changes that could occur. These include:

- *Carbon dioxide fertilisation effect*: Elevated CO_2 concentrations will increase the growth rates of crops, pastures and trees through increased photosynthetic efficiency and stimulated root growth resulting in increased biomass production and faster crop growing times (positive effect);
    - This growth stimulus is mainly for C3 plants (e.g. rice/wheat/soybeans/C3 grasses) than C4 plants (e.g. maize) due to their different photosynthetic pathways (C4 plants are already near their maximum CO_2 efficiency levels).
    - At 550ppm yields for most C3 crops could increase by 10-20% (all else being equal) through the fertilisation effect (positive impact for food production) - the benefits to C4 plant productivity are much lower.
    - The CO_2 fertilization effect appears to be enhanced under elevated temperatures, but these gains could be potentially offset by the impact of elevated temperatures on grain filling duration and pollen fertilisation/sterility effects, especially in warm areas.
- *Water use efficiency* (ratio of CO_2 uptake to evapotranspiration) tends to increase with rising concentrations (up to 10-15% more efficient at 550 ppm), mainly due to increased photosynthetic efficiency but also through stomata closure.
    - The reduction in crop water demand/unit output is a positive impact but this likely to be largely offset by increases in evaporation resulting from temperature rises.
- *Nutritional levels* of most C3 plants (grains, legumes and pastures) tend to fall as CO_2 concentrations rise – recent research on wheat and rice grown at the projected 2050 concentrations were found to contain 10% less zinc, 5% less iron, and lower protein content[17].
- *Crop insect damage* is also expected to increase as CO_2 concentrations rise, primarily due to falling nitrogen/protein contents of plant tissue (requiring insects to consume more vegetation for the same energy yield), changes to the insect life cycles, and reduced production of insect inhibitors in some plants (lowering natural insect resistance).
- The external (soil) *phosphorous requirement* of plants has been observed to increase as CO_2 concentrations increase, and the ability of plants to utilize phosphorous (internal) declines – potentially necessitating increased applications of phosphorous fertiliser to maintain yields, particularly in phosphorous deficient cropping regions[18].
- The nutritional value of pastures and grasses also falls as concentrations rise which is likely to adversely impact on livestock health, growth rates and the carrying capacity of the land.

As much of the research has focussed on temperate regions, more research is required to assess whether similar impacts are likely to be experienced in the Indo-Gangetic plains region. Nonetheless, the current understanding is that the carbon dioxide fertilisation effect is likely to have positive impacts in terms of plant growth/yields/water efficiency but also potentially adverse impacts (especially nutrition levels) that could potentially offset these gains.

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[17] "Increasing CO2 threatens human nutrition", S. Myers et al, Nature, 2014

[18] "The impact of elevated carbon dioxide levels on the phosphorous nutrition of plants", J.Jin, C.Yang and P.Sale, The Annuals of Botany, 2016

4.4. Changes in insect pest and pollinator regimes

Climate change is known to impact on the life cycle of insect pests and pollinators, but it remains a poorly researched area and considerable uncertainty remains. Studies in more temperate regions indicate that increased average temperatures alter insect herbivore/predator interactions and insect/plant interactions. Key pollinators such as bees are particularly susceptible to variations in average and extreme temperature regimes, and this is already impacting on crop pollination and yields in North America and Europe. Higher temperatures and relative humidity are also projected to increase the prevalence of plant fungus and virus outbreaks.

Given that there has been very limited research in the potential impacts of climate change on pest/pollinator regimes in South Asia there is insufficient information presently available to draw any definitive conclusions on the potential impacts for agricultural productivity in the EGP.

5. Summary and Conclusions

Although some uncertainty still surrounds the timing and magnitude of climate change, especially in relation to precipitation trends, it is evident that the projected changes to the region's climate will adversely impact on agricultural productivity in the coming decades. In the light of these changes maintaining adequate food security, and rural livelihoods, will become increasingly challenging even if warming can be limited to 2°C. While changes in the EGP are expected to be somewhat more moderate than some other sub-regions of South Asia, they are still expected to be significant.

The most significant threat in the short to medium term will be changes to the frequency and intensity of extreme weather events (particularly heat extremes, droughts and intense rainfall events). In the longer term the expected to changes mean temperatures and seasonal water availability are likely to make existing cropping regimes unviable and may necessitate a move out of agriculture for millions of people, especially if warming exceeds 2.5-3°C. Identifying and implementing appropriate adaptation measures and addressing current knowledge gaps on likely impacts will be essential to minimising the future impact of climate change and the costs of adaptation. Potential response measures include:

- Ensuring access to reliable supplies of irrigation water is essential to maintaining EGP agricultural production in the EGP, including careful management of groundwater resources;
    - Increasing farm water efficiency and reducing aggregate water demand;
- Identifying more heat and drought tolerant cultivars and introducing alternative crops more suited to the future climatic conditions;
    - Adopting agricultural and livelihood diversification strategies (including non-agricultural activities) which minimise climate related risks to household/farm incomes,
- Protecting critical farm infrastructure, livestock and soils from the impact of flooding and intense rainfall events, including improved post disaster recovery assistance mechanisms; and
- Filling critical knowledge gaps in the EGP through targeted research on: the climate sensitivity of existing crops and livestock varities, potential changes to pest and pollinator regimes, and the impact of elevated atmospheric CO_2 levels on crop productivity and nutritional levels.

The adoption of Conservation Agriculture and Sustainable Intensification (CASI) technologies can contribute to delivering more climate resilient farming systems in the short to medium term but more substantive changes to agriculture in the EGP are likely to be required in the longer term (post 2050).

Foresight for Food Systems Status Reports

The Foresight for Food Systems in the Eastern Gangetic Plains (EGP) is a project led by IFPRI that seeks to lay down the groundwork for an open, scientifically informed and participatory foresight for food exercise in the EGP region led by regional scientists and engaging with other stakeholders like policy-makers, private investors, and farmers. A set of status reports on different components of the food system for better understanding of the current status, future challenges, research and knowledge gaps has been prepared for informed policy making for a sustainable future. The status reports will provide inputs into foresight and scenario building exercises in the region.

This work is funded by the Sustainable Development Investment Portfolio (SDIP), an Australian Government development strategy to increase water, food and energy security in South Asia to facilitate economic growth and improve livelihoods, targeting the poorest and most vulnerable, particularly women and girls.

SDIP initiatives aim to build technical capacity, share and generate knowledge, facilitate transboundary dialogue and mobilise the private sector and civil society in support of this objective. The focus area for SDIP initiatives is the three Himalayan river basins – the Indus, Ganges and Brahmaputra – which cover parts of India, Pakistan, Bhutan, Nepal and Bangladesh.

SDIP is a 12-year strategy (2012-2024), recognising that many of the critical interventions required for improving the integrated management of water, food and energy at the river basin level require sustained engagement to build regional cooperation and capacity over time. The Australian Centre for International Agricultural Research (ACIAR) is one of seven partners in SDIP. ACIAR SDIP funds research and development activities that improve agriculture's contribution to sustainable food systems. For further information on the project please visit https://aciarsdip.com/component-2