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ORIGINAL PAPER

National food security in Bangladesh to 2050

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Abstract Food security in Bangladesh, with particular reference to rice and wheat was investigated by examining trends in yields, area of cropping and overall production in recent decades. Prospects for continued increases in yield and area of the different rice crops and of wheat, considering the impact of climate change, suggest that continued large increases in production were likely. Demand for rice and other food will increase for many decades with the growing population. The range of projections was compared with recent population growth as well as the impacts of possible shifts in food preferences on the demand for rice and wheat. Demand for rice production in 2050 for a medium variant population projection is expected to be 14 % less than the most conservative projection. Wheat production appears likely to remain less than demand by up to 76 % in 2050, though it has the potential to increase sufficiently to meet demand. This analysis should help policy makers to take appropriate actions for maintaining Bangladesh's food security in the future.

Keywords Food security · Bangladesh · Climate change · Rice production · Wheat production

Introduction

Food security is a global and regional concern of rapidly increasing consequences (Wahlqvist et al. 2012). Continuing population and consumption growth will mean that the global demand for food will increase for at least another 40 years (Godfray et al. 2010). There is growing concern that satisfying societal demand for food over coming decades will be increasingly challenging (Ingram 2011). The ability to produce enough food will be affected by the growing competition for land, water, and energy, and will also be affected by the urgent requirement to reduce the impact of the food system on the environment (Godfray et al. 2010). Climate impacts on agriculture are a further threat (Muller 2011).

The problems are particularly acute in Bangladesh, which has a land area of 148 million hectares (Mha), a population of over 150 million (2011) and hence a density of about 1,016 persons per km^2. This is the greatest population density of any country with the exception of a few small states such as Bahrain, Malta and Singapore. The population is projected to grow to about 200 million by 2050 (UN Population Division 2012, medium variant projection), placing further demands for food and also increasing demand for urban land. Climate change may introduce further pressures; Bangladesh is rated as the country most vulnerable to climate change (Maplecroft 2014), with risks from floods, droughts and sea level rise, all potentially impacting adversely on agricultural production. With these pressures in mind, the National Food Policy (Ministry of Food and Disaster Management of GoB 2006) nominated food security as one of Bangladesh's major challenges, and a matter of major concern for the government; the main goal of the 2006 plan was to ensure dependable food security for all people at all times. The experience of the world food crisis in 2007–8, when rice prices increased sharply as India cut exports to Bangladesh to protect its own supplies, has raised the importance of rice self sufficiency for Bangladesh and the maintenance of stocks sufficient to cope with periods of reduced supply (Dorosh and Rashid 2012).

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Food security includes availability, access to food and nutritional quality (Pinstrup-Anderson 2009). Availability is synonymous with national food security (Pinstrup-Anderson 2009; Carletto et al. 2013), and access is synonymous with household or individual food security (Ahmed et al. 2013). While it is important to meet all the elements of food security for a country and for its people, 'availability' or 'national food security' is the essential precondition for overall food security. In this paper, we examine only the national food security in terms of sufficiency of rice and wheat for the population at large. We do not consider household or individual food security or the nutritional quality. Several studies in Bangladesh, such as that by Yu et al. (2010), use the term "food security" when the focus is the availability or sufficiency of rice alone or rice and wheat (the two major food grain crops) at the national level.

Bangladesh has made considerable progress in achieving national food security by increasing annual rice production from 151 kg/capita in 1995 to 217 kg/capita in 2010 (estimated using the data available in the Statistical Yearbook published every year by the Bangladesh Bureau of Statistics) due to increases in the area irrigated and in yields. For the last few decades, the increase in production has outweighed the growth in population. In the early nineties, with the total population of 106 million net import of rice was around 3 million tonne/year (Islam and Mondal 1992). Currently (2012–13), with the population of 152 million, Bangladesh has gained self sufficiency in rice production (The Daily Star 2013a).

With a growing population, demand will increase and thus grain production must also increase to maintain national food security. Estimates of population growth in Bangladesh have been steadily falling in recent years as shown by the fall from 255 million to 202 million in the UN Population Division medium variant projections for 2050 given in Table 1. This reduction has considerable implications for assessments of the required future grain production for national food security. As shown in Table 1, several previous studies on food security in Bangladesh have used higher estimates of population, although some studies used estimates consistent with the more recent lower projections. Begum and D'Haese (2010) assessed food security to 2020 but did not quote an actual population, using growth rates instead. Yu et al. (2010) assessed food security to 2050, but did not state explicitly what population they assumed for 2050; their population estimate can be calculated from the information given as about 335 million by 2050. The studies of Hussain (2011) and Ganesh-Kumar et al. (2012) are the only ones to consider uncertainty or variation in the population projections. Ganesh-Kumar et al. (2012) (some projections only) and Amarasinghe et al. (2014) are the only studies that used projections consistent with those of the latest UN projections. In this paper, we used the up-to-date projections of the UN Population Division (2012), but allowed for uncertainty in the projections by using the high, medium and low variant projections (described further in methods).

The production of grain is the other side of the national food security story. Ganesh-Kumar et al. (2012) provided forecasts of the demand and supply of cereal for the period of 2015–2030 without considering the impact of climate change on production. Amarasinghe et al. (2014) estimated the production of rice only and did not consider climate change impacts on production. Other studies (Karim et al. 1996, 1999; Basak et al. 2010; Hussain 2011; Thomas et al. 2012; Basak and Alam 2013; Hassan et al. 2014) gave estimates of climate change impacts on either yield or production but did not quote actual production estimates and requirements. In several cases, they give the deviation due to a single effect such as temperature or CO_2 without giving the combined effect, though in other cases the combined effect is given.

Amongst the studies referred to on food security in Bangladesh (usually rice and wheat sufficiency), that of Faisal and Parveen (2004) and Yu et al. (2010) are undoubtedly the most comprehensive. They looked at both supply and demand, and included a larger range of climate change impacts than other studies. Yu et al. (2010) also comprehensively investigated the uncertainty in climate change projections. They estimated total production from productivity growth rates, without considering constraints such as water or land availability. Neither Yu et al. (2010) nor Faisal and Parveen (2004) considered uncertainty in population estimates and Yu et al. (2010) appear to have used an unrealistically high population projection, though their actual projection is unclear. Faisal and Parveen (2004) considered constraints imposed by land and water availability, which were explicitly ignored by Yu et al. (2010). However, Faisal and Parveen (2004) did not give actual estimates for future rice or wheat production. Furthermore, Faisal and Parveen (2004) based their projections on yield increases from 1990 to 1999 which, as we will show later, were less than more recent yield increases.

Land and water constraints to crop production are a key concern in Bangladesh. Groundwater is the principal source of irrigation water for the dry season *boro* rice crop, which accounts for nearly 60 % of national rice production (Ahmad et al. 2014). In some, groundwater is undoubtedly being used unsustainably; elsewhere there are longer term concerns but not immediate threats to sustainable use (Ahmad et al. 2014). Furthermore, the conversion of agricultural land to other uses is about 1 % per year (Government of Bangladesh 2010; Quasem 2011). The possible constraints to production of land and water availability must be considered. Faisal and Parveen (2004) considered that the availability of cultivable land would not be a constraint to production in 2050 as long as productivity continued to grow. They also considered that there would be sufficient water in 2050, but that the water demand for irrigation might cause significant negative impacts on other uses.

Table 1 Population projections used in Bangladesh food security studies. The UN Population Division medium variant projections are shown for comparison

Population (mllions)				
2025	2030	2050	Reference	Comment
208		255	UN Population Division (2004)	Medium variant projection
195		222	UN Population Division (2009)	Medium variant projection
	185	202	UN Population Division (2012)	Medium variant projection
		198	Faisal and Parveen (2004)	
		335	Yu et al. (2010)	Calculated from other figures in Yu et al.
		215 and 252	Hussain (2011)	
		260	Basak and Alam (2013)	
	232		Karim et al. (1996)	
	170 to 218		Ganesh-Kumar et al. (2012)	Several projections
	182		Amarasinghe et al. (2014)	

Our motivation for this study arises from: 1. the importance of national food security in Bangladesh and the implied need for reliable projections for planning purposes; 2. the appreciation that several other studies (referred to above) missed some key concerns (such as leaving out climate change considerations, and the constraints of land and water availability); 3. several other studies did not consider uncertainties in projections; and / or 4. other studies did not use up-to-date or realistic figures for population growth or the growth in grain production. In this study, our aim is to examine national food security by comparing potential supply and demand of rice and wheat for Bangladesh. We used up-to-date figures for supply and demand projections, and examined the uncertainties in the projections and the constraints of land and water availability.

Methods

Model

A spreadsheet based model was developed to analyze food security scenarios up to 2050. The model estimates the demand using current and future projected population and likely changes to the per capita consumption of rice and wheat. Rice and wheat production were estimated from historical trends of cultivated area, production, and yields, and extrapolation of the trends into the future. *Aus*, *aman,* and *boro* rice were modelled separately. *Aus* is grown in *Kharif-I* (the pre-monsoon season; March to June), *aman* is grown in *Kharif-II* (the monsoon season; July to October), and *boro* is grown in *Rabi* (the dry season; November to February), which usually extends to *Kharif-I. Aman* is the main rainfed rice whereas *boro* is fully irrigated. *Aus* is nowadays grown in a small area and is not irrigated (BBS 2012). Wheat is grown in the *Rabi* season only. The impact of climate change was introduced by changing the extrapolated production trend for the integrated impact of climate change factors including temperature, precipitation, flooding and sea level rise. The model was run for the period 1995 to 2050 where 1995 to 2010 provided the historical trend data. Projections were made for different scenarios in the period of 2011–2050 for different production (supply) and requirement (demand) scenarios. Details of population projections, production trends and climate change projections are described below.

The overall method thus used population projections for food demand and compared them to production projections based on past trends and climate change impacts. This is similar to the broad methods used by several other studies, including those of Begum and D'Haese (2010), Yu et al. (2010), Talukder and Chile (2011), Ganesh-Kumar et al. (2012) and Amarasignhe et al. (2014). Other studies also used a similar strategy, but did not explicitly give future production projections (Karim et al. 1996, 1999; Faisal and Parveen 2004; Hussain 2011; Basak et al. 2010). Although the broad methods were similar, differences in assumptions led to differences in results and overall conclusions amongst these studies, as we will discuss below.

Data

Current cultivated area, yield, and production

Historical cultivated area, yield and production of rice and wheat were obtained from the Bangladesh Statistical Yearbook, published every year by the Bangladesh Bureau of Statistics (BBS). These data have been widely used for projections and planning (e.g. Faisal and Parveen 2004; Ganesh-Kumar et al. 2012; Murshid et al. 2013; Amarasinghe et al. 2014).

Figure 1 shows the cultivated area of rice and wheat from 1977 to 2010. There has been a massive growth in the area devoted to *boro* rice from 0.86 Mha in 1977 to 4.71 Mha in 2010. Over the last decade (2001–2010) the area increased from 3.76 Mha to 4.71 Mha, an average increase of about 100,000 ha per year. In 2010, about 60 % of the net cultivable area of the country (7.9 Mha) was under *boro* cultivation in the dry season. However, from 1977 to 2010, the net cultivable area decreased from 8.3 Mha to 7.9 Mha. The increase in *boro* area is thus due to a decrease in the area of other crops such as *aus* (the *aus* season overlaps with the *boro* season) and other *Rabi* crops cultivated in the same season. The area of *aus* has declined gradually; from 3.22 Mha in 1977 to 1.025 Mha in 2005 and in 2010 was 0.98 Mha, which is about 13 % of the current net cultivable area (Fig. 1). However, the total area of rice cultivated (sum of *aman*, *aus* and *boro*) increased by about 15 % from 1977 to 2010. Planting of *aman* rice depends on the onset of the monsoon season, as a lot of water is needed to prepare the land for transplanting. As a result, the area of the crop varies from year to year within the range of 5.5 to 6.0 Mha as shown in Fig. 1. In 2010, about 50 % of the net cultivable area was under *aman* cultivation. The cultivated area of wheat in 1977 was 160,000 ha which rose to a maximum of 882,000 ha in 1999 then gradually declined to 376,000 ha in 2010 (Fig. 1).

The national average yield of *aus*, *aman* and *boro* rice has increased consistently, with some fluctuations as shown in Fig. 2, at an average rate of 0.0236, 0.0284, and 0.0561 tonne/ha/year, respectively during the period 1977 to 2010. However, the rate of yield growth since 1995 was higher and strongly linear (Fig. 3). The average rates of growth were 4.84, 2.76 and 3.61 % per year or 0.0489, 0.0411 and 0.0882 tonne/ha/year, respectively, for *aus*, *aman*, and *boro* rice. Average growth in the combined yields of the three varieties of rice during this period was 0.0759 tonne/ha/year or 4.64 % per year.

The yield growth of *boro* rice is 80 and 115 % higher than that of *aus* and *aman* rice, respectively. *Boro* is a fully irrigated crop so the risk of water stress is much less than with *aus* and *aman* rice, which are rainfed. Due to variation in rainfall over space and time, *aus* and *aman* rice suffer from in-season water stress which is the main reason of their low yield and yield growth (Islam and Mondal 1992; Jensen et al. 1993). In addition to that, *aus* and *aman* rice (particularly *aman*) also suffered damage due to inundation and flood from heavy rainfall (Roy 2013a).

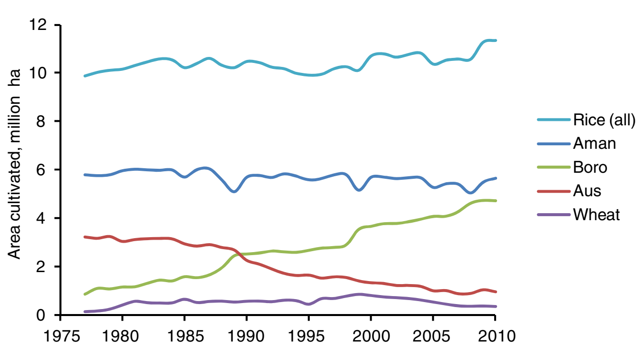

Fig. 1 Cultivated area of rice and wheat from 1977 to 2010

The total production of rice increased almost 3-fold from 11.6 million tonnes (MT) in 1977 to 32.0 MT in 2010 (Fig. 4). The increase in production was mainly due to the increase in yield (Fig. 2). *Aman* has the highest area of cultivation (50 % of the total rice area in 2010) as shown in Fig. 1. Its contribution to total rice production is about 38 %. The higher yielding *boro* covers 42 % of the total rice area and produces 57 % of the total production. The contribution of *aus* to total production is about 5 % from 9 % of the total area. The large increase in *boro* rice production is clearly a key factor in food self sufficiency of the country.

While there is growth in rice production and yield, wheat production and yield rose and fell again (Figs. 2 and 4). In 1977, total wheat production was 264,000 tonnes which increased to 1.9 MT in 1999. Since then, the total area and hence the production gradually declined to about 900,000 tonnes in 2010. The increase in total production is mainly due to the increase in total area of cultivation as yield has varied around 2 tonne/ha over the period (Fig. 2). However, there has been linear (R^2=0.92) growth in yield over the last 6 years (2006 to 2011) at a rate of 0.2 tonne/ha (Mainuddin et al. 2014).

Population

The population projections for the period of 2012–2050 are taken from the Population Division of the Department of Economic and Social Affairs of the United Nations (UN Population Division 2012) for low variant, medium variant, and high variant scenarios (Fig. 5). The low variant estimates of population growth projected that Bangladesh will reach a population of 172 million by 2050, whereas the medium and high variant projections for 2050 are 202 and 235 million.

Consumption

The production and yield of rice (as shown in Figs. 2, 3 and 4) in Bangladesh and elsewhere is given as rough rice (rice enveloped by the husk). The ratio of converting rough rice to milled rice for consumption is called the milling ratio. According to IRRI (http://www.knowledgebank.irri.org/step-by-step-production/postharvest/milling) milling ratio varies from 0.68 to 0.72 depending on the variety, and includes head and broken rice. In our estimates, we used a conservative milling ratio of 0.65. The historical trend (1990–2010) in milled rice consumption per capita per annum shows a gradual increase in consumption since 1997 (Fig. 6). Per capita consumption was

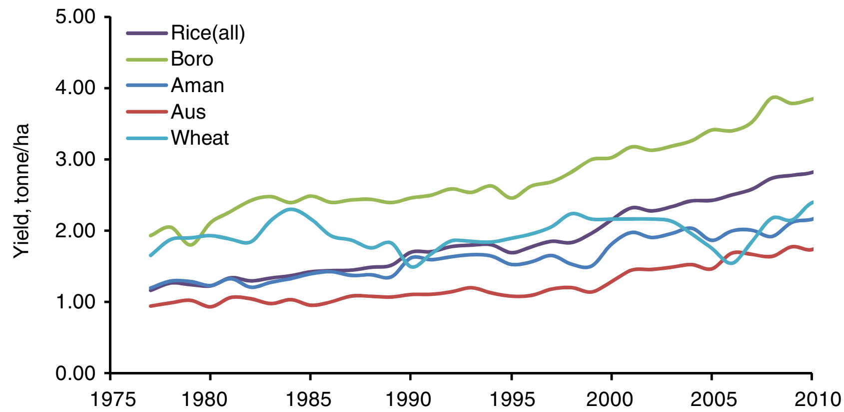

Fig. 2 National average yields of rice and wheat from 1977 to 2010

estimated by dividing the sum of total rice production and the net import of rice available from FAOSTAT (http://faostat3.fao.org/) in a year by the total population. Wheat is the other cereal consumed in Bangladesh. On average, 83 % of the food grain consumed is rice and the remaining 17 % is wheat. We considered 2010 as the base year in our analysis which shows a consumption of 146 kg of milled rice per capita per annum which is equivalent to 225 kg of rough rice. The consumption of wheat was considered as 25 kg/capita/annum. Faisal and Parveen (2004) gave a figure of 172 kg of food grain (rice+wheat) per capita per annum. According to our analysis, the consumption of food grain (rice+wheat) in 2010 was 171.3 kg/capita. Akhtar et al. (2010) reported 150.4 kg of cereal consumption per capita per annum, of which the share of rice was 91 %, which is much lower than the consumption considered here.

Impact of climate change on production

We considered the impact of climate change based on the recent modelling by Yu et al. (2010). Yu et al. (2010) projected potential future crop production and the response to multiple climate change impacts (temperature and precipitation changes, CO_2 fertilization, flood changes, and sea level rise) using Crop Environment Resource Synthesis (CERES) Rice and Wheat components of the DSSAT (Decision Support System for Agro-technology Transfer) model (Hoogenboom et al. 2003). These dynamic biophysical crop models simulate plant growth on a per ha basis, maintaining balance of water, carbon and nitrogen (Yu et al. 2010). CERES models have been applied in Bangladesh to model rice and wheat (Mahmood et al. 2003; Timsina and Humphreys 2006) and to examine the impact of climate change (Hussain 2006). Considering all climate change impacts, their projections showed losses of *aus* and *aman* median production by 1.5 and 0.6 %, respectively by 2050. *Boro* showed the highest median loss of 3 % by 2030s and 5 % by 2050s by most Global Climate Model (GCM) projections (Yu et al. 2010). The impact of climate change on wheat yield is a projected increase of 3 % by 2050. We modified the yield trends projected into the future by the losses or gains calculated by Yu et al. (2010) for the combined climate change impacts.

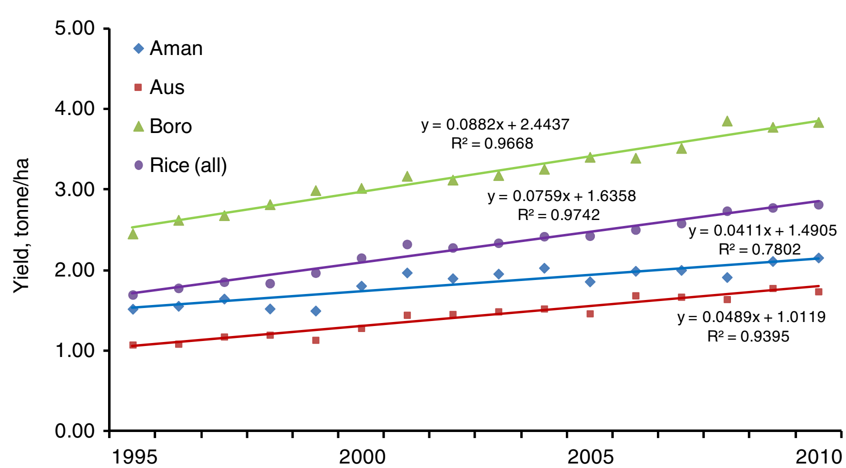

Fig. 3 Linear trends in rice yield from 1995 to 2010

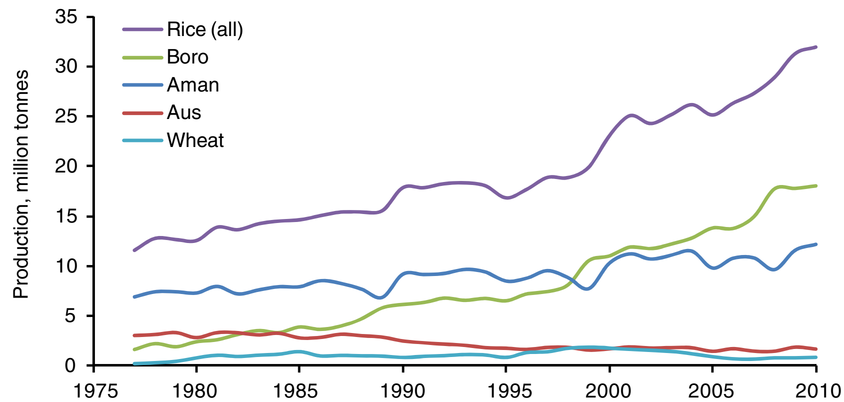

Fig. 4 Production of rice and wheat from 1977 to 2010

Scenarios

Based on the historical trends presented above, we considered the following 3 scenarios for future rice production along with a base case.

Base case: the area and yield was unchanged at the 2010 level for *aus*, *aman* and *boro* rice for the future and there was no impact of climate change.

Scenario 1: the areas of *aus*, *aman* and *boro* rice were kept unchanged at the 2010 level for the future, while yields were increased according to the trends shown in Fig. 3 until they reached to a maximum of 80 % (4.00, 5.20 and 6.00 tonne/ha, respectively for *aus*, *aman* and *boro* rice) of the potential yield (5.00, 6.50, and 7.50 tonne/ha, discussed below); after that, the yield were left constant. The impact of climate change was included in the projected yield trends.

Scenario 2: same as scenario 1 (constant area, increasing yield, climate change impact on yield) except that yield was increased to the potential yield.

Scenario 3: Same as scenario 1 except for the area of *boro* rice, which was increased linearly to 6 Mha by 2050 starting from 2011. We discuss the basis of the area increase below.

In all scenarios, we kept the area of *aus* and *aman* constant at the 2010 level. The area of *aus* has gradually declined.

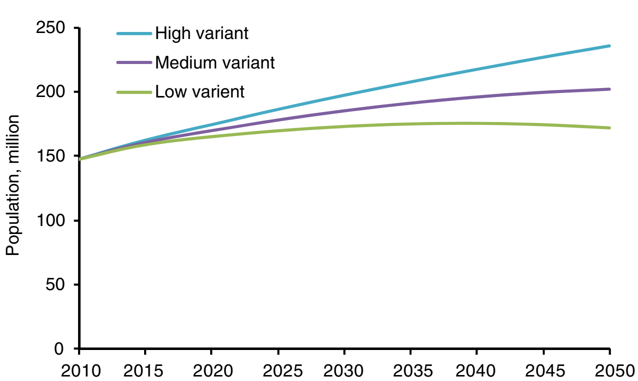

Fig. 5 Projected population of Bangladesh for different fertility scenarios (source: UN Population Division 2012)

Since 2005, the area has been about 1 Mha with a maximum of 1.07 Mha in 2009 and the minimum of 906,000 ha in 2007. In 2010 the area was 984,000 ha. It is likely that *aus* area will remain around 1 Mha. The average area of *aman* during 1995–2010 was 5.55 Mha varying within a range of 5.05 to 5.81 Mha. In the simulation, we kept the area at the 2010 value of 5.66 Mha which is very close to the average area for the period of 1995–2010. Ganesh-Kumar et al. (2012) considered the area of *aman* constant at 5.5 Mha for future projections.

As shown in Fig. 1, the *boro* acreage has been rising gradually for several decades. The question is how long will this rise continue? Ganesh-Kumar et al. (2012) projected that *boro* acreage will continue to rise until it reaches a maximum of 6.5 Mha at the latest by 2030, which is around 82 % of the net cultivable area of 7.9 Mha in 2010. This projection is much higher than 5.10 Mha by 2025 considered in the first National Water Management Plan (WARPO 2000). It is expected that the area of *boro* will rise, with government plans to increase the area copped in the southern coastal zone. Here, *boro* covers only 40 % of the net cultivable area compared to 72 % of the net cultivable area in the north-west region (Mainuddin et al. 2014), due mainly to the unavailability of freshwater for irrigation and salinity in the coastal region (Mainuddin et al. 2013). The government has already planned investment and started implementing infrastructure projects (GoB and GoN 2012; Ministry of Agriculture of GoB and FAO 2013) for the coastal region to increase dry season cropping intensity, hence, increasing overall food security. In this study, we considered for scenario 3 a conservative estimate of a linear increase from the current *boro* area to 6.0 Mha by 2050.

The maximum potential (achievable yield in the farmers' field) yields of the main cultivated varieties of *aus*, *aman* and *boro* rice grown in Bangladesh are 5.0, 6.5 and 7.5 tonnes/ha, respectively (http://www.brri.gov.bd/publications/leaflets.htm). However, there is a difference between the maximum potential yield and the actual yield achieved in the farmers'

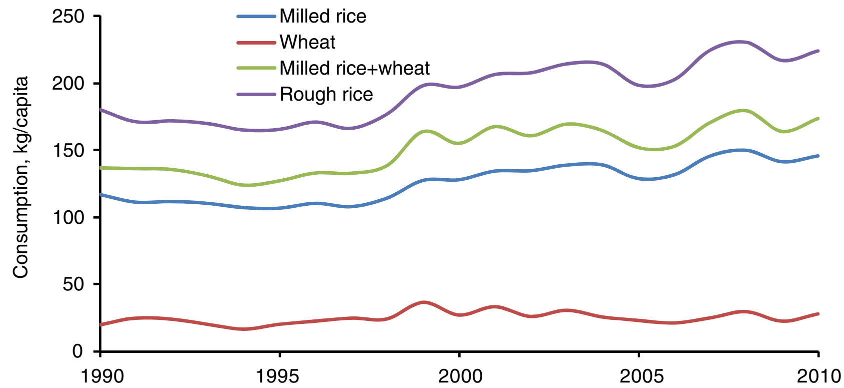

Fig. 6 Consumption of rice and wheat

field, called the 'yield gap' which is around 20 % in the south Asian region (Van Ittersum et al. 2013; Van Wart et al. 2013).

For wheat, we also consider 3 scenarios in addition to a base case.

Base case: the area and yield are unchanged at the 2010 level for the future and there is no impact of climate change.

Scenario 1: the area of wheat is kept unchanged at the 2010 level for the future, while yield increases linearly from the current (2010) until yield reaches 80 % (4.00 tonne/ha) of the potential yield (Van Ittersum et al. 2013; Van Wart et al. 2013) of 5.0 tonne/ha (http://www.BARI.gov.bd). After that, the yield remains constant. The impact of climate change is included in the projected yield trends.

Scenario 2: same as scenario 1 (constant area, increasing yield, climate change impact on yield) except that yield increases to the potential yield of 5.0 tonne/ha.

Scenario 3: same as scenario 1 except the cultivated area increases linearly to 0.5 Mha by 2050 from the current (2010) area.

For the demand, we have estimated the requirements for all three population projection scenarios (as shown in Fig. 5) with the current (Fig. 6) and future projected consumptions of rice and wheat.

Results

Estimated production of different scenarios of rice and the consumption requirements for 3 different population projections up to 2050 are shown in Fig. 7. With the increase in population, the rice consumption requirement will increase to 38.7, 45.4, and 53.0 MT of rice respectively for low variant, medium variant, and high variant population projections. So, the additional (compared to the base case of 2010) production requirements will be 6.7 (21.0 %), 13.5 (42.1 %), and 21.0 MT (65.8 % of current production) respectively for low variant, medium variant, and high variant population projections. However, the projected production of scenarios 2 and 3 is higher than the requirements for all population projections. For scenario 1, which considers only the current trend of growth in yield with the area constant at 2010 level for the future, the projected production only slightly falls below the requirements of the highest population projection by 2.3 % by 2050 (Table 2). Scenario 1 is the most conservative among all the scenarios. By 2050, the projected yields of *aus*, *aman* and *boro* with the impact of climate change are 3.69, 3.77 and 5.70 tonne/ha, respectively. Without the impact of climate change, the production of scenario 1 would be higher by about 1 % than the highest population projection.

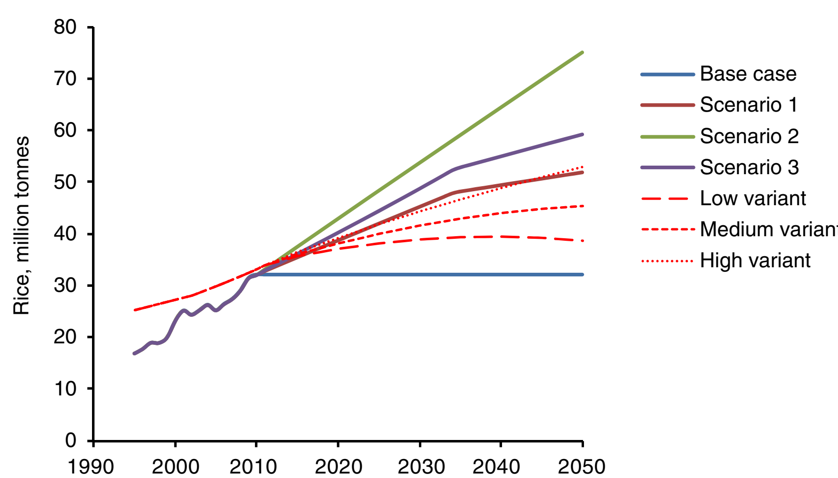

Fig. 7 Comparison of projected production of rice for different scenarios (Base case to scenario 3) with the consumption requirements for different population projection scenarios (low variant to high variant)

Table 2 Total production of rice as percentage of the consumption requirements for different population projection scenarios at 2050

Population projection	Production as % of the requirements			
	Base case	Scenario 1	Scenario 2	Scenario 3
Low variant	82.7	133.9	193.8	153.0
Medium variant	70.4	114.0	165.0	130.3
High variant	60.3	97.7	141.4	111.6

The latest statistics available (Parvez 2013a) show the total production of rice in 2012 and 2013 was 33.9 and 33.8 MT, respectively. This is expected to rise to 34.2 MT in 2014 according to the forecast of the US Department of Agriculture (USDA) cited by Parvez (2013a). In this study, projected productions of scenario 1 (most conservative) are 33.4, 34.1 and 34.7 MT which is within 1.0 to 1.4 % of the actual production of 2012 and 2013 and within 1 % of the forecast given by the USDA for 2014. The most optimistic scenario of this study (scenario 2) projected 34.2, 35.3 and 36.4 MT for 2012, 2013 and 2014, respectively. Ganesh-Kumar et al. (2012) projected rice output in 2015 is likely to be in the range of 31.2 to 35.2 MT.

An increase in production can be achieved either by increasing the area of crop cultivation or by increasing the yield of crop or both. In scenario 3, we consider growth in *boro* area to 6 Mha with linear growth in yield to 80 % of the maximum potential yield. If we consider growth in *boro* area to 6 Mha by 2050 with the maximum potential yield then the total projected production will increase to 84.2 MT.

An alternative way to consider the national food security requirement is in terms of the yield required to satisfy the projected consumption. Figure 8 shows the average yield of rice required by 2050 with the current (2010) cultivated area. The average yield required for low variant, medium variant, and high variant population projections is 3.48, 4.00, and 4.67 tonne/ha, respectively. The average growth in yield required is 0.32, 0.83, and 1.42 % per year, or 0.0102, 0.0257, and 0.0427 tonne/ha/year. The growth in average yield during 1995–2010 was 1.32 % or 0.0323 tonne/ha/year. So the current growth in average yield is much higher (59 %) than required for medium-variant population projection and only 6.7 % lower than the requirements for high variant projection. Any increase in cultivated area from the current (2010) area will reduce the required growth in average yields.

In the scenarios, we have considered consumption of rice fixed at 225 kg of rough rice (146 kg/capita of milled rice) for the whole simulation period. With economic development (Parvez 2013b), fish and meat consumption are likely to increase (Delgado et al. 1999, 2007); as a result rice consumption would decrease. According to a Household Income and Expenditure Survey (Parvez 2013c) per capita milled rice consumption fell by 10 kg between 2000 and 2010. This is not visible in Fig. 6, in which consumption is estimated from production. A portion of the production is preserved as seed for the next season and the Government of Bangladesh stores at least 3 months of food grain to maintain security against any unexpected natural disasters. This is not considered in the consumption estimated in Fig. 6. To see the impact of reduced consumption, we estimated the requirements considering the consumption at 225 kg/capita (146 kg/capita of milled rice) up to 2020 and then going down linearly to 200 kg/capita (130 kg or milled rice) by 2050. The comparison of the estimated requirements with the different production scenarios is shown in Fig. 9. Due to reduced consumption, even the most conservative production scenario (scenario 1) will produce surplus to the requirements by 50.7, 28.3, and 10.0 % respectively for low variant, medium variant, and high variant population projections.

The future projection of wheat production is much less optimistic than rice (Fig. 10). At the current consumption rate (25 kg/capita/year), the demand for wheat will grow to 4.30, 5.05, and 5.89 MT by 2050, respectively, for low variant, medium variant, and high variant population projections. Current production is only 0.90 MT. If there is no increase in production, the current production will meet 21 % of the

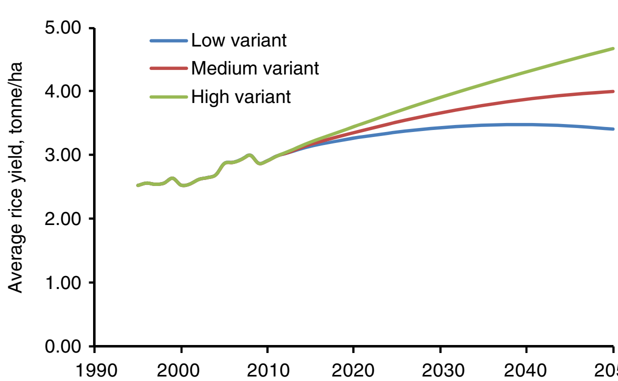

Fig. 8 Average yield of rice required to maintain food security by 2050 with the current (2010) cultivated area

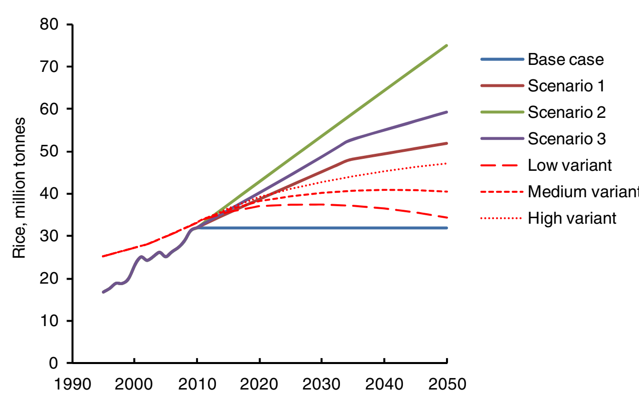

Fig. 9 Comparison of projected production of rice for different scenarios (Base case to scenario 3) with the consumption requirements for different population projection scenarios (low variant to high variant) considering lower consumption per capita after 2021

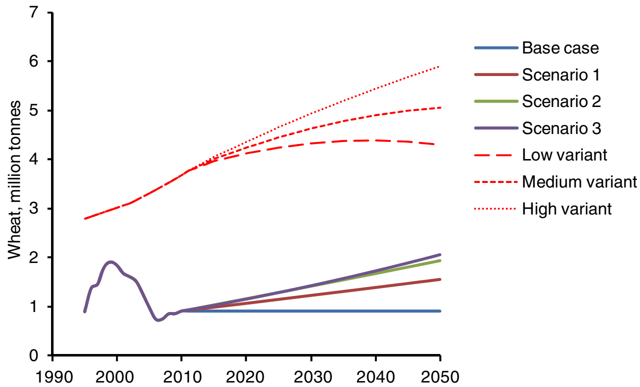

Fig. 10 Comparison of projected production of wheat for different scenarios (Base case to scenario 3) with the consumption requirements for different population projection scenarios (low variant to high variant)

requirements if low variant population projection is considered (Table 3). Scenario 3 (most optimistic scenario, area increases linearly to 0.5 Mha by 2050 and yield increases to 4.0 tonne/ha), will be able to reduce the gap between production and the requirements (Table 3). By 2050, this gap will remain at 2.24, 3.0 and 3.8 MT respectively for low, medium and high variant population projections. If the consumption of wheat increases, then the gap between the production and requirements will widen. Self sufficiency of wheat can be reached in 2045 and 2050, respectively, for low variant and medium variant population projections if the cultivated area of wheat is gradually increased to 1 Mha and the yield increased to 5.0 tonnes/ha by 2050.

Discussion

Bangladesh has made considerable progress in controlling population growth. According to the latest Population and Housing Census in 2011, the current annual population growth rate is 1.37 %, down from 1.58 % in 2001 (The Daily Star 2012). During this period, the number of children per woman has reduced from 3.3 to 2.3 and made Bangladesh 'a low fertility country' according to the United Nations Population Fund (Hosen 2013). Thus, a low variant population projection is the most likely scenario for Bangladesh. However, the medium variant projection is used in Bangladesh for policy and planning (BBS 2010), and it is a safer basis on which to plan. The high variant population projection is unlikely for Bangladesh.

Projected demand for rice and wheat depends mainly on assumptions about population growth. As noted in the introduction, other studies have used a range of population projections varying from the low variant projection to a population greater than the high variant projection. Karim et al. (1996); Yu et al. (2010); Hussain (2011), and Basak and Alam (2013) all appear to have used projections at or above the high variant projection, though the actual projection used by Yu et al. (2010) is a little unclear. These latter studies are thus likely to have erred on the pessimistic side of food security assessments, at least in respect of the demand side. Projected demand also depends on assumptions about food preferences. We show that there may be some decline in the demand for grains due to a shift towards a higher animal protein diet.

The scenarios considered here show total production in 2050 of 51.8 (scenario 1) to 75.0 (scenario 2) MT including the contribution of *boro* of 26.8 to 33.5 MT. Yu et al. (2010) projected total rice production of 73.2, 74.6 and 85.6 MT by 2050 for worst, variable and optimal climate scenarios; the contribution of *boro* rice to the total production was estimated to be 37.4 to 38.5 MT. Thus our most optimistic projections are similar to the most pessimistic projections of Yu et al. (2010). Ganesh-Kumar et al. (2012) and Amarasinghe et al. (2014) projected rice production to grow to nearly 39 and 49 MT respectively by 2030. The most conservative scenario of this study (scenario 1) shows the projected production of 45.1 MT by 2030. The increase in total production by Ganesh-Kumar et al. (2012) is mainly due to increase in area, as they did not consider increases in yield. They projected yields of *aus*, *aman* and *boro* rice to be 1.9, 3.0 and 3.18 tonne/ha by 2030. The actual yield of *aus*, *aman* and *boro* in 2010 was 1.74, 2.16 and 3.84 tonne/ha, so the most productive crop (*boro*) has already exceeded their 2030 yield projection.

The projected growth in production results from increases in yield. The current growth in rice yields in turn results from improved management, the introduction of new varieties, and new technology, particularly the spread of irrigation of modern rice varieties (Hossain et al. 2005; Amarasinghe et al. 2014). Much of the growth in yield at the national level comprises increases in yield of the lower yielding districts. The gap between actual and potential yield is decreasing, and the spatial variation in yield is also reducing (Mainuddin et al. 2014). These improvements are likely to continue.

New varieties with greater yield potential explain much of the increasing yields in recent years (Hossain and Tiexeira da Silva 2013). In the analysis, we considered the potential yield of the current dominant varieties only. However, there are new varieties, including hybrid varieties such as the recently released BRRI hybrid

Table 3 Total production of wheat as percentage of the consumption requirements for different population projection scenarios at 2050

Population projection	Production as % of the requirements			
	Base case	Scenario 1	Scenario 2	Scenario 3
Low variant	21.0	36.1	45.1	47.9
Medium variant	17.9	30.7	38.4	40.8
High variant	15.3	26.3	32.9	35.0

varieties 54, 55 and 56 (http://www.brri.gov.bd/publications/leaflets.htm) for *boro,* with potential yields of 8.0 to 9.0 tonne/ha. For *aman*, BRRI drought tolerant hybrid variety 57 with a potential yield of 6.5 tonne/ha was released in 2010. These varieties and other recently released high yielding, hybrid, short-duration and fast growing, drought and salt resistant varieties are gradually replacing current low yielding varieties (Ahmad 2013a; Hoque 2013; Parvez 2013d; The Financial Express 2013; The Daily Star 2013b). Thus it is likely that yield will continue to rise with potential yields greater than we have considered. In the future, the expanded availability of modern rice varieties could withstand climate change impacts without the yield penalties assumed in our analysis.

In addition to the varietal development, new farming technologies are being developed to grow four crops in a year including three rice crops (Ahmad 2013b; The Financial Express 2013). The Bangladesh Agricultural Research Institute (BARI) introduced a four-crop rotation during the 2011–12 and 2012–13 cropping seasons with a potential harvest of over 34 tonnes of rice equivalent from each hectare of land (Ahmad 2013b). The output is more than twice the current usual farm harvest of 14.37 tonnes in a double crop a year rotation. Bangladesh's cropping intensity has reached 191 % (Ahmad 2013b), making the country one of the most intensive cropping zones in the world. The introduction of a four-crop rotation would further increase the cropping intensity and thereby increase the total farm output. Bangladesh had about 9,300 ha of quadruple cropping area in 2011 (BBS 2012). The four crops rotation if widely implemented would boost the production beyond our projections.

For wheat, there is a big gap between the current (2.40 tonne/ha) yield and the expected yield considered for the scenarios (4.0 to 5.0 tonne/ha) by 2050. There is continuing development of wheat varieties resistant to pests, diseases and to some extent salinity in the soil, and the yield of these varieties is also higher than the potential yield considered here (http://www.BARI.gov.bd; Rawson et al. 2013; Mainuddin et al. 2013). Some of these varieties have recently been released (http://www.BARI.gov.bd). In addition, there is continuing development of improved farming technologies and agronomic and management practices which are expected to further enhance yield. Thus, in the future the expected yield might be achievable.

Thus, it appears reasonable to suppose that the projected yields of both rice and wheat are achievable. However, achieving the overall production will depend on the availability of water and land resources, and these are likely to be the main threats to maintaining food grain self sufficiency to 2050 and beyond. For projections, which involve no increase in area (rice scenarios 1 and 2 and wheat scenarios 1 and 2), the irrigation water demand will be similar to the current demand of about 31 km^3 (Mainuddin et al. 2014). An increase in area of *boro* rice to 6 Mha by 2050 will increase the irrigation demand to about 40 km^3 (Mainuddin et al. 2014). Climate change may further increase demand by about 3 % for dry climate change scenarios (Mainuddin et al. 2015). Groundwater is the main source of irrigation and supplies about 80 % of the total irrigated area of the country, and is growing. There is no growth in surface water use.

In recent years, there have been serious concerns about the sustainability of groundwater use, particularly for the crop-intensive northwest region of the country (Shamsudduha et al. 2009; Jahan et al. 2010; Shahid and Hazarika 2010; Rahman and Mahbub 2012). The over-use of groundwater is most evident in a small sub-region known as the Barind Tract; the sustainable levels of groundwater use in the northwest region more generally have not been assessed in detail (Kirby et al. 2013). Based on the current trend, it is likely that increased demand due to increase in area will further stress the groundwater resources. These concerns, combined with concerns over naturally occurring arsenic contamination of shallow groundwater (BGS and DPHE 2001) has led the Government of Bangladesh to plan to decrease dependence on groundwater by increasing use of surface water for irrigation and replacing rice with wheat or other crops that use less water (Government of Bangladesh 2010). Nevertheless, it appears overall that there is scope to increase rice production with the available water, as concluded also by Faisal and Parveen (2004) and Ahmad et al. (2014). Amarasinghe et al. (2014) conclude that the likelihood of a rice surplus for export leads to an alternative choice of scaling back rice production to the requirement for self-sufficiency in order to limit the pressure on groundwater resources.

The biggest risk to food security may be the availability of agricultural land in the future. The conversion of arable agricultural land to other uses is 1 % per year (Government of Bangladesh 2010; Quasem 2011), and the area has decreased by 68,700 ha/year over the last decade (Hossain 2013). If this continues to 2050, 2.75 Mha of productive agricultural land will be lost reducing the net cultivable area from 7.9 Mha to 5.15 Mha, which is less than the maximum area (6.0 Mha) considered in the rice scenarios. The Government of Bangladesh is drafting laws to protect agricultural land (Roy 2013b). In addition, land in the coastal zone may be lost to rising sea levels. Rising sea levels were considered by Faisal and Parveen (2004) and Yu et al. (2010). Following Yu et al. (2010) we have factored them into our climate change projections.

Thus the projected production increases if achieved will be greater than those required for food grain self sufficiency even under fairly pessimistic scenarios, leading to a generally positive outlook for national food security in future decades. This conclusion was also reached by Faisal and Parveen (2004, projection to 2050), Talukder and Chile (2011, projection to 2020), Amarasinghe et al. (2014, projection to 2030). Hussain (2011) concluded that available technologies will meet the demand for cereals to 2025 or beyond, but it will be difficult to meet demand in 2050. Ganesh-Kumar et al. (2012) assessed a range of population and production scenarios to 2030, and concluded that there could be either a surplus or deficit of rice; they also concluded that a surplus, if any, would diminish after 2020 whereas deficits would grow throughout. In contrast, Karim et al. (1996, 1999), Begum and D'Haese (2010), Basak and Alam (2013) concluded that food grain self sufficiency is unlikely, though they all suggest that deficits can be mitigated with crop research and other adaptation measures. Yu et al. (2010) conclude that climate change impacts on rice and wheat production will necessitate greater reliance on other crops and imported food grains. As we noted above in the discussion of population projections, Karim et al. (1996), Yu et al. (2010), and Basak and Alam (2013) all used high population projections which partly explains their pessimistic conclusions about food security.

Thus, the outlook for food, or at least rice, security is generally positive at the national level, though there are serious risks and challenges. Beyond this, there remain problems of distribution and ensuring that the disadvantaged benefit. Distributional aspects (affordability and accessibility) are outside the scope of this paper, though we observe that food security at household and individual levels is major concern for the Government (Government of Bangladesh 2006). Bangladesh is making steady progress in this regard with the incidence of malnutrition declining (FAO, IFAD and WFP 2013).

Conclusions

Bangladesh has recently achieved self-sufficiency in rice, due mainly to increased yields and the greatly increased area of groundwater irrigated dry season rice over the last several decades. The expected population growth will increase the demand for rice and other food for many decades. However, rice yields are well below potential and the current trends in yield, combined with the continued development of higher yielding varieties and more productive management practices, should enable Bangladesh to remain self sufficient in rice at least to 2050. Only the lowest yield projections coupled with the highest population projections (which seem unlikely) show a shortfall of production by 2050. Wheat production, on the other hand, is less than demand, and appears likely to continue to be insufficient to 2050. Nevertheless, the demand for wheat is much less than that for rice and with increases in yield, cultivated area, and better practices, wheat can potentially meet demand by 2050.

Ensuring continued national food security will demand solutions to key challenges. The most serious challenge for the future appears to be the declining area of agricultural land, about 1 % of which is being converted each year into other uses. Water for irrigation will be a major challenge, with concerns about unsustainable groundwater use. Sustainable groundwater use in some areas combined with use of more surface water and moving some production to other less intensively cultivated areas will help meet this challenge. Climate change poses some challenges, particularly the potentially greater flooding and salinity in the coastal zone resulting from sea level rise. Climate change is also projected to reduce yields; this impact is built into the projections and so does not appear to be a particularly serious challenge.

The paper deals only with food security in terms of total availability of food grain at the country level which does not ensure access to adequate food at household and individual levels. Apart from availability, affordability, accessibility, and nutritional quality are essential elements of overall food security which are not considered in this study.

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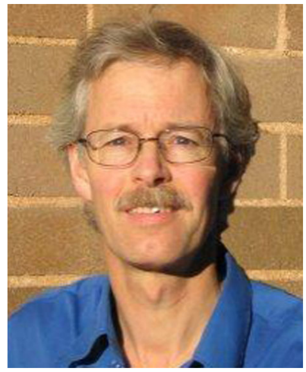

Dr. Mac Kirby researches water and food production in large river basins. He has led projects on the Murray-Darling Basin in Australia and in south and southeast Asia including Bangladesh. He has also worked on several other major river basins in Asia, Africa and South America. His work encompasses both biophysical and economic aspects of water use and food production, particularly irrigation, with the aim of providing information about major issues and trends within the basins. These include future prospects under scenarios of climate change, development and changed management of land and rivers.