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Food Security: Near future projections of the impact of drought in Asia

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ICAS: Institute for Climate and Atmospheric Science

SRI: Sustainability Research Institute

SEE: School of Earth and Environment

CCCEP: Centre for Climate Change Economics and Policy

FOREWORD

The challenge of moving towards a food secure world – where "all people, at all times, have physical and economic access to sufficient, safe, and nutritious food to meet their dietary needs and food preferences for an active and healthy life" (FAO World Food Summit, 1996) – is a huge one. The global population is growing and human interactions with food are changing (driven by changes in urbanisation, globalisation and the nutritional transition associated with the growth of the global middle class), such that global demands for food are growing. On the supply side, the world has limited scope for expansion of the amount of agricultural land, and there is increasing recognition of the environmental impacts of agriculture that must be reduced for long term sustainability. On top of this, as climate changes, the potential for weather events to impact on food production grows. Local or regional droughts can have catastrophic consequences where the drought happens, but can, working through the market, have considerable knock on consequences for people globally through increasing volatility of prices.

Understanding how weather will impact on food production in the near future is, therefore, of great importance. This report is both timely and significant for three reasons. First, this report focuses on the 2020s whereas the majority of existing research projects drought to the 2050s and beyond. This gives it immediacy for policy makers. Second, the methodology demonstrates that impact predictions are possible by coupling climatic modelling with socio-economic drivers, and where there are indications of changing risk then that can drive mitigation and adaptation strategies. Third, the results highlight areas where risks are high, and thus the overall potential for impacts, locally and globally. This report emphasises that there are strong gains to be made through 'systems thinking', coupling both environmental risks with and assessment of society's ability to cope with them.

Professor Tim Benton

UK Champion for Global Food Security
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CENTRE DIRECTOR'S FOREWORD

The threat posed by climate change related drought in Asia has typically been presented in terms of its impacts in the 2050's and beyond. This has always been the Achilles' heel for climate change adaptation– it is too far out of range for policy makers to contemplate. This means that unlike the attention given to fossil fuel reduction either the issues aren't dealt with in the mainstream or at best are relegated to the preserve of the third sector. We can all understand the possibility of running out of fuel for our cars or homes but have we thought about the likely impacts of drought in the next 10 years?

If you are not in academia, working on overseas development or in a third sector organisation, concerns over food security and drought may well mean you don't lose sleep over global scale modelling or "adaptation" to climate change. Nor did I. Of course, like many people I'm aware of the issues but doing something about it was entirely different. To be honest by the 2050s the usefulness of my contribution to society will have long passed. I will either be dependant on society or most probably no longer here to worry. In reality I'm one of those who has been rather involved on energy and fossil fuel issues, activities related to the so called "mitigation" of climate change, mainly because I hope that together with my colleagues we can make a difference.

We therefore commissioned this report to find out what the nearer term impacts of climate change might be on an increasingly global issue – food security. The results of the analysis present a new and rather concerning evidence base that suggests climate change will affect all of us sooner than we expected. We have published this report to encourage further debate and instigate action - to make an impact on the policy makers and business leaders who can no longer afford to wait and see on adaptation – these issues will be felt on their watch.

Asian governments are facing severe challenges, and this grows as both the population and urbanisation increases, in turn creating more pressure on crop productions as human diets improve. This is further challenged by the potential of bio fuels and, whilst not commented on in this report, the authors acknowledge those impacts.

I’m delighted that Professor Forster and Dr Jackson could produce this report. Whilst the insights are very much presented as provision of evidence rather than policy options or solutions, this marks the start of engaging policy makers into the “here and now’ issue of food security. We hope that our “5 insights” approach will make a complicated issue accessible and meaningful. As one reporter recently headlined in an Asian newspaper when covering the forthcoming report “hunger looms” and there is a “Once in lifetime opportunity” for action by policy makers on food security to avoid a perfect storm.

Jon Price

Director, Centre for Low Carbon Futures

PREFACE

To make effective policy around the complex international issues of climate change, policy makers need access to up to date objective information. For the last 15 years I have been a lead author on Intergovernmental Panel of Climate Change (IPCC) reports that have directly informed UN climate negotiations of the latest science. These reports have focused on predicting changes for the 2050-2100 period. These dates, being beyond immediate planning horizons, could be one of the reasons why negotiations towards meaningful international action have dragged out over decades. In this work we choose a very different approach, focusing on the 2020s, highlighting decisions and actions that need to be addressed immediately. We choose to address one of the most pressing issues facing today's global society – food security.

Making shorter-term predictions is difficult because any climate signal can get lost in the randomness of weather. We manage this by averaging the projections from 12 of the world's state-of-the-science climate models, minimising both the effects of randomness and model errors. To our surprise we find that clear signals of climate change emerge within the next 10 years. Within only this short time, droughts will, on average, become months longer and markedly more severe (132% and 154% on average for wheat and maize) across Asia. China and India have the world's largest populations and are Asia's largest food producers. We predict that their wheat and maize harvests will be strongly affected by droughts in their growing seasons unless states and communities can quickly adapt their agricultural practices. The short time period makes adaptation more challenging and brings a greater threat to food security. With current infrastructure we find that China has a greater capacity to adapt and manage this threat, whilst India has a more challenging infrastructure and poses a greater food security risk. By sharing our detailed results with policy makers we would hope to join the effort of building effective adaptation policies for immediate deployment.

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KEY POLICY INSIGHTS

An increased risk of drought brought on by climate change poses a major threat to food security. To make informed and timely decisions addressing this key aspect of global food security today's policy makers and planners urgently require an understanding of risks in the near future (the 2020s) and an understanding of adaptive capacity, country by country. Research to date, however, has focused on projections for the 2050s and beyond.

This report examines the potential risks from climate driven drought to food production of wheat, maize and rice across Asia in the 2020s. State-of-the-science climate projections from 12 of the world's leading climate modelling centres were sourced from CMIP5, the fifth phase of the Coupled Model Intercomparison Project developed to underpin the forthcoming 5th Assessment Report from the Intergovernmental Panel on Climate Change (IPCC). Multi-model projections of soil moisture for the 2020s were used to assess the potential drought risk in this near term future.

The projections of drought risk were coupled with an analysis of adaptive capacity based on projections of seven key socio-economic drivers to determine which crop producing regions are expected to be most vulnerable to the effects of climate change driven drought on future harvests.

1. Focusing climate change models on the 2020s shows immediate decision and action on adaptation is needed. To make effective policy around the complex international issues of climate change, policy makers need access to up to date objective information. Similarly industry needs to be aware of the urgent risks and opportunities present in the near term so that they can plan appropriately.

Reports to date have focused on predicting changes for the 2050-2100 period. These dates, being beyond immediate planning horizons, could be one of the reasons why negotiations towards meaningful international action have dragged out over decades.

This new research uses projections modelled from 12 of the world's state-of the-science climate models. We find that clear signals of climate change emerge within the next 10 years, well within the planning horizons of both policy makers and industry leaders.

RECOMMENDATION: POLICY MAKERS AND INDUSTRY LEADERS SHOULD CONSIDER THE DETAILED RESULTS AS PRESENTED IN THIS STUDY WHICH DEMONSTRATE THE NEED FOR INCREASED EMPHASIS AND EFFORT OF BUILDING EFFECTIVE ADAPTATION POLICIES FOR IMMEDIATE DEPLOYMENT IN THE REGIONS HIGHLIGHTED.

2. There is an increased risk of more severe droughts in the 2020s. Compared to the 1990-2005 period, the 2020s will bring marked increases in drought severity across much of Asia from a combination of larger deficits in soil moisture for longer periods of time.

RECOMMENDATION: IMMEDIATE ACTIONS ARE NEEDED TO IMPROVE WATER RESOURCE MANAGEMENT. ACTIONS SHOULD INCLUDE SUSTAINABLE USE AND SAFE-GUARDING OF GROUND WATER SUPPLIES AS WELL AS IMPROVED HARVESTING OF RAINFALL.

3. The increased drought risk is an imminent threat to food security on a global scale. The 2020s will bring significant increases in drought severity for major wheat and maize producing nations including; China, Pakistan, Turkey and Iran. In China the increased drought risk is widespread, notably in Chongqing and neighbouring provinces. Key croplands such as the Huang He River Valley, Jilin and Liaoning provinces are also affected.

These impending changes should be of global concern since China, the most populous country in the world, is the largest producer of cereal crops. The short time frame makes adaptation more challenging.

RECOMMENDATION: ADAPTATION POLICIES MUST GO BEYOND WATER RESOURCE MANAGEMENT AND INCLUDE ADAPTATION OF FARMING PRACTICES SUCH AS ALTERED PLANTING DATES, IMPROVED TILLAGE AND MULCHING APPROACHES, AND MORE EFFECTIVE USE OF FERTILISERS AND PESTICIDES.

4. Adaptive capacity for the largest producers in Asia is mixed. Indonesia, China and Pakistan were found to be relatively well placed to adapt to climate change. Northern India, however, was found to have one of the lowest adaptive capacities in Asia for wheat production and central and northern India one of the lowest for maize production. Adaptation is critical in this region if global shortages of these key crops are to be avoided since India is the world's second largest producer of wheat and the seventh largest producer of maize.

RECOMMENDATION: ACTION MUST BE TAKEN TO REDUCE SOCIOECONOMIC BARRIERS TO DEVELOPING ADAPTIVE CAPACITY. MEASURES SHOULD INCLUDE REDUCING WEALTH INEQUALITY, IMPROVING ACCESS TO FAIR TRADE, ENCOURAGING WIDESPREAD DISSEMINATION OF NEW TECHNOLOGIES.

5. Socioeconomic changes necessary to build adaptive capacity are driven by the local context. The effectiveness of adaptive capacity measures varies between wheat and maize crops, between rich and poor nations and between different climate types. Regions with the greatest reductions in adaptive capacity from 1990-2005 to the 2020s are places with authoritarian regimes and/or arid ecosystems. Rice, wheat and maize production in middle income countries is especially vulnerable to drought.

RECOMMENDATION: FUTURE POLICY MEASURES NEED BE FLEXIBLE, BE REGULARLY MONITORED AND REVIEWED, AND ENGAGE WITH FARMERS AT A LOCAL LEVEL. TARGETING INVESTMENT AND TRAINING TOWARDS AGRICULTURAL SYSTEMS OF MIDDLE-INCOME COUNTRIES WOULD HELP ALLEVIATE THE NEEDS OF SOME OF THE MOST VULNERABLE COMMUNITIES.

1. INTRODUCTION

The dual impact of population growth and climate change is making food security an increasingly important issue for global society. One of the clearest threats to agricultural production from climate change is through possible increases in the frequency, duration or intensity of drought. The socio-economic impacts of droughts can be far reaching; historically droughts have led to migration of peoples, wars and collapse of governments (e.g. the failure of monsoons in India [Grove, 2007; Lal and Islam, 2010]). Recent droughts in Asia have continued to have far reaching impacts. The land area affected by dust storms in China has increased since 2000, crops failed in 2000-2002 in South Asia due to drought, water shortages and forest fires in South-East Asia were caused by droughts in 1997-1998 (Parry et al., 2007). These issues are particularly pressing in the developing world where, in general, agro-ecosystems have less resilience, households have fewer assets to rely on if farming suffers, and where there are less developed social safety nets to help ameliorate crises.

This report quantifies the potential change in drought risk over the next two decades, employing the latest projections of climate change made by twelve climate modelling centres across the world. The report looks at where 2020s harvests would be most vulnerable to drought examining the potential risk to future harvests for three main crop types (wheat, maize and rice). The aim is to provide governments and policy makers with the state-of-the-science assessment of near term drought risk in Asia and its potential effect, in order to build timely adaptation strategies to improve the food security in the region. While adverse climate impacts may increase further into the future, we concentrate on short-term projections as this is a timeframe more immediate to current policy goals.

1.1 GLOBAL AND ASIAN DROUGHT RISK

The recent food price spikes in 2008 and 2011 have triggered a rise in hunger and serious social unrest in a number of countries. This global crisis, plus the more recent famine in the Horn of Africa, illustrates potential threats caused to global food security by climate change and natural variability, and the urgent need to further understand threats to the global food system.

It is important to realise that food security is not only influenced by weather related problems that affect the supply of food. Food security is equally (if not more) influenced by factors that change the demand for food. This includes income levels, population growth, and changing diets. As such, the UK Government's chief scientist, Professor Sir John Beddington, argues that the world faces a perfect storm of problems thanks to the fact that, over the next generation, we expect our demand for food to be rising at exactly the same time as our ability to produce food may be diminishing. This concern is based, therefore, not only on climate models that project it will be more difficult in the future to produce cereal in many regions (Parry et al., 2005), but also demographic models that show the world's population reaching between 8.1 billion and 10.6 billion by the 2050s (UN DESA, 2012). These problems will disproportionately affect the developing world where the majority of people live (UN DESA, 2012).

The most recent research on climate change is sobering. While projections suggest that yields in higher latitude countries may benefit from carbon dioxide (CO_2) fertilisation and a longer growing season, many tropical areas are likely to experience reduced yields. For instance, global average spring wheat yields are projected to decrease by up to 25% over the next 50 years (Challinor, 2011), and some regions, such as South Asia and Southern Africa, may be affected sooner (Lobell et al., 2008). Parts of Asia have already seen a decrease in agricultural yields due to rising temperatures and extreme weather events. For example, the majority of China's population is involved in agriculture, hence depending on climate adaptation for their future livelihoods (Fraser et al., 2008). The drought in the northeast of China in 2008–2009 caused economic losses of at least US$2.3 billion and left more than 10 million people struggling with water shortages (Wang et al., 2011). Some studies have shown that whether an increase or decrease in crop yields is projected with climate change, depends upon whether or not the CO_2 fertilisation effect plays a physiologically important role (Lapola et al., 2009). While there remains large uncertainty regarding the impact of any CO_2 fertilisation effect, the IPCC forecasts with medium confidence that without the effects of CO_2 fertilisation agricultural yields will suffer a decrease of 2.5 to 10% by 2020 and of 5 to 30% by 2050 compared to 1990 (Parry et al., 2007). Furthermore, the agriculture sector's response to climate change will also be affected by the decreasing availability of fresh water in large parts of Asia. This can have far reaching impacts on the global food trade if Asia, which currently is largely food self-sufficient, needs to start importing significant quantities of food.

A number of studies have been conducted into the impact of climate on crop yield, agriculture and potential adaptation measures in China (Challinor et al., 2010; Fraser et al., 2008; Simelton et al., 2009; Tao and Zhang, 2010; Yang et al., 2007). Wang et al. (2011) examined soil moisture changes in China with a four model ensemble. They found that droughts in China were frequent and growing increasingly common, even though they were not always reported. Over the past 60 years 37% of China's area became drier, while 22% got wetter. Northern and central regions experienced the strongest drying trend. Fraser et al. (2008) investigated to what extent drought affected crop yields in China in the period 1961 – 2000. The results revealed that urbanisation, a low number of people employed in agriculture, a high proportion of cultivated land and fixed capital investment in agriculture all increased the sensitivity of harvests to rainfall anomalies for rice. In terms of adaptation, agricultural management factors play a key role for wheat and maize, whereas adaptation measures for rice are much more linked to social capital (Fraser et al., 2008).

1.2 POPULATION TRENDS

World population has now exceeded 7 billion people and is likely to increase to just over 9.3 billion by the middle of the century.

Developed countries will only see a marginal increase from 1.2 to 1.3 billion with the less developed regions seeing an increase from 5.7 to 8 billion (UN DESA). Over 5.4 billion people will be living in Asia, with 1.3 billion of these concentrated in China. Africa's population will double in the next four decades from just over 1 billion to 2.2 billion. It is difficult to project what these changes might mean in terms of the global carbon footprint as carbon emissions are closely linked to the development path of different countries and regions. However, the carbon emissions of high-income countries are currently 6–10 times as large as that of low-income countries (de Sherbinin et al., 2007). Samson et al. (2011) show that vulnerability to the impacts of climate change will be worst in areas with projected large population trends such as Central America, central South America, the Arabian Peninsula, Southeast Asia and large parts of Africa. High latitude regions, including most developed countries, will be least affected.

2. PROJECTIONS FOR THE 2020s

2.1 SOIL MOISTURE AND DROUGHT

Soil moisture is sensitive to the medium to longer-term effects of changes in the hydrological cycle and is the primary repository of water for the growth of crops. Variations in soil moisture have also been used to characterise global and regional drought (e.g. Sheffield and Wood, 2007).

The annual mean (October-October) soil moisture for the 1990-2005 baseline period is shown in Figure 1. Many parts of Asia have high levels of soil moisture relative to some other regions of the tropics due to their large seasonal monsoon rains.

Figure 1 also shows the projected multi-model annual mean soil moisture for the 2020s (November 2019 to October 2029). The patterns are almost identical indicating that there are only small changes in average soil moisture between the 1990-2005 period and the 2020s both across Asia and globally. This is mainly due to the relatively short time period for the projection. Further, any significant changes in soil moisture between wet and dry seasons could also be confounded within the annual mean change. Differences between soil moisture projections of different climate models (not shown) were much larger and are illustrated in the Appendix (Figures A.2 to A.7).

The regional trends in soil moisture are shown more clearly by the drought index DI (see Methods). An index value of one indicates no change in annual mean soil moisture. A ratio greater than one represents a projected reduction in soil moisture and, therefore, a greater risk of drought during the 2020s than experienced during the recent past. The results are shown in Figure 2 for Asia and a global scale figure is included in the appendices (Figure A.1).

For the majority of the populated global land area the drought index (D_I) shows changes in annual mean soil moisture of less than 1%. This is also true for Asia, although some regions in China show a reduction in soil moisture and likely have a greater risk of exposure to drought in the 2020s. India experiences the opposite with some regions projected to experience an increase in soil moisture. The small spatial extent of these changes and their small size is indicative of a range of responses between the 44 simulations (see Appendix, Figures A.2 to A.7). Roughly half the models show significant drying in China but not always in the same location.

As noted by the Commission on Sustainable Agriculture and Climate Change (2012) future drought and its effects on food production are as likely to arise from variations within the growing season as from long-term trends in soil moisture and precipitation, so it is also necessary to examine other indicators of drought. Figure 3 shows results for projected changes in drought number per decade (D_N), drought duration (D_D) and drought severity (D_S).

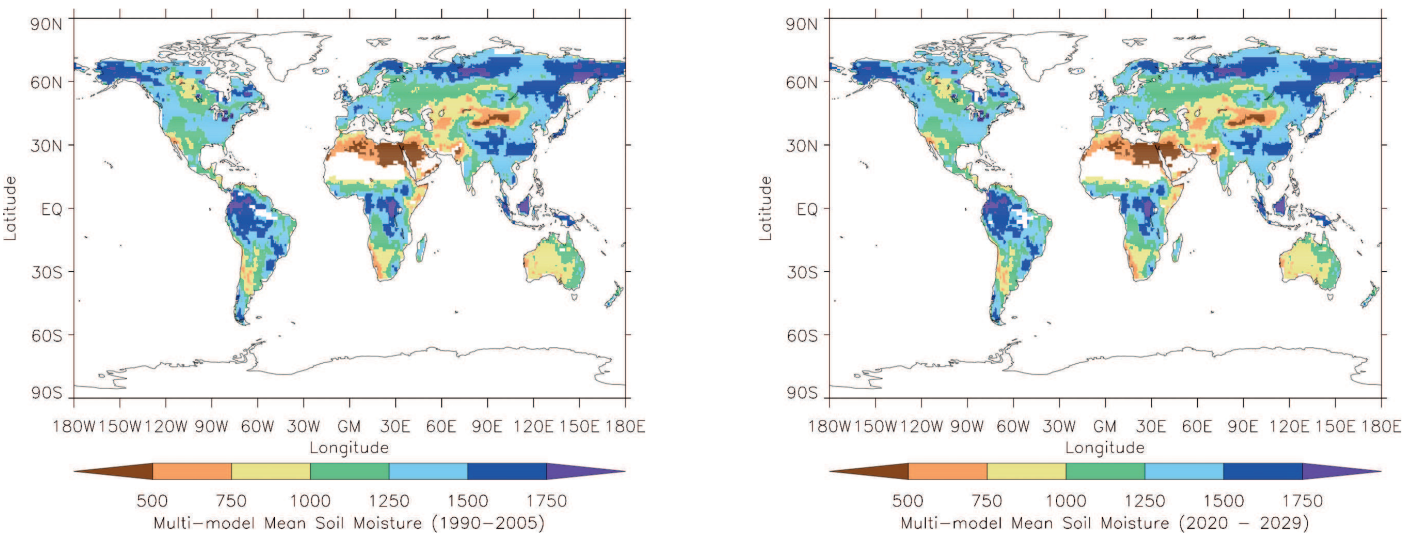


Figure 1: Multi-model annual mean soil moisture (kg m-^{2}) for 1990-2005 (left) and the 2020s (right) showing only small changes in annual mean soil moisture.

The number of droughts per decade takes no account of the duration or severity of the drought events but highlights monthly variability in soil moisture. For regions with relatively large numbers of droughts, this measure is an indicator of a potentially greater risk of drought than regions with smaller numbers of drought events. China and South East Asia stand out as having a relatively large number of droughts in 1990-2005. This will be, in part, due to the seasonal character of monsoonal rains. Parts of China and South East Asia are projected to have an increase in the number of droughts in the 2020s. At a global scale, the median change across all models in drought numbers from 1990-2005 to the 2020s was zero, consistent with the small projected change in global average soil moisture.

Drought duration (DD) is longest in North West Asia and its global pattern is sustained in the 2020s with a median increase in drought duration of 0.9 months (see Appendix Figure A.8). Many regions in Asia are projected to experience a shortening of drought duration, although China sees an increase in drought duration of around three months in its northern provinces, and there are larger increases in drought duration over Pakistan and Afghanistan.

Drought severity (D_S) by the 2020s is projected to become more severe at a global scale with the median of all 44 ensemble model runs for drought severity increasing from a shortfall in soil moisture of 337 kg m^{-2} to a shortfall of 541 kg m^{-2}. Drought severity in Asia increased in wheat and maize croplands by 132% and 154% respectively. In Asia, this change is seen most strongly in central and eastern China. In contrast, many parts of India are projected to experience a reduction in drought severity. Variation in D_N, D_D and D_S between different climate models is not shown but figures A.2 to A.7 illustrate the underlying variation between models using D_I

Figure 4 ranks the drought indices for individual countries in Asia according to the overall amount of drying between the recent past and the 2020s. The drought index (D_I) shows clearly the countries that experienced a wetting of soil moisture and those which experienced a drying. Drought measures which allow for monthly variations in soil moisture (D_D and D_S) show large increases in drought in many countries regardless of the long-term wetting or drying trend in soil moisture. For China and Afghanistan an overall drying coincides with the increase in drought severity and drought duration. Pakistan sees increases in drought severity and duration despite going towards a slightly wetter climate overall.

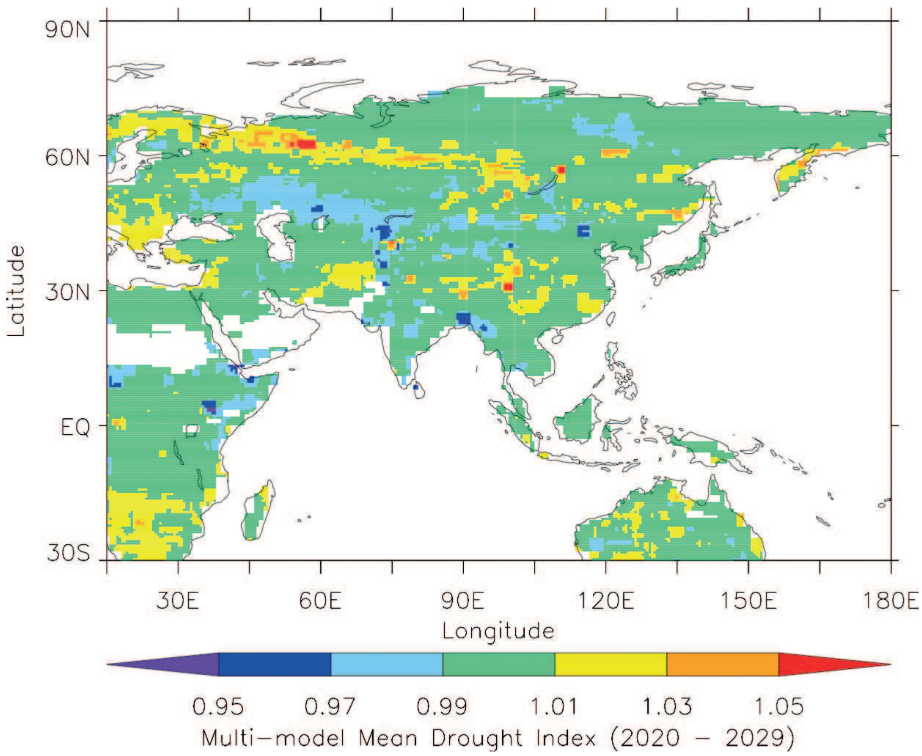


Figure 2: Projected drought index D_I for the 2020s showing small changes in drought risk overall with regional increases in parts of China and regional decreases in parts of India.

Figure 3: Drought number per decade (D_N) (top row), drought duration (D_D) (months) (middle row) and drought severity (D_S) (kg m^{-2}) (bottom row). The left-hand column shows multi-model mean values over 1990-2005, the central column mean values for the 2020s and the right-hand column the difference between the two periods. Whilst there are insignificant changes in numbers of droughts, drought duration and drought severity are projected to worsen by the 2020s.

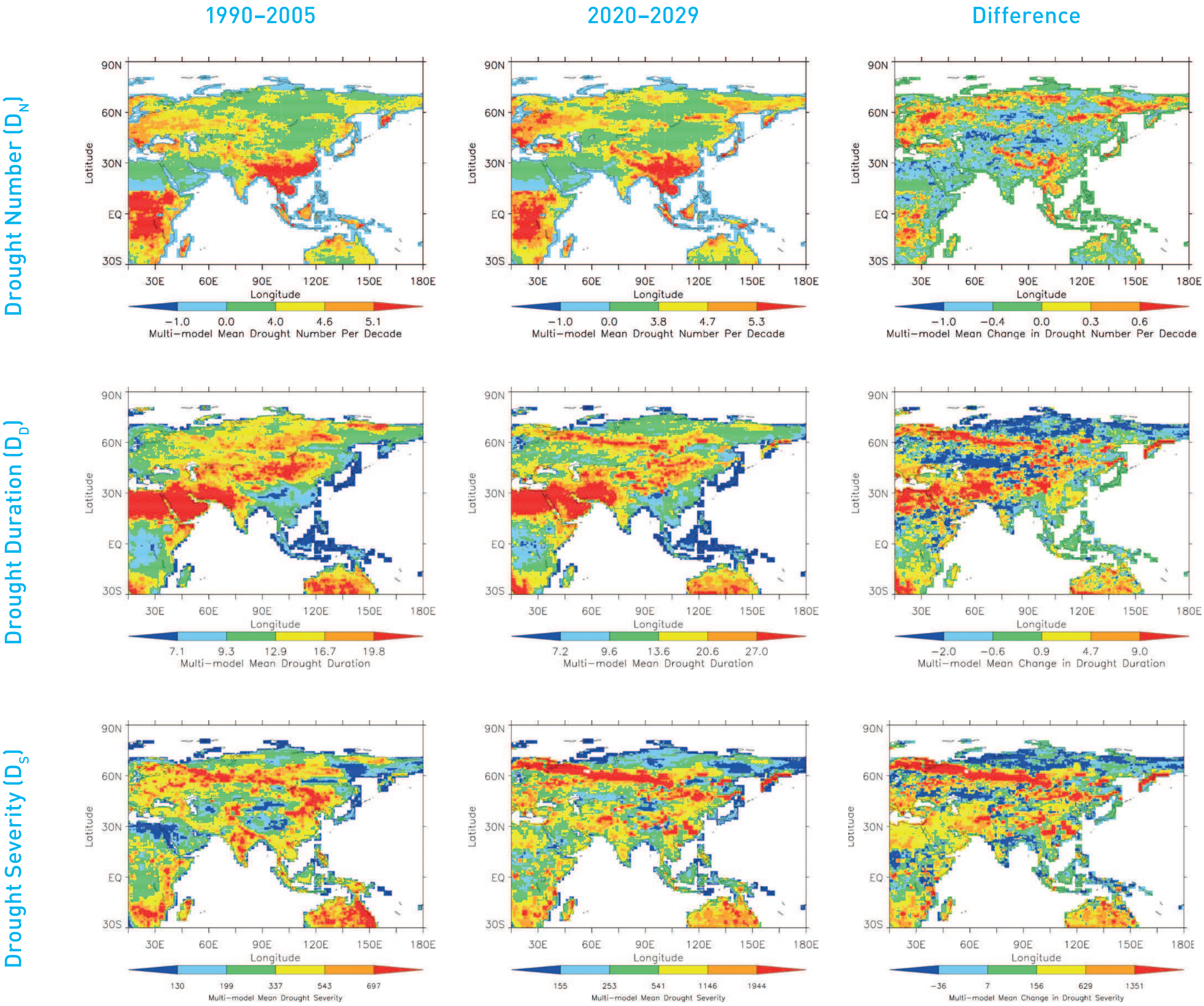
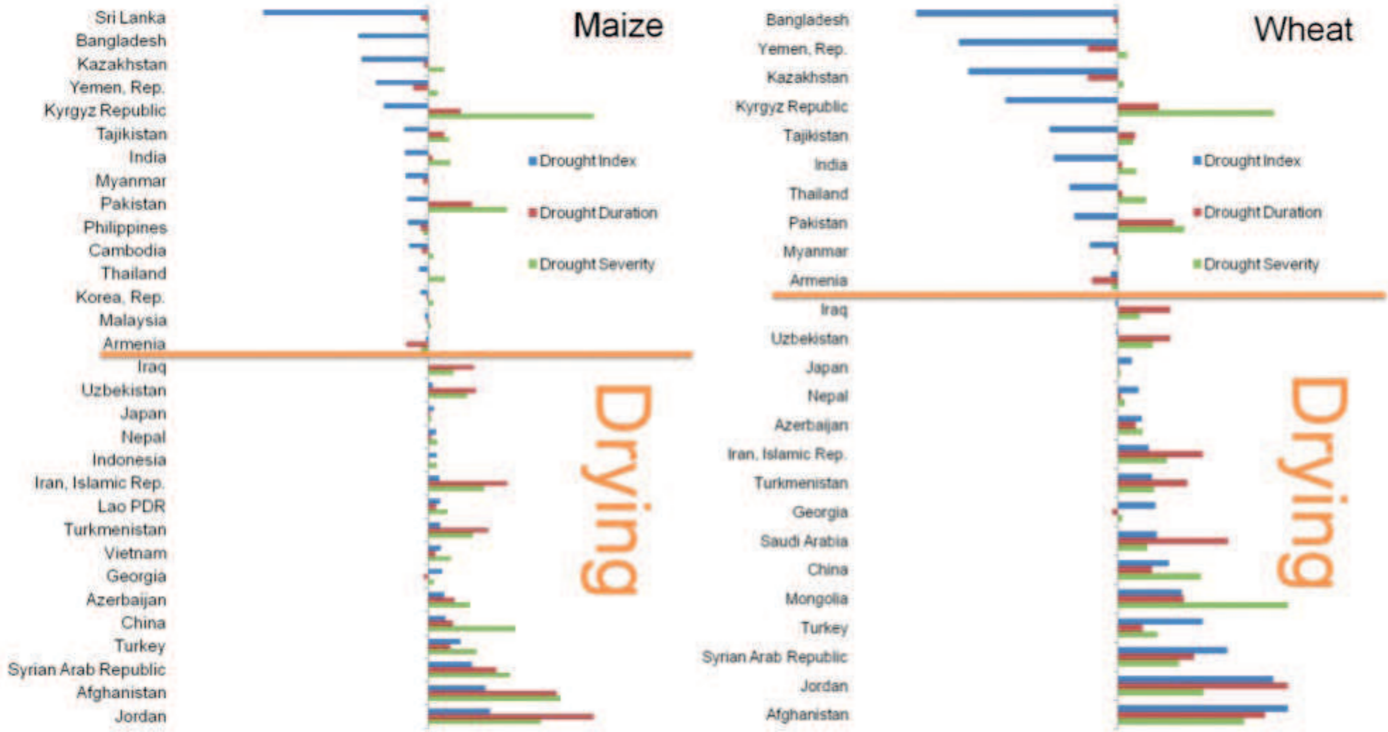


Figure 4: Countries in Asia ranked in order of changes in drought index (D_I). Countries with the greatest increase in drought risk are those with the largest values for D_S (green bars). D_I, D_S and D_D were standardised so they are distributed about zero with a maximum absolute value of one.



2.2 ADAPTIVE CAPACITY

The adaptive capacity index (ACI) varies from a minimum of zero, the weakest possible adaptability to drought, with larger values representing greater resilience of agricultural production to drought. ACI is presented as a scalar quantity with interpretation of results concentrating on relative differences between regions rather than the absolute values of the index.

In our baseline analysis, over the world we observed that regions with the greatest adaptive capacity for wheat include much of western Russia, northern India, southeastern South America, and southeastern Africa. In terms of maize, regions with the least adaptive capacity include the northeastern USA, southeastern South America, southeastern Africa, and central/northern India. (See Appendix Figure A.13).

Figure 5 shows our assessment of adaptive capacity for wheat and maize in the 2020s, projected from the 1990-2005 baseline. Regression relationships required to project ACI for rice to the 2020s were not statistically significant (at the 5% level) so the adaptive capacity index map is not shown. This may be because much of the world's rice is irrigated, uses improved varieties and benefits from fertiliser inputs and is therefore not as affected by changes in soil moisture as wheat or maize; or unproductive rice fields have been converted to more economically productive crops, such as maize or sugar cane (Mainuddin and Kirby, 2009).

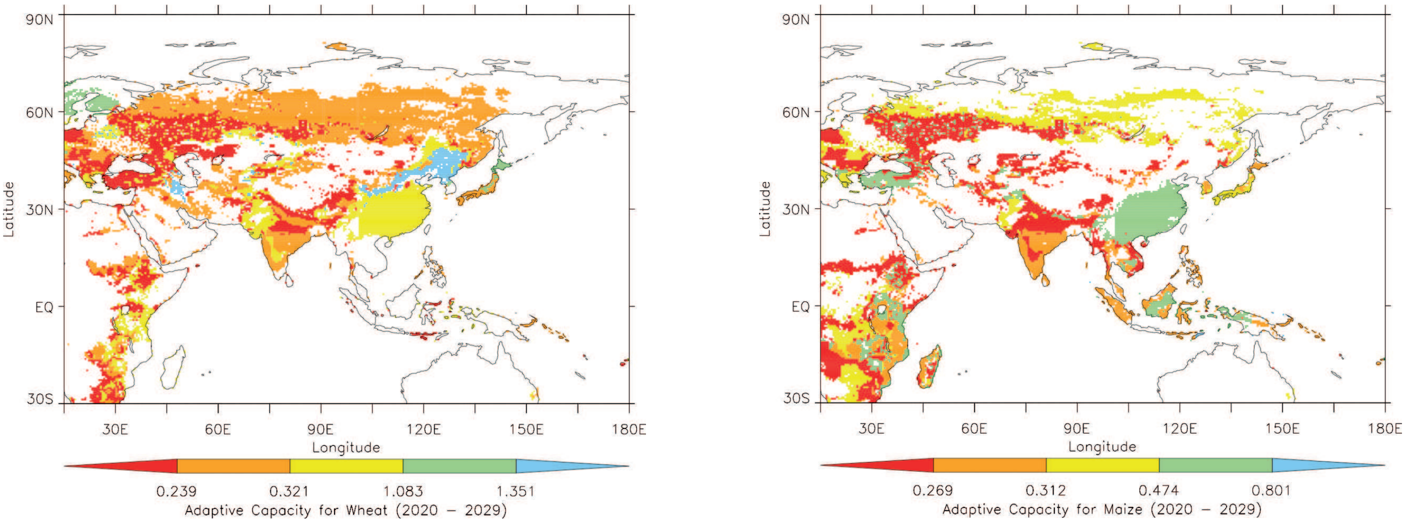


Figure 5: Adaptive capacity index (ACI) for wheat (left) and maize (right) projected to the 2020s. Smaller values for ACI indicate a relatively weak capacity to adapt to climate change and, therefore, greater vulnerability of food production to future droughts. The scale for each plot is based on the 1st quartile, median, 3rd quartile and 90% percentile of the underlying data (see Methods).

2.3 FUTURE HARVESTS

Asian countries are some of the largest wheat and maize producers in the world, and by far the largest producers of rice. Taken together, Asian countries account for around 60% of the world's wheat harvest, 27% of its maize harvest and 94% of its rice harvest (see Table A.4 in Appendix). The worth of these cereal harvests within the Asian region is over $100 billion annually.

Here we ask what is the potential risk to their maize and wheat harvests in the 2020s? This risk reflects the likelihood of future climatological droughts combined with the projected adaptive capacity of the given country.

Figures 6 to 9 summarise, by country, our results for projected adaptive capacity and the increase in drought severity and also show the volume of maize and wheat production in 2010. Figure 6 shows no clear relationship exists between the volume of maize production for a country and its projected adaptive capacity. This highlights potential vulnerability in the global agricultural system from large volume producers of maize with low adaptive capacity (notably India and the Philippines). Whilst adaptive capacity for China is relatively strong, its position as the dominant producer in Asia leaves the region, and world markets, highly dependent on the successful implementation of its adaptation strategies.

Figure 7 shows there is an increased risk of severe drought in the 2020s in most maize croplands (154% increase on average when weighted by production). While there is no clear relationship between the volume of production and drought severity, there are countries with both large harvests and a relatively large increase in the risk of severe droughts. These countries include China, with production considerably greater than other countries, Turkey and Pakistan (the 7th and 8th largest producers respectively).

There was also no clear relationship between wheat production and adaptive capacity (Figure 8). Global food supply appears particularly vulnerable to the drought threat posed to wheat production in India. India makes a much greater contribution to wheat production than it does for maize yet has a relatively low adaptive capacity for both crops. Successful implementation of adaptation strategies is vital in China and is also important in Pakistan, Turkey and Iran to address the threat to wheat production posed by drought in the 2020s.

Figure 9 shows all major wheat producing nations in Asia have an increased risk of severe drought in wheat croplands in the 2020s (132% increase on average when weighted by production). Many of the largest wheat producers, notably China, Pakistan, Turkey and Iran, are projected to have more than a 100% increase in the risk of severe drought. Implementation of adaptation strategies in these countries will have to be very effective to mitigate the risk presented to global food security.

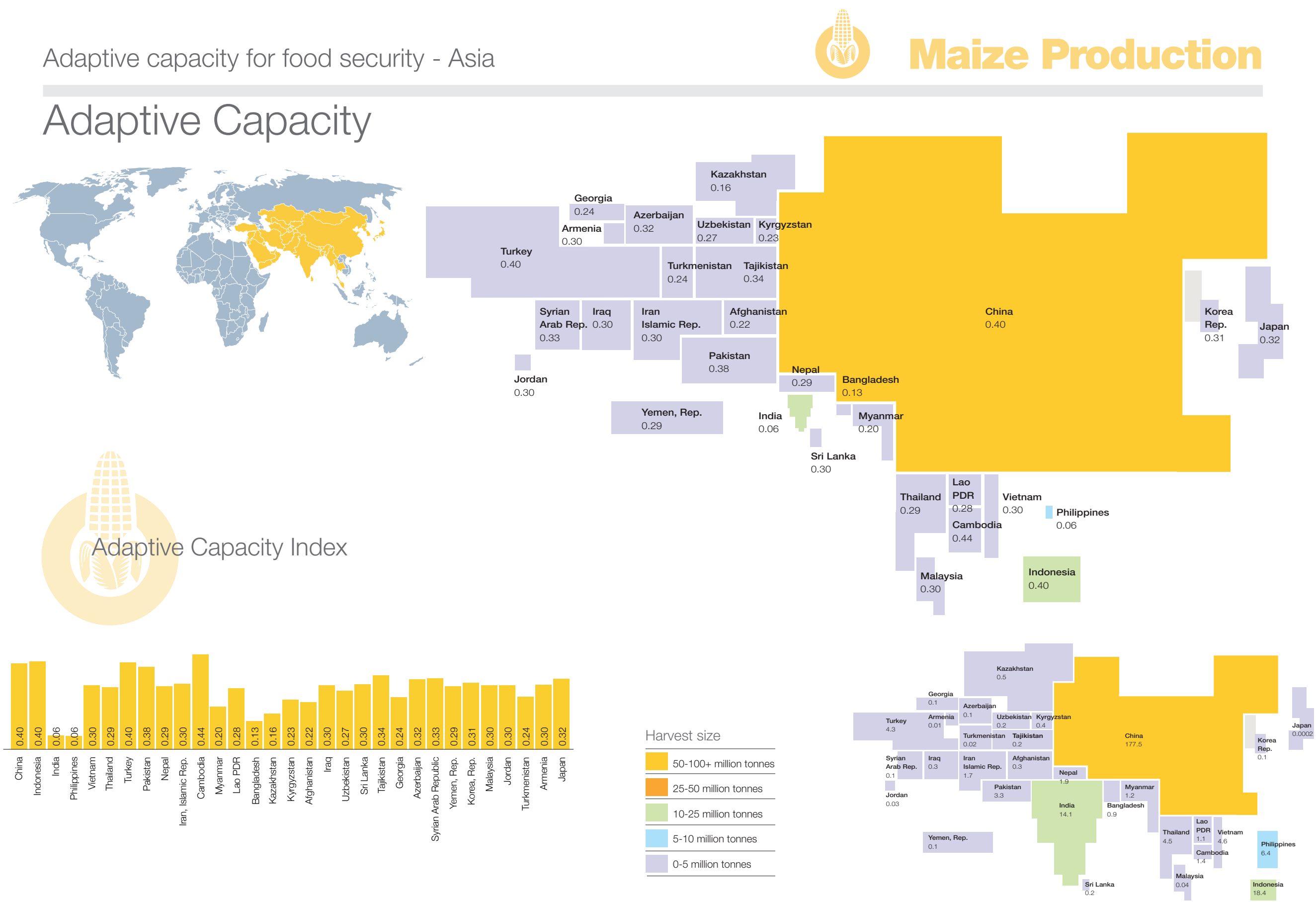


Figure 6: Adaptive capacity index for maize production has a minimum possible value of zero and greater values indicate greater capacity to adapt to drought risk in the 2020s. The upper right graphic shows the size of countries inflated where adaptive capacity is relatively strong and reduced where it is relatively weak. The lower left graphic ranks adaptive capacity in order of decreasing maize production (left to right) and the lower right graphic shows maize production by country in 2010.

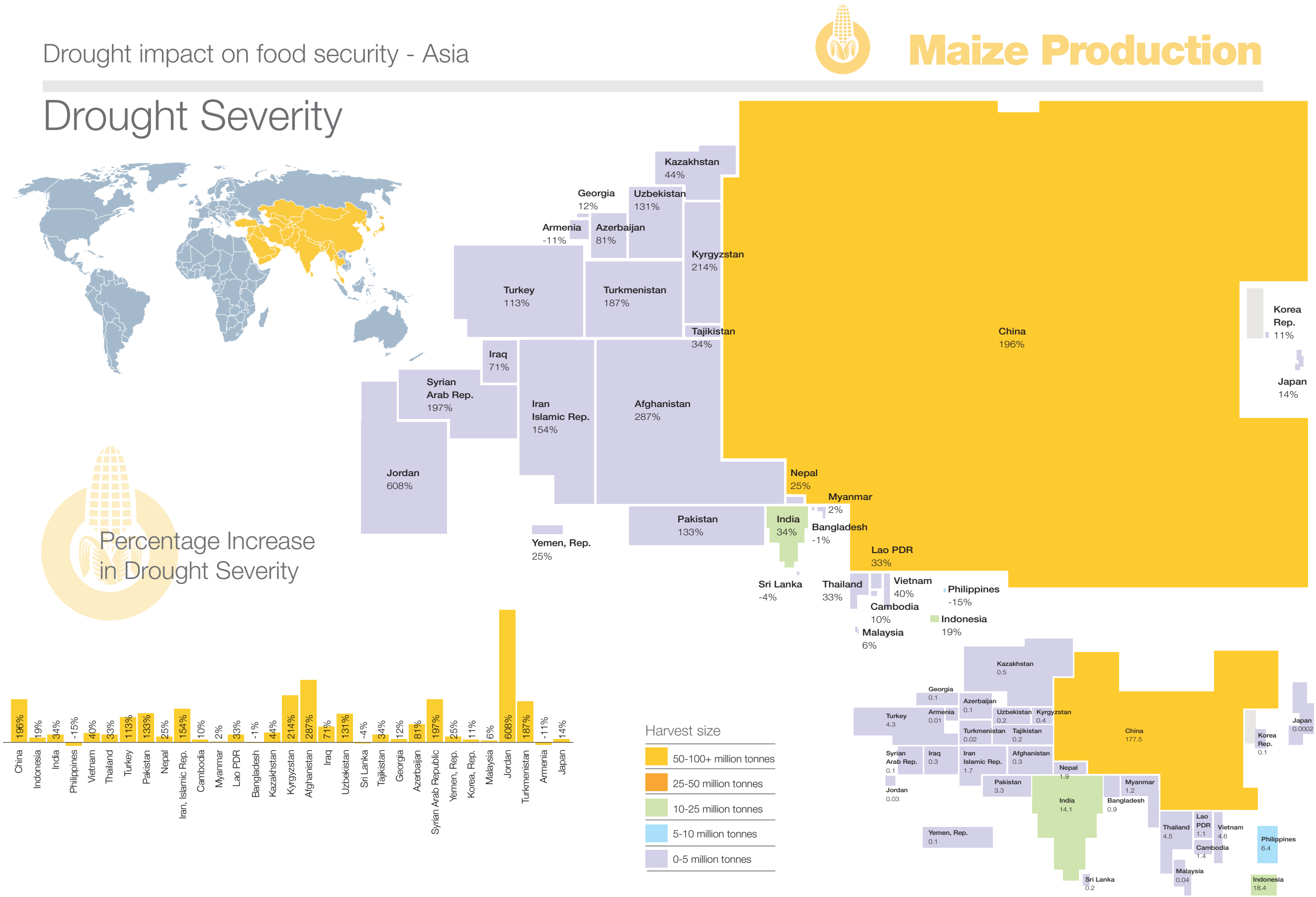


Figure 7: Percentage increase in drought severity projected for the 2020s compared with 1990-2005. The upper right graphic shows the size of countries inflated where the increase in drought severity is relatively large and reduced where it is relatively small. The lower left graphic ranks the increase in drought severity in order of decreasing maize production (left to right) and the lower right graphic shows maize production by country in 2010.

Adaptive capacity for food security - Asia

Wheat Production

Adaptive Capacity

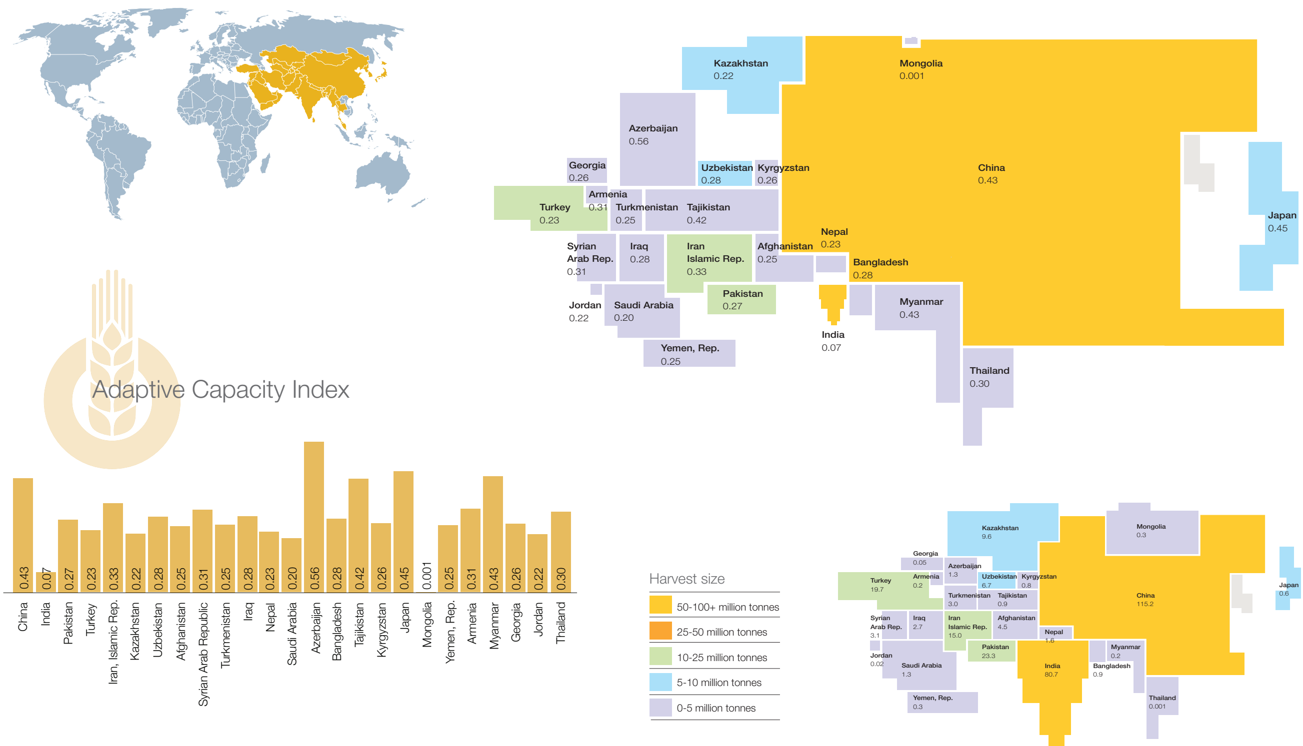


Figure 8: Adaptive capacity index for wheat production has a minimum possible value of zero and greater values indicate greater capacity to adapt to drought risk in the 2020s. The upper right graphic shows the size of countries inflated where adaptive capacity is relatively strong and reduced where it is relatively weak. The lower left graphic ranks adaptive capacity in order of decreasing wheat production (left to right) and the lower right graphic shows wheat production by country in 2010.

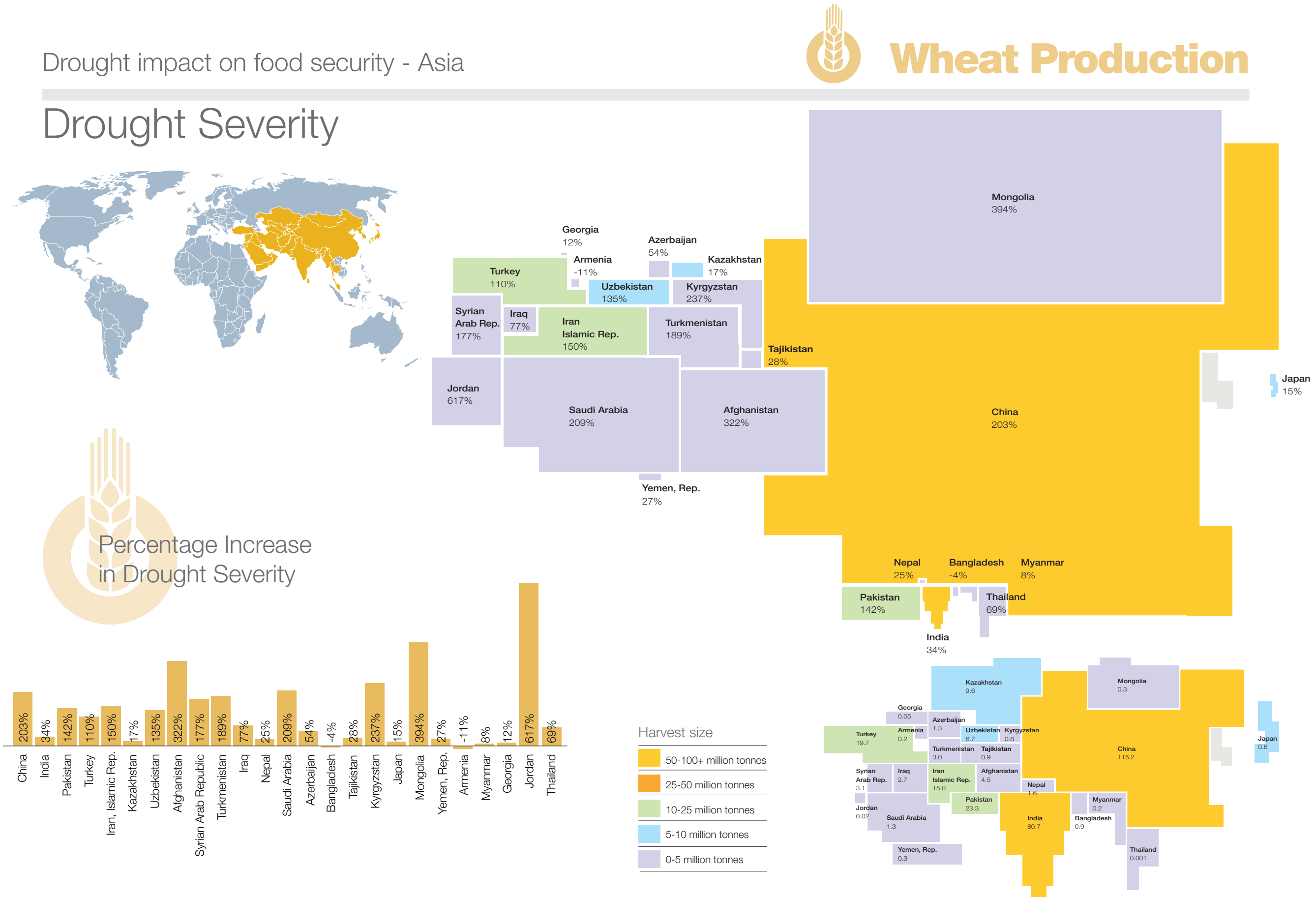


Figure 9: Percentage increase in drought severity projected for the 2020s compared with 1990-2005. The upper right graphic shows the size of countries inflated where the increase in drought severity is relatively large and reduced where it is relatively small. The lower left graphic ranks the increase in drought severity in order of decreasing wheat production (left to right) and the lower right graphic shows wheat production by country in 2010.

CASE STUDY 1: CHINA

China is currently the most populous country in the world with 1.3 billion people[1]. It is the largest producer of maize in Asia and the largest producer of wheat and rice in the world. Maize is grown mainly in central and eastern China, with the exception of south-eastern China where rice dominates, and is the dominant crop in the north-eastern regions of Jilin and Liaoning (Leff et al., 2004). Wheat is grown in similar regions as maize although coverage extends, in pockets, further west.

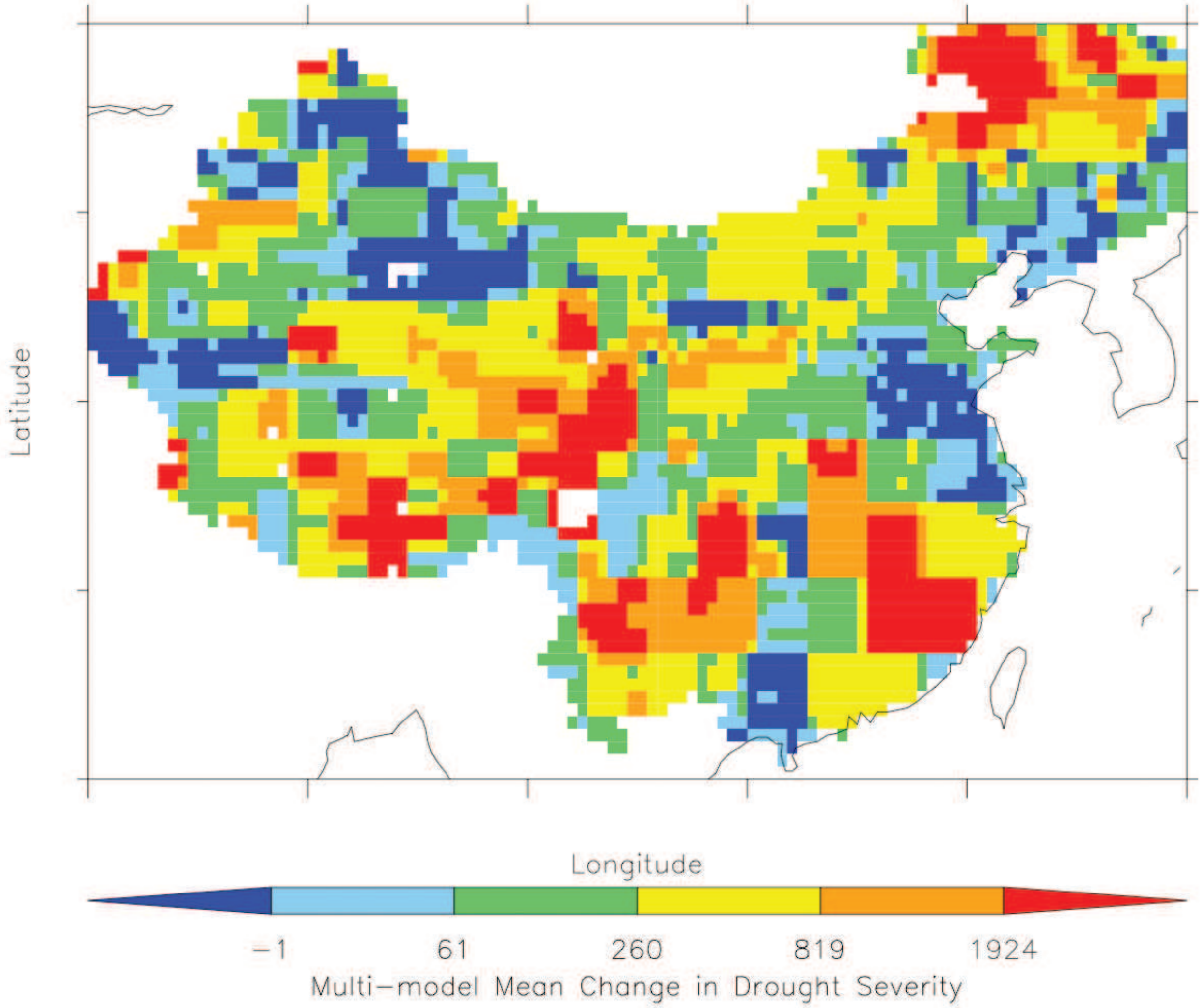
Soil moisture trends across China from 1990-2005 to the 2020s are projected to be weak (Figure 2) largely reflecting the relatively short period of time for trends to develop. There are regional variations, however, with parts of central, southern and eastern China projected to experience drier soils. Both wheat and maize croplands are projected to dry overall. Maize croplands are projected to experience one of the largest reductions in growing season mean soil moisture levels, relative to 1990-2005, of all the Asian countries. The effects of drying across croplands in China are magnified by an increase in drought severity due to regional scale increases in both numbers and durations of droughts (Figure 3). Figure 10 shows the projected increase in severity of droughts is widespread across China (light-blue to red shading with red representing the greatest increase in drought severity). A much smaller area of China is projected to experience less severe droughts (dark-blue shading). Whilst there was variability in the results from different climate models (Appendix Figures A11 and A12), 34 of the 44 climate model simulations found drought severity increased for wheat croplands and 33 of the 44 simulations found drought severity increased for maize croplands in China.

Simelton et al. (2012) projected the adaptive capacity of China to improve from 1990-2005 to 2075-2090 from a 1990-2005 baseline, which was already judged to be stronger than that of many other Asian countries, notably India. The improvements in adaptive capacity index for China are expected to be apparent during the 2020s (Figure 5). Northern China is projected to have one of the greatest adaptive capacities for wheat croplands and central, southern and eastern China one of the greatest adaptive capacities for maize croplands.

IN SUMMARY, CHINA IS PROJECTED TO HAVE AN INCREASED RISK OF DROUGHT AFFECTING WHEAT AND MAIZE PRODUCTION IN THE 2020S COMPARED TO 1990-2005. THIS ARISES FROM A COMBINATION OF A WEAK DRYING TREND AND INCREASED DROUGHT SEVERITY. THE INCREASE IN DROUGHT SEVERITY IS WIDESPREAD (FIGURE 10 LIGHT-BLUE TO RED SHADING) AND IN SOME REGIONS PARTICULARLY LARGE (FIGURE 10 ORANGE AND RED SHADING). SUSTAINED IMPROVEMENTS IN ADAPTIVE CAPACITY ARE EXPECTED, HOWEVER, TO ENSURE CHINA IS RELATIVELY WELL PLACED TO ADAPT, AT LEAST IN PART, TO THE EFFECTS OF CLIMATE CHANGE.

[1] United Nations, Department of Economic and Social Affairs (http://esa.un.org/unpd/wpp/Excel-Data/population.htm)

Figure 10: Multi-model mean change in drought severity (D_S) (kg m^{-2}) over China from the baseline period (1990-2005) to the 2020s. Increased drought severity is widespread but most notable for Chongqing and neighbouring provinces.



CASE STUDY 2: INDIA

India is the second most populous country in the world with a population of 1.2 billion people[2]. The United Nations forecasts India overtaking China as the most populous country by 2030 with a population of 1.5 billion people. After China, India is the second largest producer of wheat in the world and the third largest producer of maize in Asia (after China and Indonesia). Wheat and maize production is predominately located in the central and northern regions of India (Leff et al., 2004).

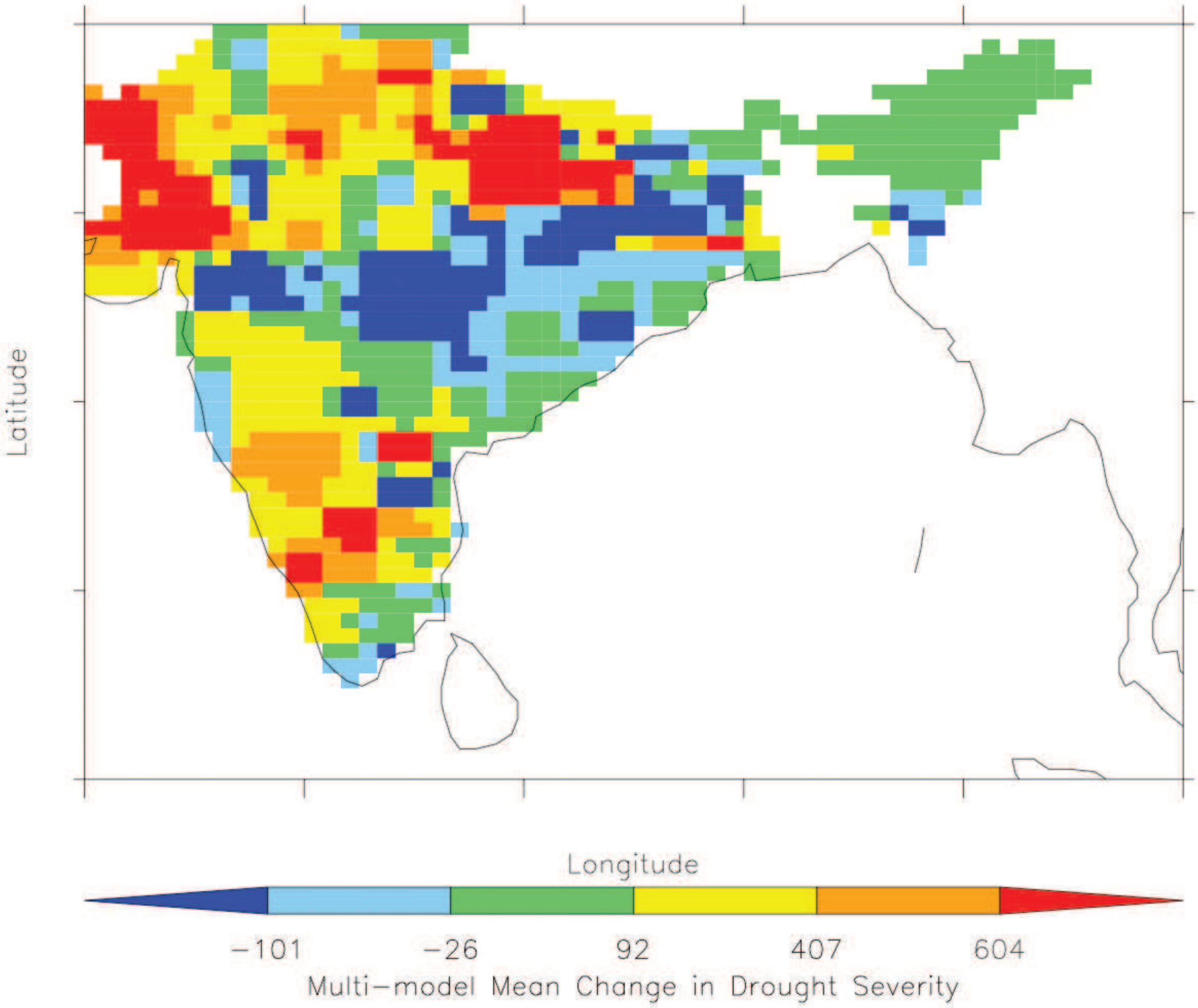
Soil moisture trends across India from 1990-2005 to the 2020s are projected to be weak (Figure 2) but tending to be wetter for the country as a whole (Figure 4). While the number of droughts lasting longer than three months is projected to reduce in the 2020s in most regions, this is offset by increases in drought duration in central and southern India and increases in drought severity in parts of southern and northern India (shown in Figure 11 by yellow, orange and red shading with red representing the greatest increase in drought severity). Parts of central India are projected to experience less severe droughts (shown in Figure 11 by blue shading). Changes in the intensity and geographic coverage of monsoonal rains are likely a significant factor. The overall effect is a projected increase in drought risk for maize and wheat production, although there is some disagreement between the individual climate model simulations used. Only 24 of the 44 simulations found drought severity increasing for wheat cropland, and 23 of the 44 simulations found drought severity increasing for maize croplands in India.

In their analysis of the period 1990-2005, Simelton et al. (2012) found northern India to be a region with one of the lowest adaptive capacities for wheat production, and central and northern India to have one of the lowest adaptive capacities for maize production. This weakness in capacity to adapt to climate change effects on wheat and maize production is projected to continue through to the 2020s (Figure 5).

IN SUMMARY, THE RISK OF ADVERSE CLIMATE IMPACTS ON HARVESTS OF WHEAT AND MAIZE IN INDIA, WHILE UNCERTAIN, IS PROJECTED TO INCREASE IN THE 2020S COMPARED TO 1990-2005. WHILE INDIA IS NOT EXPECTED TO BE AS SEVERELY AFFECTED AS MANY OTHER ASIAN COUNTRIES BY CHANGES IN SOIL MOISTURE LEVELS IN THE 2020S, INCREASED VARIABILITY IN SOIL MOISTURE LEVELS WILL LIKELY CAUSE LONGER AND MORE SEVERE DROUGHTS WHEN THEY DO OCCUR, ESPECIALLY IN NORTHERN CROPLANDS (FIGURE 11 YELLOW, ORANGE AND RED SHADING). CONTINUED WEAKNESS IN INDIA'S CAPACITY TO ADAPT TO CLIMATE CHANGES POTENTIALLY EXACERBATES THE PROBLEM.

[2] United Nations, Department of Economic and Social Affairs (http://esa.un.org/unpd/wpp/Excel-Data/population.htm)

Figure 11: Multi-model mean change in drought severity (D_S) (kg m-[2]) over India from the baseline period (1990-2005) to the 2020s. Regional variation in drought severity is pronounced with increased severity projected for northern and southern regions.



3. KEY FINDINGS AND ADAPTATION STRATEGIES

Key findings of this work are that despite the small overall drying of soil between now and the 2020s, climatological droughts are expected to become more severe globally, with China, Pakistan, Mongolia and Afghanistan some of the worst affected countries in Asia. Parts of northern India will also be affected. Of these countries, China is best placed to adapt to the change, and Afghanistan and Mongolia most at risk to food security issues.

India is predicted to have one of the lowest adaptive capacities, putting its large harvests of wheat and maize under threat (India is currently the world's second largest producer of wheat and seventh largest producer of maize). Although we find less of a country-wide drying trend here current drought risks to harvest are high and these will remain.

Simelton et al. (2012) showed that vulnerability was generally higher in authoritarian and 'flawed' democracies' than in full democracies. They also showed that rice, wheat and maize production in middle income countries is especially vulnerable to droughts. These countries may find themselves without the better adaptive capacity often linked to traditional agricultural methods in low income countries, and without the financial means to invest in better agricultural technologies, like innovations in seed quality and fertiliser use, available to high income countries.

Fraser et al. (2012) likewise suggest that many of the socio-economic factors that influence adaptive capacity are specific to particular contexts. For instance, the amount of cropland per capita was found to be significant in terms of explaining adaptive capacity for wheat. The authors noted that this relationship was stronger in poorer countries than in rich ones. Fraser et al. (2012) hypothesised that this may be because having access to cropland is more important in determining adaptive capacity in poor parts of the world where farmers may adapt to drought by planting larger areas, leaving fields fallow to conserve moisture, or by reducing planting density to lessen moisture competition between plants.

Fraser et al. (2012) also stress that access to land may be less important for wheat grown in wealthier countries where adaptation may be based around access to farm inputs (e.g. purchasing drought tolerant seed varieties). For wheat harvests and countries where the wealth inequality was found to have a significant effect, Fraser et al.'s (2012) results demonstrate that the greater the inequity in wealth, the lower the adaptive capacity. More intensive fertiliser use decreased adaptive capacity in cold and temperate regions but was, when significant, positively associated with adaptive capacity in tropical and arid countries.

Fraser et al. (2012) conclude that their assessment provides suggestive evidence that increasing fertiliser use in tropical and arid countries may help buffer wheat yields from drought, but that this same strategy may not have the same effect elsewhere. Results were different for maize. The same work suggests that high population densities may hinder adaptation to drought in dry regions. But high rural populations help buffer maize harvests from the impacts of drought in regions with temperate climates. This may be because arid regions cannot support high population densities and, therefore, the extra people in such regions hurt farmers' ability to adapt to drought. By contrast in temperate regions, the extra people may be used in labour intensive adaption strategies (Fraser et al., 2012).

When the adaptive capacity models were used to project changes in adaptive capacity for the 2020s (shown for Asia in Figure 5), results show that regions with the largest decreases in adaptive capacity are in areas with authoritarian regimes and arid ecosystems. In particular, Russian wheat and South American maize farmers are projected to have decreased adaptive capacity (Appendix Figure A.13). Overall, adaptive capacity is projected to increase in tropical areas (e.g. eastern China) and cold areas that have high incomes and hybrid regimes or democratic governments (e.g. central North America). To some extent the increased socio-economic adaptability to drought impact in China offsets the possible effects of increasing droughts themselves that may lead to a slight decrease in vulnerability.

Challinor et al. (2010) investigated how spring wheat in North-East China would be impacted by changes in mean temperature and water availability under one particular climate scenario during the 21st Century. In parallel, they constructed a vulnerability index that was based on socio-economic data and highlighted the underlying socio-economic factors that made different farming systems more or less sensitive to declining rainfall. Their results indicate that there will be a reduction in spring wheat in this area, but it might be possible to implement significant adaptive measures even within the present socio-economic context (Challinor et al., 2010). Hence, the overall conclusion of their study was that although climate change poses real threats to agricultural productivity in China, adaptation strategies based on using available land, labour and capital resources may be sufficient to overcome the problems posed by future droughts. However, this requires that farmers be able and willing to use flexible adaptation strategies, such as changing planting dates and using more heat tolerant varieties (Tao and Zhang, 2010). More specifically, the success of adaptive measures during the northward shift of the agricultural climate zone in northeast China was largely influenced by the level of farmer engagement, the participation of non-governmental organisations, the assistance of groups to disseminate agricultural technology and the focus of the policy framework set by the central and local governments (Yang et al., 2007; Chen et al., 2011). These studies clearly illustrate that adaptation strategies can be effective but they need to be designed according to specific regional contexts.

Successful adaptation is probably already occurring in China. Statistical data show that although many parts of China had an increase in drought-affected areas in the 1990s and 2000s, the national food security levels (measured as kg grain/capita) were met through domestic policy interventions (Simelton, 2011).

THE DISCUSSION ABOVE SHOWS THAT ADAPTATION STRATEGIES NEED TO ADDRESS BOTH THE BIOPHYSICAL AND SOCIO-ECONOMIC ASPECTS OF DROUGHT. STRATEGIES NEED TO BE REGIONAL, CROP AND INCOME-LEVEL SPECIFIC. ANY STRATEGY WOULD NEED EFFECTIVE MONITORING AND WOULD NEED TO BE REGULARLY UPDATED AS COUNTRIES GO THROUGH THE TRANSITION FROM A LOW TO MIDDLE INCOME ECONOMY (SIMELTON ET AL., 2012). FURTHERMORE, WHILE MANY COUNTRIES IN SOUTHEAST ASIA ARE NET EXPORTERS OF GRAIN, MALNUTRITION PREVAILS, SUGGESTING THAT ACCESS TO NUTRITIOUS FOOD IS A MATTER OF INCOME DISTRIBUTION RATHER THAN OF SUPPLY PER SE. IT IS EXPECTED THAT TRADE CAN OFFSET CLIMATE VARIABILITY IMPACTS TO SOME EXTENT BY BALANCING FOOD PRICES AND ENABLING ACCESS TO, AND AVAILABILITY OF, FOOD (NELSON ET AL., 2010).

4. DISCUSSION OF LIMITATIONS

This study generally finds small multi-model average trends in soil moisture over the next 20 years. The relatively short-term projection means that it is difficult to distinguish the climate change signal from shorter term variability. Models could be seeing an increase in the monsoon circulation driving rainfall increases that compensate for the general drying of the region (Wang et al. 2011). There is a considerable model spread and certain models show an intensified drought risk. It is difficult to rank models for their accuracy; therefore any model integration can be considered equally valid and those that indicate drought conditions imply a potential future risk.

Climate model projections give only one possible future; inherent variability in the climate system can affect the prediction skill of 2020 droughts, as can limitations in the physics of climate models.

Our results rely on a somewhat crude projection of present-day adaptive capacity index based on one economic scenario. Although countries can change their development pathways (for better or worse) overnight, the socio-economic variables selected for this study are of a more slow-moving nature than the biophysical. The adaptive capacity, therefore, should be considered a possible trend given the A1B scenario. B2 socio-economic scenarios were also tested but provided no significant difference given the short time period (Fraser et al., 2012). Projection of the adaptive capacity index was also based on classification of current climate using Koppen's climate zones (Kottek et al. 2006). While this assumption may not hold true in some of the more extreme climate projections from the 12 underlying climate models, this approach is appropriate for the gradual soil moisture trends in the multi-model mean climate.

Within this framework, our vulnerable regions should not be seen as the only possible ones, as ground water availability was not taken into account in the study, but could have a very large effect on vulnerability (Fraser et al., 2012). Thus focus in terms of climate change adaptation should not only rest on those countries or regions that are already at risk, but also on those that could potentially experience higher vulnerability in the future when ground water availability decreases in areas that currently highly depend on these reserves.

In general it should also be noted that projections for the demand and supply of food in Asia are difficult to make and depend on a variety of factors that are not necessarily controlled within the region, e.g. global food prices (Parry et al., 2007).

5. METHODS

5.1 ADAPTIVE CAPACITY FRAMEWORK

This section builds a framework for understanding and quantifying vulnerability and adaptive measures that we use to assess the impact of drought and associated risks, showing how the framework addresses national scales and the agricultural sector.

Whilst climate change mitigation has received a substantial amount of attention since the early 1990s, research and policy on adaptation to climate change has lagged (Fankhauser et al., 1999). However, there is currently increased attention to climate change adaptation (Osberghaus et al., 2010). The key concepts that inform the analysis in this report are defined in Box 1.

It is important to note that adaptation to climate change takes different forms, with some authors arguing that there are two broad types of adaptation: adaptation that takes place after an event or wider changes, which is usually called spontaneous or autonomous adaptation (Engle, 2011) and adaptation that takes place in advance of an anticipated climatic impact which is described as anticipatory and planned adaptation (Smith, 1997).

It has also been argued that adaptations in the developing world are typically autonomous adaptations in that they happen in response to weather events. In the future, however, there is a recognition that adaptation must become more proactive and that policy should seek to foster the ability of communities to act in anticipation of problems. Sometimes this is called "increasing the adaptive capacity and resilience of communities" (Adger et al., 2003).

KEY TERMS

ADAPTATION

Adaptation refers to adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.

ADAPTIVE CAPACITY

Adaptive capacity is the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences.

VULNERABILITY

Vulnerability is the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate change and variation to which a system is exposed, its sensitivity, and its adaptive capacity.

(Parry et al., 2007)

Box 1

The need for more policies and strategies that lead to proactive adaptation is due to the rising awareness that future climate stresses are likely to be unprecedented and hence autonomous adaptations by themselves will not be sufficient and will be unlikely to result in optimal outcomes (CEC, 2009). But anticipatory or proactive adaptation also faces a number of difficulties largely related to uncertainties concerning the magnitude, geographical location and timing of future climate impacts (Smith, 1997). Nevertheless, the potential impacts of climate change (Smith, 1997) necessitate a planned approach to adaptation, as failing to prepare for hazards, risks and a change in social conditions is likely to result in negative impacts (Adger, 2006). However, only when adaptation actions become integrated across different sectors and scales, and both autonomous and planned adaptation are accounted for, can effective, efficient and equitable adaptation be achieved in practice (Adger et al., 2005a).

Knowing the vulnerability of a system is a necessary baseline for assessing and designing adaptation measures. To help in the task of understanding the vulnerability context of agriculture, Fraser et al. (2011) suggest a framework that contains three overlapping components. These are the resilience of the agro-ecosystem to potential climatic stressors (defined as the ability of an agro-ecosystem to remain productive under climatic stresses), the socio-economic affluence of the households that depend on the agro-ecosystem (defined as the household's ability to sustain their livelihoods in the event of decline in productivity on their farm) and the capacity of institutions to provide support and relief in the event of an emergency (see Figure 12). A heuristic assessment of all three components would then give a measure of vulnerability (Fraser et al., 2011). When vulnerability is viewed in this way, it has been suggested that financial, political and institutional resources actually have a greater impact on vulnerability than environmental change (Twyman et al., 2011).

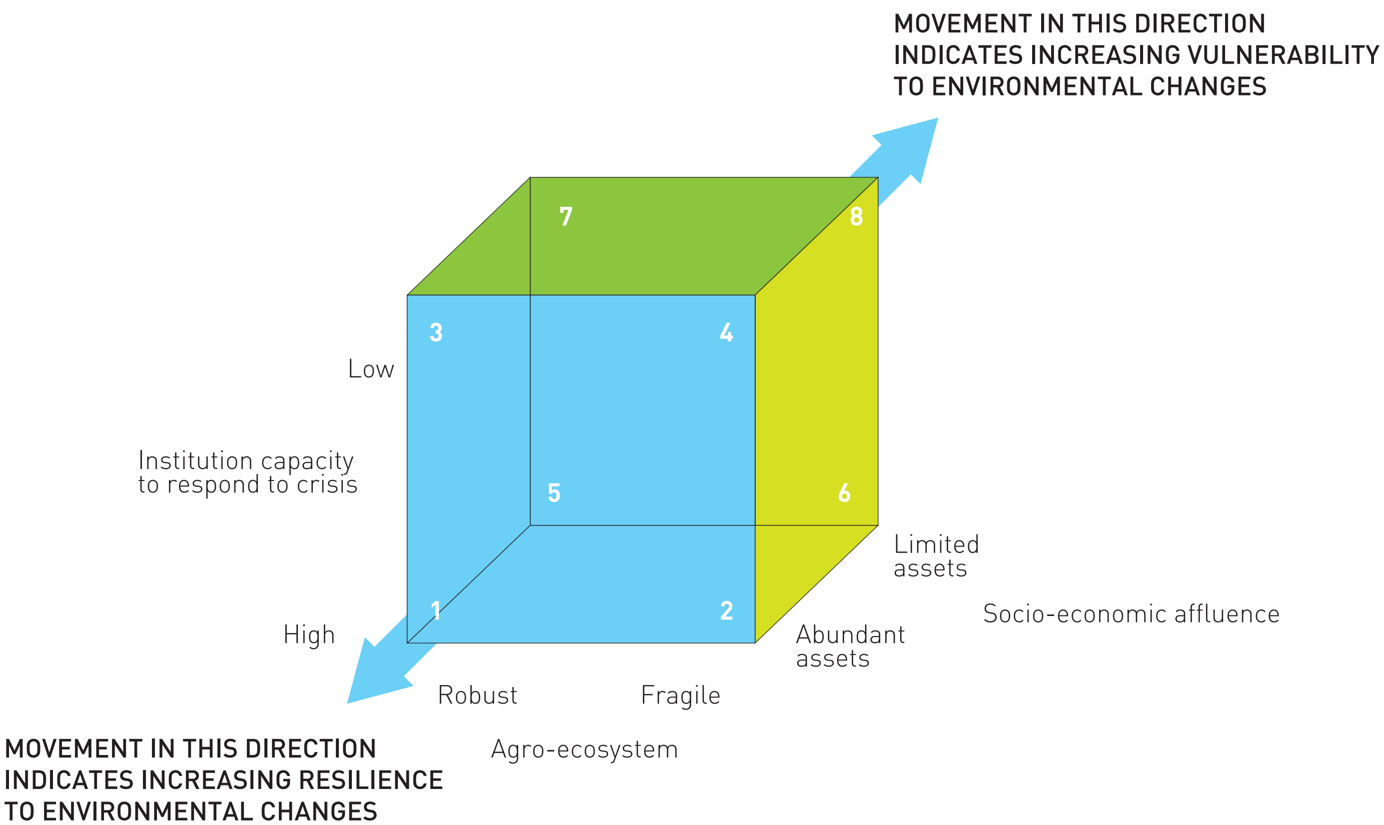


Figure 12: Generic vulnerability framework that allows for the assessment of three overlapping components: Institution capacity to respond to crisis, agro-ecosystem and socio-economic affluence. (Reproduced from Fraser et al., 2011).

5.2 ADAPTATION AT THE NATIONAL SCALE

It is often assumed that the state should be a major actor in the adaptation process and that its role is to create the right environment in which adaptation can take place efficiently, equally and effectively (Fankhauser et al., 1999). The state is an important actor due to its ability to provide legal and statutory resources (Eakin and Lemos, 2006), institutional frameworks for action (Folke et al., 2005) and public goods (Fankhauser et al., 1999) such as public information, investment in research, new technologies and adaptation measures, and risk assessments to protect society from the impacts of climate change (Osberghaus et al., 2010; Tompkins and Adger, 2005).

Globally there are marked differences between the capacity of different nation states, and the characteristics of a specific state will have a marked impact on its ability to deal with and respond to climatic stresses. The broader socio-economic and political context will not only strongly shape the ability of nation states to adapt but will also constrain or even cancel out initiatives at smaller scales (Smit and Wandel, 2006). It should also be noted that it is often those groups or states already in a vulnerable or disadvantaged position that will experience the greatest amount of vulnerability due to climate impacts in the future (Adger, 2006). Adaptive capacity at all scales thus needs to be regarded as dynamic and very much dependent on factors such as natural and human resources, the governance and institutional framework, available technologies, financial resources, the development status, social networks, current climate vulnerability and prior stressors (Parry et al., 2007). In many countries, climate stresses are just part of a multitude of stresses that the country and its society need to deal with and adapt to, and a state's and society's ability to cope with its current situation will have a substantial impact on its adaptive capacity. As Fielding (2011) states; "When it comes to internal migration, social-system-and-social-system-change trumps environmental-drivers-and-environmental-change every time."

5.3 AGRICULTURE AND ADAPTATION

The agricultural sector is regarded as one of the sectors most vulnerable to the impacts of climate change, but how it responds will depend on a variety of biophysical and socio-economic factors (Parry et al., 2004). Biophysical effects are determined by the amount of soil moisture and ground water availability, levels of precipitation and the levels of CO_2 and temperature (Parry et al., 2004). As these vary between different geographical regions and will be affected to varying degrees by climate change, agricultural responses will also diverge (Parry et al., 2004). Research into the different agricultural responses according to different emission scenarios has found that developing countries will generally experience a decrease in crop yields, whereas developed countries will likely see an increase (Fussel, 2010; Parry et al., 2004). Furthermore, less industrialised countries rely more heavily on agriculture in terms of employment and GDP than industrialised countries and thus will be more vulnerable if the agricultural sector is impacted by climate change (Kandlikar and Risbey, 2000).

In the agricultural context, adaptation has been defined as 'the process of maintaining various farming objectives (such as yield, basic survival and aversion of hunger, profitability) in the face of changes in external conditions' (Kandlikar and Risbey, 2000: 532). Adaptation options can be varied even if a specific demand for an amount of food under a specific climatic change has been identified, and could include diversifying the choice of crop or variety, increasing the area that is cropped, changing the quantities that are being imported or changing the quantities that are being transported regionally, with each of these options having a different effect on the food system (Challinor, 2009). It needs to be noted though that farmers may not have the resources to implement adaptive measures, especially in less industrialised countries, and may also face large risks when trying out new technologies or methods should these fail (Kandlikar and Risbey, 2000). It should thus be the responsibility of the government to ensure that the right institutional and macro-economic framework is in place for farmers across different levels to be able to take adaptive measures (Challinor et al., 2007).

5.4 DROUGHT AND ADAPTIVE CAPACITY MODELLING

We use the research of Simelton et al. (2012) and Fraser et al. (2011; 2012) to develop our methodology for assessing the impact of drought. The method of assessing harvest-related drought risk involves a multi-stage process, each producing its own set of results. These stages are outlined below:

a. Present-day to 2020s soil moisture trends.

These were calculated using the monthly mean total column soil moisture diagnostic from the Coupled Model Intercomparison Project phase 5 (CMIP5) data set (http://cmip-pcmdi.llnl.gov/cmip5/). This is a database of the latest climate model integrations to support the next IPCC climate change assessment report. We make use of multiple model runs from various modelling centres using the RCP 8.5 scenario (see Table A.1). This scenario continues to have rapid increases in greenhouse gases with CO_2 equivalent concentration increasing to ~1370 ppm by 2100 (Moss et al., 2008). The socio-economic characteristics are not prescribed for RCP8.5 but are broadly representative of a future where global population continues to increase, economic growth is regionally focused and uptake of technological change is fragmented (Moss et al., 2008; Riahi et al., 2007). However, the available scenarios differ little in the 2020s, where we analyse them, and only diverge significantly after 2050 in terms of their climate response (Meinshausen et al., 2011). In the results we analyse the multi-model mean soil moisture trends. The range of model results is summarised in the appendices. To compute trends we compare a 1990-2005 baseline period (selected for consistency with the adaptive capacity index results of Simelton et el., 2010) against projected soil moisture for 2020-2029 selected to represent the near future. The multi-model mean is shown as this has invariably proven to be a better predictor of climate change than any given individual model (IPCC, 2007).

b. Drought measures.

We use the soil moisture from a) to compute a series of drought measures, using ideas developed from Fraser et al. (2010) and Sheffield and Wood (2008). Soil moisture was used to develop the drought measures because it reflects the moisture available for crop growth and is derived from physically based climate models which simulate changes in precipitation, evaporation and run-off. The drought measures used were defined as:

D_I **Drought index** – the ratio of multi-model annual (October-October) mean soil moisture (kg m^{-2}) for the 1990-2005 baseline period to the equivalent projected soil moisture values for the 2020s. The October-October time period was used to approximate both northern and southern hemisphere growing seasons (Fraser et al., 2012).

D_N **Drought number** – the multi-model mean number of droughts per decade. A drought was defined as a period lasting longer than three consecutive months during which soil moisture was less than its monthly mean value from the 1990-2005 baseline period.

D_D **Drought duration** – the multi-model mean drought duration in months. A drought was defined as a period lasting longer than three consecutive months during which soil moisture was less than its monthly mean value from the 1990-2005 baseline period.

D_S **Drought severity** – the multi-model mean accumulated shortfall in monthly soil moisture (kg m^{-2}) for periods of drought. A drought was defined as a period lasting longer than three consecutive months during which soil moisture was less than its monthly mean value from the 1990-2005 baseline period. The shortfall was determined by subtracting the monthly mean soil moisture for the 1990-2005 baseline period from the projected monthly soil moisture in the 2020s.

c. Adaptive capacity index (ACI) for the present.

This used the methodology outlined in Fraser et al. (2012). The adaptive capacity index represents the ability of a region to adapt its agricultural production in response to inter-annual variations in soil moisture levels. Regions which have experienced large changes in crop yield in response to relatively minor droughts are interpreted as having a low adaptive capacity. The methodology used to calculate the index is outlined in Fraser et al. (2012). Drought was quantified using the annual mean (October-October) drought index (D_I) observed over the 1990-2005 period. The ACI was derived for each region using the ratio between the drought index (D_I) time series and harvests observed over the 1990-2005 period. ACI starts from zero with increasing values representing a greater ability to adapt agricultural production to the challenges of drought. Vulnerable and resilient regions were identified and ACI maps were produced on a 0.5 x 0.5 degree grid for wheat, maize and rice harvest where crop coverage was at least 1% of the land base (Leff et al. 2004).

d. Adaptive capacity index (ACI) for the future (2020s).

Following Fraser et al. (2012) all Asian countries were categorised in terms of what climatic zone the crop land in the country fell into (temperate, tropical, arid, and cold following Koppen's climate zones [Kottek et al., 2006]), the level of Gross National Income per capita in 2008 (low, lower middle, upper middle and high income following World Bank categories [World Bank, 2009]), and type of government (authoritarian regime, hybrid regime, flawed democracy, full democracy following the Economist's Intelligence Unit's classification system (The Economist, 2009). While this meant there were 64 hypothetical "types" of country, in reality, this resulted in 32 different types of rice producing country, 36 types of wheat producing country and 34 types of maize producing country. Using these different types of cereal producing country as the basis of our analysis we developed linear models of adaptive capacity for rice, maize and wheat where the adaptive capacity index was regressed against seven country-level socio-economic, political, and ecological variables taken from the International Futures (IF) scenario A1B for the corresponding baseline and scenario period (Table 1). The rice ACI was not analysed further as statistically significant relationships required to project ACI to the 2020s were not found at the 5% significance level.

e. Future potential harvest.

The potential for drought affected harvests in the future was given by comparing the relationship between future climatological droughts, given by one of the drought measures and the adaptive capacity index. Both the chances of a climatological drought through soil moisture trends (D_I) or climatic extreme (D_N, D_D and D_S), and the propensity of a region to have its harvest affected by drought are considered. This projection allows for the expected underlying socio-economic trends in the various grain growing countries.

VARIABLE	UNIT	SOURCE	GLOBAL CHANGES IN THE 2020S
RURAL POPULATION	% of population	IF 2009	-72%
CROPLAND PER CAPITA	ha /capita	IF 2009	-19%
SAFE WATER	%	IF 2009	1%
GINI COEFFICIENT (MEASURE OF INEQUALITY IN WEALTH)	0-1	IF 2009	-21%
AGRICULTURE VALUE ADDED TO GDP PER HA	$/ha cropland	IF 2009	17%
GDP PER CAPITA	$PPP/capita	IF 2009	3%
FERTILISER INTENSITY	kg/ha	FAO, 2008 (fertiliser); IF, 2009 (cereal yield)	36%

Table 1: Socio-economic variables used to create the adaptive capacity model (based on Fraser et al., 2012).

APPENDIX

A copy of the appendices will shortly be available online at www.lowcarbonfutures.org.

Please contact Sarah Schepers at sarah.schepers@lowcarbonfutures if you would like to receive a copy by email.

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