Agricultural Water Management 179 (2017) 34–46

Contents lists available at ScienceDirect

Agricultural Water Management

journal homepage: www.elsevier.com/locate/agwat

Agricultural production, water use and food availability in Pakistan: Historical trends, and projections to 2050

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ARTICLE INFO

Article history:
Received 10 February 2016
Received in revised form 30 May 2016
Accepted 1 June 2016
Available online 16 June 2016

Keywords:
Food security
Irrigation efficiency
Groundwater use
Sustainability
Pakistan

ABSTRACT

Forty seven percent of the population of Pakistan is food insecure, access to food is uneven and malnutrition is widespread. In addition, food production depends greatly on irrigation, including the use of substantial volumes of water from already stressed aquifers. Our aim in this paper is to examine the implications of continued population growth on the required production of food and the implied water demand.

We examine the historical trends of crop production, water use, food availability and population growth in Pakistan, and project them forward to 2050. Food availability has improved over recent decades, mostly as a result of increasing the area and water use of crops and fodder, and partly as a result of importing more pulses and cooking oils. We show that a continuation of current trends leads to nearly a doubling of the (already unsustainable) groundwater use. There is uncertainty in the magnitude of climate change impacts, but climate change may further exacerbate matters. To avoid further increases of groundwater use, some combination would be required of: more dams and other irrigation infrastructure; increasing crop yields (particularly yields per unit volume of water) at a greater rate than in the past; a change in crop mix away from high water use crops like rice and sugarcane, to crops that use less water; and, exporting less and importing more food. The alternatives appear difficult to implement quickly, so it appears likely that in the short to medium term more groundwater will be consumed, with attendant problems of water quality and sustainability. Our analysis provides new perspectives on past trends and future food and water (including groundwater) challenges.

1. Introduction

According to the World Food Program, despite a good wheat harvest in 2014, more than half the population of Pakistan consumed less than the recommended caloric intake of 2100 kcal per person per day, and 47% of the population were food insecure (WFP, 2014). Ahmad and Farooq (2010) noted that despite significant improvements over recent decades in the food supply, the average per capita daily availability has remained at about 2400 kcal since 1990, access is uneven and malnutrition remains widespread (see also Khan and Shah, 2011; Bashir et al., 2012; Hussain and Routray, 2012).

Pakistan's food production depends greatly on irrigation, which provides more than 90% of the country's wheat, most of the pulses and nearly all of most other crops (FAO, 2015). Irrigation of pasture also provides the main feed for milk production and a substantial fraction of the feed for meat livestock (Dost, 2006; GoP, 2010; FAO, 2015). However, with the growing population, the per capita water availability has fallen, groundwater is being overused, and water quality is threatened by salinity in particular (Briscoe and Qamar, 2005; Condon et al., 2014). The provision of more food for a larger population in the future must be contemplated without additional supplies of water, and perhaps with using less water than today (Briscoe and Qamar, 2005). Briscoe and Qamar (2005), Kugelman (2009), the Water Sector Task Force (2012) and Condon et al. (2014) all suggest that the challenges of water scarcity can be overcome, and propose solutions that include both supply and demand: new dams (though Kugelman does not favour this option) and other infrastructure, improved water productivity in agriculture, and improved institutions governing water allocation and use.

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http://dx.doi.org/10.1016/j.agwat.2016.06.001
0378-3774/

Climate change is also expected to impact food production and food security, both because of potential changes to the amount and timing of water available for irrigation and because of the direct effect on crop yields due to changes in temperature. There is uncertainty regarding future water availability in the Indus basin, with a projections based on different climate models showing both reductions and increases in precipitation, with an increase in water availability somewhat the more likely by 2050 (Immerzeel and Bierkens, 2012; Yu et al., 2013; Lutz et al., 2014a,b; Nepal and Shrestha, 2015). However, Laghari et al. (2012) suggest that while there may be increases in water availability in the short term due to glacier melting, by 2046–2065 the availability will be significantly decreased. Rising temperatures will affect snow and ice hydrology, but the impact on volumes of river flow is projected to be within the range of current variations (Yu et al., 2013). The changing patterns of precipitation and snow and glacier melting may alter the timing of flows. Archer et al. (2010) suggested that "the evidence remains conflicting as to whether [climate] change will have a positive or negative effect on water resources", but suggested that it will play a more minor role than other factors, such as the reduction in storage due to sedimentation of dams, the continuing use of groundwater and, more generally, population growth and economic development including the development of new water infrastructure (see also Immerzeel and Bierkens, 2012).

In terms of crop yields, many projections for Pakistan show that there may be declines in the yields of staple crops such as rice and wheat (Iqbal et al., 2009; Zhu et al., 2013; Ahmad et al., 2015; Shakoor et al., 2015) due to a range of factors such as changed length of the growing season, though the wheat may be affected positively or negatively in different climate zones in Pakistan (Sultana et al., 2009). Adaptations such as changed sowing dates, more efficient use of water and greater research and development for higher yielding crop varieties may offset the negative impacts of climate change (Sultana et al., 2009; Yu et al., 2013; Zhu et al., 2013; Ahmad et al., 2015; Gorst et al., 2015).

With population growth, more food must be produced (or imported) in the future even to maintain the current level of food security in Pakistan, and more again to improve food security. Population projections for Pakistan have been revised downwards in recent years (Table 1), and this has implications for food security assessments. The downward revision from 2002 to 2012 with some reversed upward revision to 2015 suggests that there is some uncertainty in projections. Ahmad and Farooq (2010), Bashir et al. (2012) and Zulfiqar and Hussain (2014) used population projections consistent with earlier, higher projections, whereas Briscoe and Qamar (2005) (who considered water issues rather than food security) used a projection consistent with more recent lower projections (Table 1). Pakistan Government studies have likewise used projections that vary from the earlier higher projections to the more recent, lower projections. Zhu et al. (2013) state that population growth affects their food supply assessments, but do not state what growth assumptions they used. No study that we know of has considered the recent lower projections for food security assessments, nor has any study other than Zulfiqar and Hussain (2014) considered the uncertainty in population projections.

Thus, while there is much literature on food security in Pakistan, there is a clear gap in quantified projections of the relationships amongst water use, population projections, food production and food security. There will be trade-offs amongst several factors, including: the building of additional water storage in dams or additional irrigation infrastructure; the implied unsustainable mining of ever greater volumes of groundwater if infrastructure is not built; the importation of food; and the food availability per capita. Beyond the provision of a desired level of food availability there are also issues of distribution, access and nutritional quality which are outside the scope of this paper.

Our aim in this paper is to assess some choices for Pakistan about potential future agricultural production, water use, and food availability. We approach the assessment by first reviewing the growth in recent decades of agricultural production, per capita food availability and the volume of water used in food production in Pakistan. We then estimate potential growth in production and per capita food availability for the next few decades and the implied volume of water required. In the projections we examine the range of potential outcomes through several scenarios, including climate change and population scenarios, and including scenarios in which no more water is used than currently and scenarios in which we assume that there is continuing growth in water use, implying further degradation of the water resource. We discuss the implications of the projections in terms of the challenges and choices facing Pakistan.

Table 1
Population projections for Pakistan.

2025	2050	Source
250	349	United Nations (2002)
218[a]	271	United Nations (2012)
227	*265*[b]	United Nations (2015)
	310	
	359[b]	
	350	Ministry of Climate Change (2012)
227		Planning Commission (2014)
230		Briscoe and Qamar (2005)
	340	Ahmad and Farooq (2010)
	340 (in 2045)	Bashir et al. (2012)
245[c]		Zulfiqar and Hussain (2014)
250		
255[c]		

[a] Interpolated from the 2020 and 2030 figures given in United Nations (2012).
[b] The figures in italics are the lower 95 percentile and the upper 95 percentile estimates of the United Nations (2015) revision.
[c] The figures in italics are the described by Zulfiqar and Hussain (2014) as the lower limit and upper limit.

2. Methods

The focus of our assessment is Pakistan, and the relationship of food production to irrigation. Fig. 1 shows a map of Pakistan, with the main rivers and the groundwater salinity in the main areas of irrigation; salinity constraints to groundwater use is an issue to which we will later return.

2.1. Historical crop production and per capita food availability

We used several sources of historical data, listed in Table 2, on crop areas, crop production, crop yield, food availability, food imports, food exports, canal water flows, and population (both historical and projected). We grouped crops into groups which reflect the main food types and main water use types, namely: wheat, rice, other grains, sugar crops (which are dominated by sugarcane), pulses, oil crops (oilseeds and vegetable oils), fruit and nuts, vegetables and roots, meat (including offal and animal fat), milk, and fish (including other aquatic animal foods). The food availability for the food groups was divided by population to give food availability per capita. The historical period considered is from 1960-61 to 2012-13.

For some crops, particularly rice and wheat, we used linear regression to assess historical trends. We will show in the results section that many of the trends are approximately linear, so we regard linear regression as reasonable.

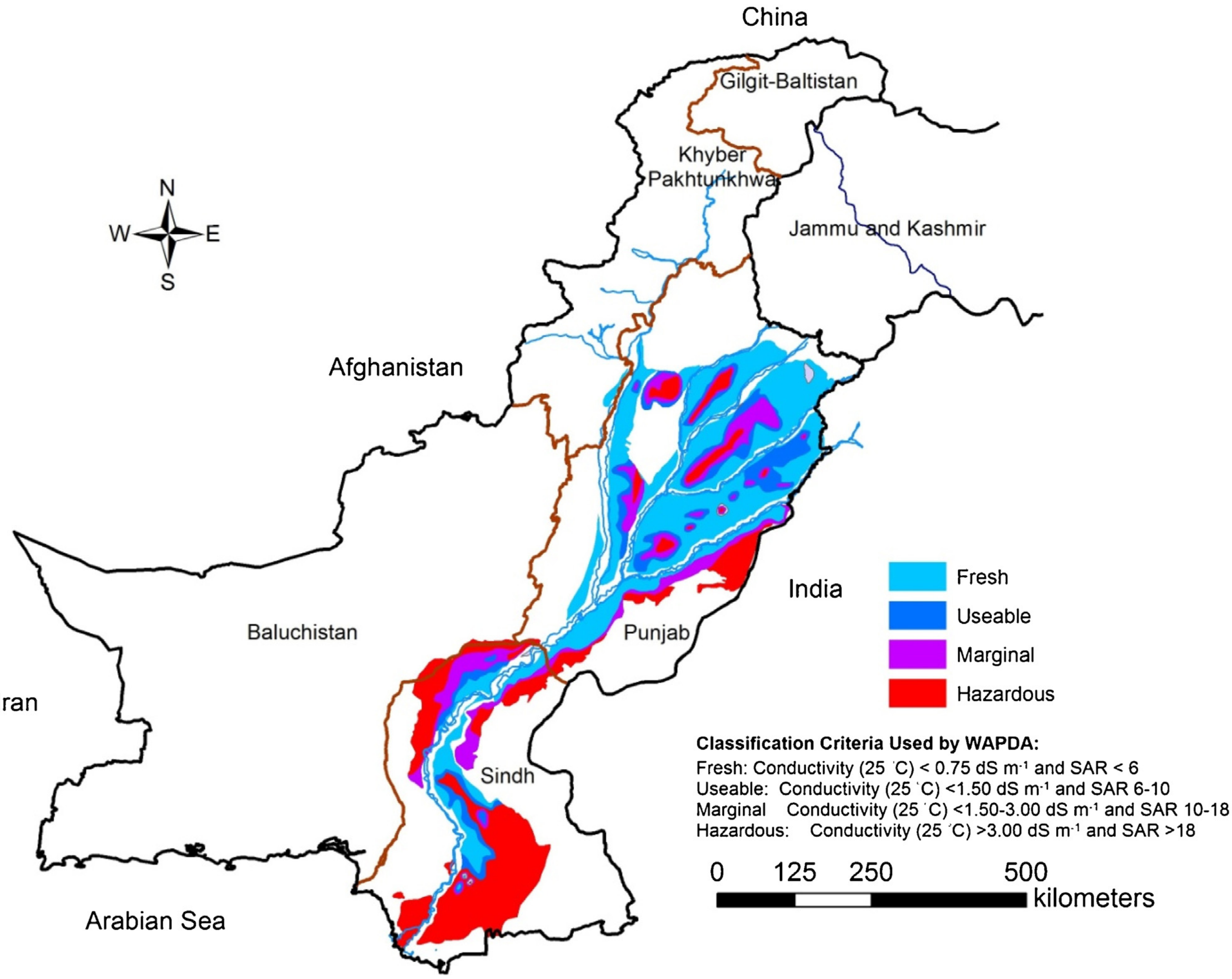

Fig. 1. Map of Pakistan, showing the provinces and groundwater salinity. Most of the major irrigation areas overly the areas of groundwater shown on the map, the only notable exception being an irrigation area in Khyber Pakhtunkha in northwest Pakistan, near Peshawar.

Table 2
Data sources.

Crop area	http://www.amis.pk/Agristatistics/area.aspx
Crop production	http://www.amis.pk/Agristatistics/production.aspx
Crop yield	computed from the above, and compared with http://www.amis.pk/Agristatistics/yield.aspx
Crop potential yield	http://www.aari.punjab.gov.pk/research/verities; for rice, also Mushtaq and Akram (2007)
Fodder area	1976-77 to 1999-00 from Dost (2003)
	1994-95 to 2011-12 from http://www.mnfsr.gov.pk/gop/index.php?q=aHR0cDovLzE5Mi4xNjguNzAuMTM2L21uZnNyL3B1YkRldGFpbHMuYXNweA%3D%3D
	1960-61 to 1975-76 by extrapolating backwards from the above
Food availability[a]	http://faostat.fao.org/site/368/DesktopDefault.aspx?PageID=368#ancor
Population and population growth	http://esa.un.org/unpd/wpp/unpp/panel_population.htm
Canal water flows	Obtained directly from the Water and Power Development Authority, Pakistan.

[a] In the FAOSTAT tables, food availability = production + imports – exports + change in stocks – feed – seed – processing – waste – other utilisation.

2.2. Historical water use

Bastiaanssen et al. (2012), Cheema (2012) and Cheema et al. (2014) described the overall water balance of the irrigated areas of the Indus basin for 2007 based on a combination of remote sensing modelling of evapotranspiration and water balance modelling. Cheema (2012) gave the figures for the irrigated areas of the Pakistan portion of the Indus basin; in 2007, after accounting for rain and other components of the water balance, 77 billion cubic metres (bcm, where 1 bcm equals one cubic kilometre) of surface water and 40 bcm of groundwater was required to satisfy an overall evapotranspiration requirement of 154 bcm. The overall evapotranspiration requirement estimated by Cheema (2012) is similar to that estimated by Bastiaanssen et al. (2002) and Liaqat et al. (2015).

Estimates of evapotranspiration by remote sensing is difficult for long historical periods due to changing data availability. Modelling of crop water evapotranspiration and crop water balances can be made for earlier years, but summing the results to the national scale is problematic. Data on crop areas are available, but there is no information on fallow areas, nor on crop sequences. Also fodder areas are provided as a lumped value for both Rabi and Kharif. It is not possible to determine, for example, how much wheat is followed by rice and how much by fallow or another crop. Similarly,

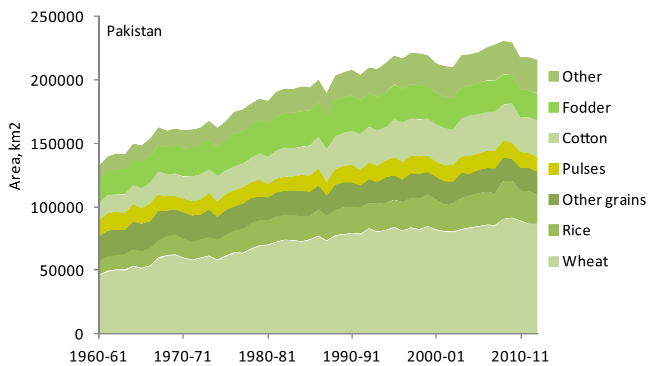

Fig. 2. Areas of major crops. Data source: Pakistan crop data (see Table 2).

there are no statistics on inter-cropping of fodder with orchards or other crops. This makes a national scale evapotranspiration estimate uncertain, and hence introduces uncertainty into other water balance terms.

Therefore, we used the estimate of Cheema (2012) for the total irrigation requirement of the irrigated area in the Indus of Pakistan, and simply extrapolate it backwards in time by the ratio of the total irrigated crop area in any year divided by the area in 2007. The irrigation requirement is the required supply of water to satisfy the evapotranspiration and surface runoff leaving irrigation areas. As shown in Fig. 2, the areas of major irrigated crops have remained in roughly equal proportions from 1960 to 2013, so the estimate of total irrigation requirement in earlier years, while approximate, is probably not unreasonable.

Following Bastiaanssen et al. (2012), Cheema (2012) and Cheema et al. (2014), we subtracted surface water input (taken as equal to canal water diversion multiplied by an efficiency factor) from the total irrigation requirement above to calculate the groundwater requirement. We set the efficiency factor (at 0.63) such that the groundwater requirement in 2007 is the same as that calculated by Cheema (2012). The groundwater requirement thus calculated is (as defined by Bastiaanssen et al., 2012; Cheema, 2012, and Cheema et al., 2014) the volume required to satisfy the evapotranspiration and surface runoff leaving irrigation areas, after the surface water supply is taken into account.

2.3. Scenarios of future water use

We assessed water use and agricultural production under 12 scenarios, encompassing combinations of two water use, two yield, and three population growth scenarios. The scenarios are not predictions; rather, they are potential choices for the future regarding water use and food. The period considered in the scenarios was from the present to 2050. Our aim was to examine to what extent a continuation of current trends in water use and food production – which might be termed business as usual – will maintain or improve food availability in Pakistan in coming decades. We also examine some factors which may influence the business as usual trends.

We assumed two scenarios for future water use. In the first, we assumed that water use in the future is the same as current water use and thus, under an assumption that the irrigation applied per unit area remains the same, the gross areas of crops in each province remain as they are currently. In this case, any change to crop production comes only from changes in yield.

The second scenario is that the area of crops in the future continues to increase as it has in the past. The linear regression of past trends of area was projected into the future. Thus, under an assumption that the irrigation applied per unit area remains the same (which is equivalent to assuming constant crop water use per unit area), the volumes of water use increase as they have in the past. The increased water requirement calculated, if the scenario is realised, would have to come from new dams and other infrastructure, or from increased pumping of groundwater (which is probably unsustainable), or from more efficient use of water. The scenario thus sets some quantitative targets for future water resources policy.

As noted in the introduction, there is considerable uncertainty in the climate change impacts on water availability to 2050, with decreases and increases both possible as well as changes in seasonal availability. Moreover, other factors will play a greater role in determining future water resources (Archer et al., 2010). Therefore, while we do consider the impacts of climate change on crop yields (discussed below), we do not attempt to quantify the impacts of climate change on water resources and hence the availability of water for food production. We also do not consider the impact of extreme events, though they are likely also to have an impact (Planning Commission, 2010). To the extent that climate change may influence water availability, it can be considered to increase or decrease the requirements calculated in the second scenario above for new dams or pumping from groundwater.

2.4. Crop production projections and projected per capita availability

Yields of many crops in Pakistan, and particularly of the major crops, have increased steadily over recent decades. With continued development of new varieties and continued improvement in farming techniques, it is reasonable to suppose that they will continue to increase to 2050 and beyond (e.g. Fischer et al., 2014). We used two scenarios for yield increases. In the first, we assumed that the yields of the major crops and crop groups identified above will increase in line with simple linear projections of past increases. We will discuss the merits of this assumption below in relation to the data and results.

In the second scenario, we assumed that climate change will negatively affect yields. As discussed in the introduction, climate change may negatively affect yields, though negative effects may be partly offset by adaptations such as changed sowing dates. In view of the uncertainties in climate change impacts, we do not attempt a comprehensive calculation of climate change effects, opting instead to provide a simple indication of the possible negative effects of climate change. We discounted the yields calculated in the first yield scenario above, with the discount starting at zero in 2015 and increasing linearly to 10% by 2050. That is, we indicate what might be the amount of food that would need to be supplied by other means if climate change were indeed to have a negative impact of 10% on yields. Three of the four climate change scenarios used by Zhu et al. (2013) led to yield declines in wheat of about 10%.

The two water scenarios and two yield scenarios give four projections of national crop and crop group production to 2050. We calculated food availability from national production using the following assumptions.

1. We assumed that the proportion of the rice crop exported remains as at present.
2. We assumed that the proportion of the pulses and oils food supply imported remains as at present.
3. For all crop groups, we assumed that the fraction of production (less exports in the case of rice) that is available as food remains as at present – that is, the fraction that becomes feed, seed, processing losses, waste, and other utilisation remains as at present.

We will discuss the assumptions in relation to Pakistan's choices regarding water use and food supply in the discussion.

We calculated food availability per capita for the main crops using the UN Population Division high, medium and low variant population projections (United Nations, 2015; Table 2).

3. Results

3.1. Historical crop production and per capita food availability

The production, imports and exports of some major crops and crop or other food groups is shown in Fig. 3 for 1961–2013. Where relevant, the figure also shows the area of crops. Wheat, rice and sugar crops show a modest increase in area over the period, and a greater increase in production resulting from an increase in yields (production per unit area). Other grains (millet, sorghum, barley and maize) and oil crops (which includes oil from cotton production, though the crop is mainly grown for its fibre) show no change or a small decline in area over the period. The large increases of production in the later part of the period for these crops, in addition to any yield increases, may be due partly to a change in the mix of crops in the group; maize, for example, increased from 40% of other grains in 1961 to 90% in 2013. Pulses show no increase in either area or production, and hence no increase in yield over the period, whereas vegetables and fruit and nuts show an increase in production and area but little or no increase in yields. The production of meat and seafood has increased greatly, though the latter is nevertheless a small production. Milk production per unit area of irrigated fodder has increased greatly from a low base, with the area of fodder production (mostly for milk, though partly for meat) remaining static or decreasing in recent years. Rice is the main food export and the proportion of production exported increased over the period; in recent years, exports have been about 3.5 m Tonnes annually. Fish is also exported, but in smaller amounts than rice. The domestic supply of pulses and oils relies partly on imports; wheat is also imported in most years, though with rising production in recent years, the quantity imported is a decreasing fraction of overall availability and some wheat has been exported recently. Here and in what follows, we take availability to be production + imports – exports + change in stocks – feed – seed – processing – waste – other utilisation, as per the FAO food balances (see data sources in Table 2).

The increase in production is about equal to or greater than the increase in population for all food groups except the pulses, which show a large decrease in per capita production (Table 3), and also in per capita availability. However, due to exports of slightly more than half the crop, rice also shows a decrease in per capita availability (Table 3). Other grains and sugar crops also show decreases in per capita availability. The changing balance of food availability amongst the various food groups has resulted in a modest increase in energy and protein in the average Pakistani diet over the period, but with little change in energy from about 1970 onwards (Fig. 4). However, the increases in oil, meat and milk have resulted in roughly a doubling of fat in the diet (Fig. 4).

3.2. Historical and projected water use

The calculated irrigation water demand increased by about 70% in Pakistan from 1960 to 2013 (Fig. 5). However, the diversion of water from the river system into canals for delivery to crops has remained more or less the same since the early 1970s. Groundwater use has increased to make up the difference between the water actually delivered to crops and that required. The increase in groundwater use is also shown by the increase in the number of tubewells, which in the Punjab (the main area of groundwater use) rose from about 150,000 in 1980 to just under 1 million in 2010 (Siddiqi and Wescoat, 2013). The groundwater requirement in 2007 was about 40 bcm (as calculated by Cheema, 2012), and has increased somewhat since then.

The projected future water demand and groundwater use shown in Fig. 5 is based on projecting the future areas of the crops and then re-calculating the water requirements (Methods section above). If crop areas and crop water use increase as projected, the minimum future requirement for net groundwater pumping (or alternative supply such as greater surface water use via more dams and canals) will increase to about 82 bcm per year in 2050.

3.3. Crop production projections and projected per capita availability

In this section, we discuss in detail projections of wheat and rice production and availability, and then briefly summarise the possible projections for other crop and food groups. We choose wheat and rice for the detailed projections because: 1. wheat is the most important source of energy and protein in the Pakistani diet, and rice is amongst the most important other crops; 2. in contrast to wheat, much rice is exported and examining rice illustrates the impact of trade issues; 3. most of the other crop and food groups (except sugar crops and milk) referred to above are mixed groups and projections are complicated by the changing mix of crops in the group.

Fig. 6 shows the area, yield and production of wheat from 1960 to the present, and the linear projections to 2050. As shown in Table 3, wheat availability per capita increased modestly over the period from 1961 to 2013. Fig. 7 shows the annual per capita availability over the period, and projections of potential availability under five scenarios. All five scenarios assume that there are no wheat exports or imports in the future. Since the exports and imports have diminished since 1961 to a small fraction of production (Fig. 3), this assumption appears to be reasonable, though Zhu et al. (2013) suggest that wheat imports may increase in the future to meet Pakistan's food requirements. The four projections shown in blue dotted lines are all based on assuming that production increases

Table 3
Increase in food production and availability in Pakistan from 1961 to 2013. The increase was calculated as (average for 2009-13 ÷ average for 1961–64). The population increased during the period by about 3.6 times.

	Wheat	Rice	Other grains	Sugar crops[a]	Pulses	Oil crops[b]	Fruit and nuts	Vegetables	Meat and fat	Milk	Sea food
Increase in total production	5.8	5	3.5	3.5	0.9	5.4	5.1	8.6	7.6	5.8	6.2
Increase in per capita production	1.6	1.4	1	1	0.3	1.5	1.4	2.4	2.1	1.6	1.8
Per capita production 2013, kg/cap/yr	135	38	28	385	6	34	35	51	28	218	3
Increase in total availability[c]	4.1	2.8	2.5	2.8	1.5	17.3	4.5	8.5	7.4	5.8	5.5
Increase in per capita availability[c]	1.2	0.8	0.7	0.8	0.4	2.3	4.9	1.3	2.4	1.6	1.6
Per capita availability[c] 2013, kg/cap/yr	116	12	16	19	7	14	30	45	27	186	2

[a] The production of sugar crops is that of raw sugar cane and beet, dominantly cane in Pakistan. The weight of sugar after processing is a small fraction of the weight of cane and beet, hence the food availability per capita is much less than the production.
[b] As with sugar crops, much of the weight of oil crops is lost in processing for oil, hence the food availability per capita is much less than the production.
[c] Food availability = production + imports – exports + change in stocks – feed – seed – processing – waste – other utilisation (see Table 2).

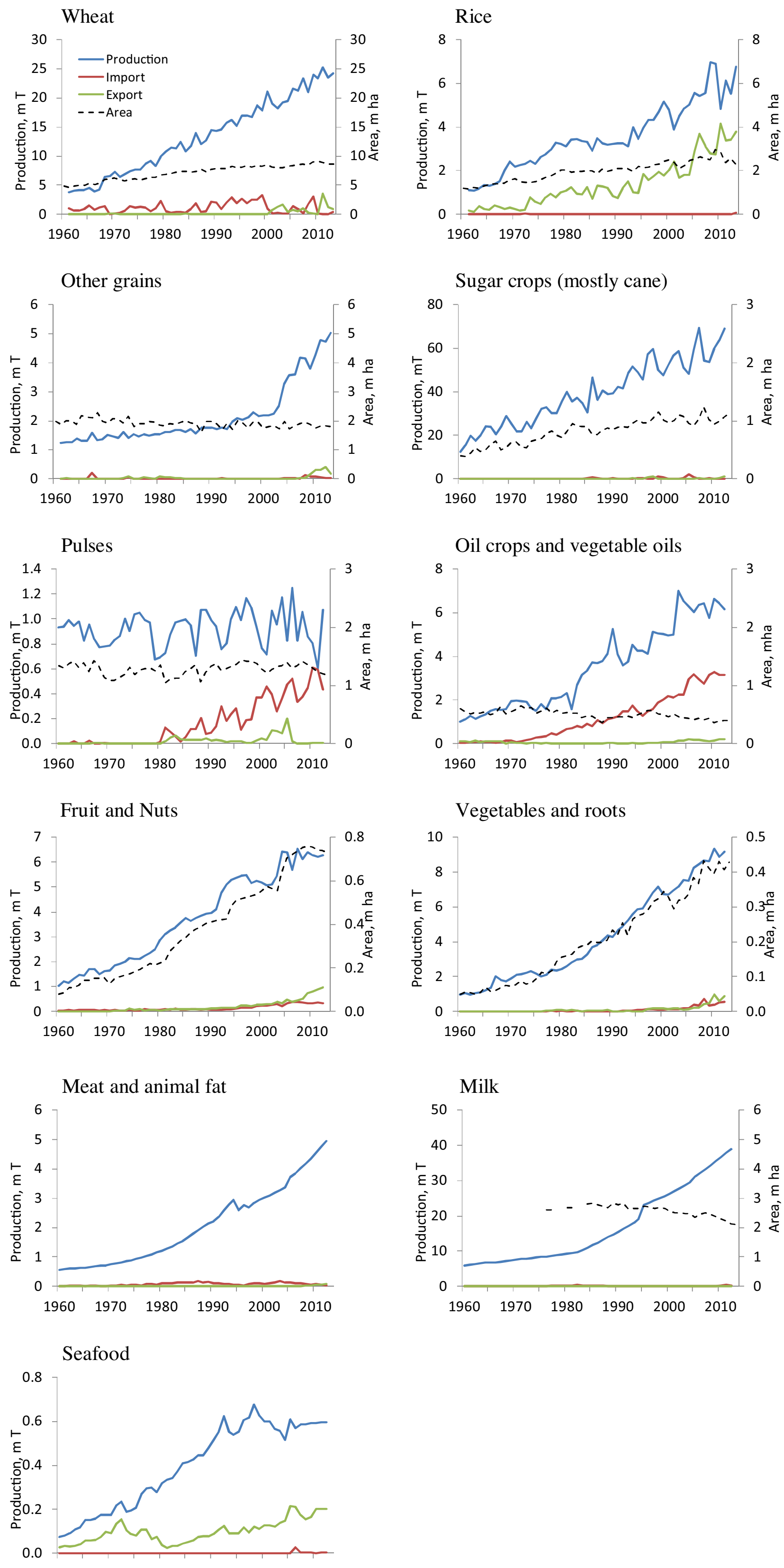

Fig. 3. Production, exports and imports of major crops and food groups, with areas of crops, in Pakistan. Data source: FAO food balance sheets (see Table 2).

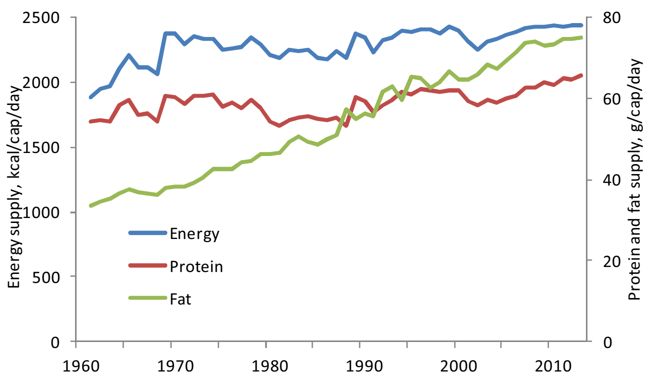

Fig. 4. Energy, protein and fat supply in Pakistan. Data source: FAO food balance sheets (see Table 2).

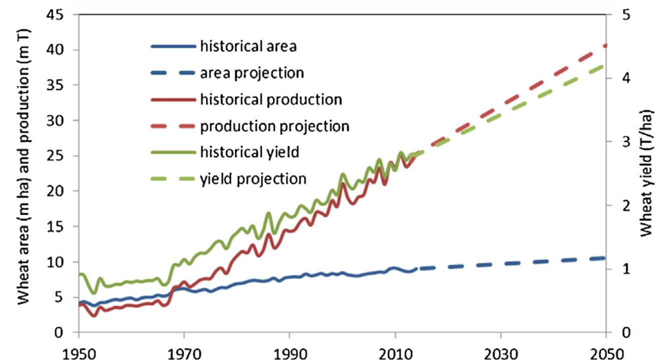

Fig. 6. Historical and projected wheat area, production and yield. Source: Agriculture Marketing Information Service (AMIS) (see) and authors' calculations.

result only from yield increases, with the area of wheat remaining as it is currently. These projections are based on the scenario of no increase in water use. Wheat yields increased linearly from about 1967 to 2013, and we projected this linear trend to 2050 to produce the yield only projections (Fig. 6). The resulting production was divided by the UN Population Division low, medium and high variant population projections to give the projections labelled in Fig. 7 as "low population", "yield only" and "high population". The yield only scenario (medium population projection) leads to a decrease (of about 10% from the present figure) by 2050 in availability per capita, whereas the high population leads to a significant decrease (of 22%) and the low population to an increase (of 4%). If yield increases were 10% less than those projected due to the negative impacts of climate change, the resulting per capita availability is that shown as the line labelled "10% yield decline", and represents a decrease of about 19% by 2050. In terms of total crop production, a decrease of 10% in per capita availability represents a shortfall of about 4 million tonnes of wheat for the projected medium population of 310 million (United Nations, 2015) in 2050.

However, the area of wheat production may continue to increase, and the resulting projection for the medium variant population projection is shown as the red dotted line labelled "yield and area" in Fig. 7. This projections is based on the scenario of an increase in water use, due to the increased area of crops. The per capita availability of wheat under this scenario decreases from the present figure by about 4% to 2050, or about 6% less than for the assumption of a yield increase alone. For clarity, we do not show

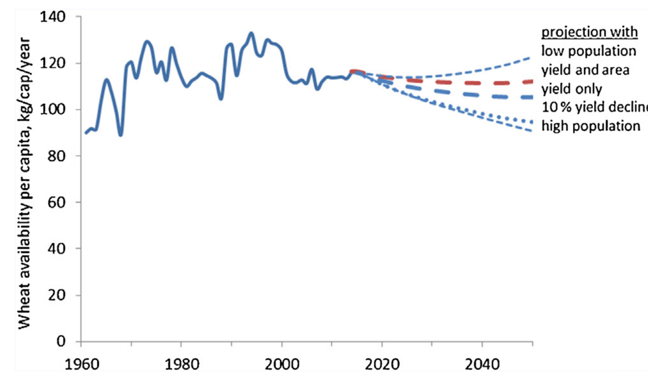

Fig. 7. Historical wheat availability per capita and projected availability under several scenarios. Source: FAO food balance sheets (see Table 2) and authors' calculations.

projections using an area increase for the other population variants or a lesser rate of yield increase induced by climate change, but they vary about the red line in the same manner as the yield only scenarios vary about the thick blue dotted line.

For rice, the picture is very different, as shown in Figs. 8 and 9. The yields and production of rice stagnated in the 1980s (Fig. 8). Since the early 1990s, production has increased considerably mainly due to yield increases, with the area increasing but modestly. We therefore used two yield projection scenarios, with an optimistic projection resulting from projecting the trend from 1990

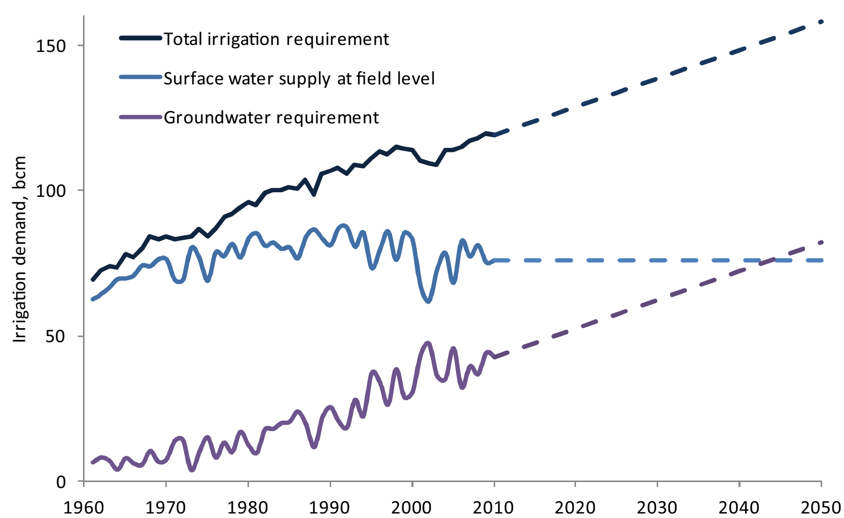

Fig. 5. Historical (to 2013) and projected (2013–2050) total irrigation requirement, surface water supply to the field, and groundwater requirement. Source: authors' calculations based on figures from Cheema (2012) and Cheema et al. (2014) for 2007.

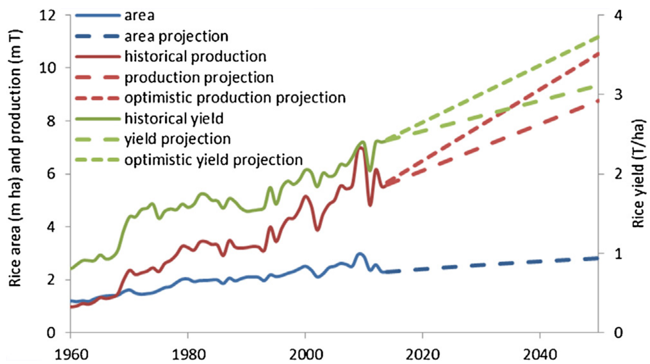

Fig. 8. Historical and projected rice area, production and yield. Source: Agriculture Marketing Information Service (AMIS) (see Table 2) and authors' calculations. Note that two yield and production projections are made, one by projecting the trends from 1969 to the present, and the other "optimistic projection" by projecting the trends from 1990 to the present.

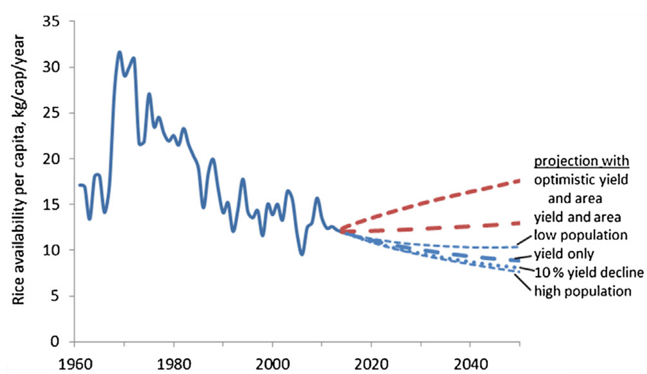

Fig. 9. Historical rice availability per capita and projected availability under several scenarios. Source: FAO food balance sheets (see Table 2) and authors' calculations.

onwards, as shown in Fig. 8. The rice availability per capita projections shown in Fig. 9 assume that exports will grow much as they have done in the past; specifically, that the volume of exports will be such as to maintain the same ratio of exports to total production under the assumption that both yield and area increase in the future. With the exception of the scenario labelled "optimistic yield and area", the scenarios are the same as for wheat above and use the linear projections of yield and area since the late 1960s (Fig. 8). The lines on Fig. 9 represent changes in per capita availability of a 26% decrease (yield only, medium variant population projection), 36% decrease (high population), 13% decrease (low population), 32% decrease (10% yield decline due to possible climate change impact on yield), and 8% increase (yield and area, in which both increase). In terms of total crop production, a decrease of 38% in per capita availability represents a shortfall of about 2 million tonnes of rice for the projected population of 310 million in 2050. The scenario of greater rate of yield increases labelled "optimistic yield and area", and represents an increase in per capita rice availability of 47% from the present figure (assuming exports increase in line with the past trend).

The likely projections of availability of other crops and foods can be assessed from their historical trends (Table 3) in relation to the trends for wheat and rice. The per capita availability of other grains decreased slightly from 1961 to 2013 (Table 3). Like wheat, exports and imports are small relative to production, so future projections under the various scenarios are similar to those for wheat but with a slightly lower forecast per capita availability for 2050. However, the detail of future projections differs from crop to crop within the group, with likely increases in availability per capita for maize, but decreases for other crops in the group. The projections for sugar crops are likewise similar to those for wheat, but again with a slightly lower forecast per capita availability for 2050.

In the case of pulses, the production, area and yield of the group has remained more or less constant since 1961, and any reasonable projection is for declining per capita availability, with the level of the decline dependent on the amount of imports. For oil crops, in contrast, projections under the various scenarios are for slightly greater increases in future per capita availability from domestic production than was the case for wheat. On the assumption that imports also continue to grow, the projections for oil are for a considerable increase in per capita availability to 2050. For fruit and nuts, and vegetables, the increase in production since 1961 is primarily due to an increase in area (Fig. 3), and not yield. Thus the implication of the scenarios with increases in production from yield increases alone is that there will be no increases; hence, if imports remain very low, the per capita availability will decrease considerably in the future. On the other hand, if the areas continue to increase as they have in the past, per capita availability will increase to 2050 by about the same amount as for wheat in the case of fruit and nuts, or more than that of wheat for vegetables.

Whereas the implications for water use of the other crops mentioned so far (other grains, sugar crops, pulses, oilcrops, fruit and nuts, vegetables) are similar to those for wheat and rice, the remaining food groups carry a different implication for water. Some meat production comes from rainfed rangeland, and hence depends less closely on irrigation water. For milk, the area of irrigated pasture has decreased in recent years, and the large rise in production depends mainly on gains in yield due to better feed and management of the dairy herd. Seafood obviously does not depend on irrigation water. For these food groups, future production depends on factors not considered here, and our methods of projection are not relevant. Any simple projection of past trends will show increasing availability per capita for these food groups; whether such projections are reasonable is the main question, but is beyond the scope of this paper.

4. Discussion

The analysis has examined the interactions of food availability, water availability and use, and the increasing population, in terms of both past trends and future projections.

We are not aware of quantified trends of historical water use or projected water use in agriculture in the literature with which to compare our estimates. The estimates are for the total irrigation water use and the groundwater requirement in Pakistan as a whole, based on the estimates for 2007 by Bastiaanssen et al. (2012), Cheema (2012), Karimi et al. (2013) and Cheema et al. (2014). As noted in Section 2.2, Cheema (2012) estimated that 77 bcm of surface water was required in 2007 to satisfy crop water requirements. The average annual net inflows of the basin are about 175 bcm, of which 128 bcm are diverted for irrigation (Briscoe and Qamar, 2005; Archer et al., 2010) and the remainder discharges to the sea, goes to other uses (urban and industrial) or is lost by seepage or evaporation (though the losses may be balanced by flows of groundwater returning to the rivers, Karimi et al., 2013). Of the 128 bcm diverted for irrigation, some is lost through seepage and evaporation from the canal system, leaving less (77 bcm in 2007) to supply the crops.

Karimi et al. (2013) suggest that the net groundwater depletion (after natural recharge and recharge from the irrigation systems) for the whole Indus Basin (including India) was about 30 bcm per year. The total use and groundwater use are not distributed evenly among or within provinces. In Sindh province, much of the groundwater is saline, and groundwater use is limited (Ahmad et al., 2014; Cheema et al., 2014). The main groundwater use is in the Punjab province (Ahmad et al., 2014; Cheema et al., 2014), where it has led to some areas of declining groundwater levels, increased pumping costs and deteriorating quality due to induced salinisation (Qureshi, 2015). The use within parts of the Punjab thus appears to be unsustainable at current levels of use, let alone future use. Briscoe and Qamar (2005), Archer et al. (2010), Qureshi et al. (2010), and Qureshi (2015) also point out that Pakistan's groundwater use is unsustainable.

If groundwater use is unsustainable, how long can such use continue before the resource is seriously depleted or even runs out? Greenman et al. (1967) estimated that the usable resource in part of the Punjab amounted to about 2 billion acre-feet, or about 2500 bcm. More groundwater could be used by diluting moderately saline groundwater with fresh surface water. Given Karimi et al.'s (2013) estimate of about 30 bcm net depletion per year for the Indus as a whole, and assuming as a rough rule of thumb that perhaps half of that comes from the Pakistan Punjab, current depletion rates would exhaust 2500 bcm in a little under 170 years. Richey et al. (2015) assessed the volume of the groundwater resource and depletion rates for the whole Indus Basin (and several other aquifers globally), and estimated that a 90% depletion of the top 200 m of the aquifer would, at current depletion rates, take between about 422 and 9800 years. Richey et al.'s estimates appear not to take account of the unusable nature of the saline groundwater which is found deeper in the aquifer; we have therefore ignored their estimates for depletion times to greater depths in the aquifer, and it is possible that not all of the top 200 m is available. Thus, taking the lower end of the estimates as a conservative figure, the current rate of groundwater use might be assumed to use much if not all of the resource in a period of order 200 years. If groundwater use in Pakistan increases from about 40 bcm in 2007 to about 82 bcm in 2050 (as we estimate, in the absence of a change in policy or other adaptations), the depletion time reduces (on our conservative estimate) to around 50 years. These are very rough estimates at best and deliberately conservative, but we are aware of no better information with which to make better estimates. The estimates suggest that, while there may be no immediate cause for alarm, there is an urgent need to better understand the groundwater resource and to plan for more sustainable (i.e. less) use of the resource.

Our analysis uses the assumption that crop yields will continue to rise in the future as they have in the past. The increase in actual yields is a product of both the increasing potential yields under ideal conditions of newer crop varieties and improved management including the use of more inputs such as fertilisers. As shown in the Appendix A, the potential yields in Pakistan of some of the major crops are greater (by factors of around two to three) than current actual yields. There is thus considerable scope to increase current yields to close the gap between actual and potential yields. Furthermore, as shown in the Appendix A, the potential yields are themselves increasing with the release of newer varieties, thus providing ever more scope to increase actual yields. Watto and Mugera (2014), for example, showed that yields of cotton could be increased by up to 28% by adopting newer varieties and by educating farmers in more efficient practices. The Water Sector Task Force (2012) noted substantial differences between national average yields of several crops and those attained by progressive farmers. We therefore regard the assumption of a continuing increase in yields as reasonable.

As was noted in the introduction, Pakistan produces and imports enough food now (per capita, on average) for its population, with access and distribution a major factor in the high levels of food insecurity. The projections suggest that (on average) there is likely to be a modest decline in the per capita availability of staples, though a modest rise in that of other foods, to 2050. Overall, there may be scope to provide enough food (in total and per capita on average), provided that there is some combination of the following five options, which involve both the supply and demand of food and hence water.

1. The areas and water use of food crops continues to increase. As we showed for wheat, continuation of current trends in the increase of area and yields leads to modest shortfalls in the overall production; a modest increase in the rate at which area and water use increase would lead to sufficient production to maintain current per capita availability. For rice, the same picture emerges if we consider the trends in yields since 1969, but the greater rate of increase in yields since 1990 gives a more optimistic picture in which, with area also increasing, production may be sufficient to improve current per capita availability. In addition to the increases in water use for irrigated crop production, more water will be required to satisfy the urban and industrial demands associated with a growing population and expanding economy. The increased irrigation and other demands in turn require either that groundwater be used in ever greater volumes, or that more dams and other irrigation infrastructure be developed to divert more water for irrigation, or both.

As outlined above, groundwater use overall already exceeds recharge (particularly in fresh groundwater quality areas of the Punjab), which in the long run is unsustainable. The projected increase in groundwater use required to maintain past trends would greatly increase the rate at which groundwater is depleted (Fig. 5).

The strategy of developing more dams and other irrigation infrastructure is attractive, but is also challenging. The Water Sector Task Force (2012) point out that, after the development of two major dams (Mangla and Tarbela) and associated canals in the 1960s and 1970s, a lack of agreement both within Pakistan and externally amongst potential finance donors has stymied further development. Furthermore, a major new dam would not be available for many years even in the unlikely event that construction were started immediately. Zhu et al. (2013) concluded that greater storage in the absence of other adaptations cannot improve crop productivity and production.

There is a third possibility for finding more water for continued increases in water use – that currently "wasted" water may be saved. Zhu et al. (2013) concluded that improved water use efficiency, if it can be achieved, would form an important part of adaptations to maintain food supply in the face of climate change. Ahmad et al. (2009) also concluded that a more equitable distribution of water between the head and tail reaches of water delivery canals would also improve average productivity. The irrigation system of Pakistan, particularly the canal delivery system, is inefficient in the sense that (as noted above) much water is lost from the canals before delivery to the crop (Cheema, 2012; Karimi et al., 2013; Ahmad et al., 2014; Cheema et al., 2014). However, much of this recharges groundwater and is available for re-use, particularly in the Punjab where much of the groundwater is fresh and there is already much groundwater use (Ahmad et al., 2014). Qureshi et al. (2010) and Ahmad et al. (2014) point out that while improvements to the (low) irrigation efficiency in Pakistan (particularly the Punjab) may reduce water use without loss of yield at the field scale, this will not necessarily translate to savings at the basin scale. The situation in Sindh (and some parts of the Punjab) is different; there, much of the groundwater is saline (Fig. 1), and seepage from canals and fields cannot be reused (Ahmad et al., 2014). In these areas reducing seepage from canals and fields (bearing in mind that a leaching fraction should be maintained to prevent a build-up of salinity in the soil) can lead to an increase in the overall volume available for productive use. Overall, the volume of water that might be saved is much less than that lost at the national scale through inefficiencies, but may nevertheless amount to several billion cubic metres. It should be noted, however, that some of the water that percolates into saline aquifers returns to the river system either naturally or through the managed drainage system, and if it is diverted to crop production this water will no longer be available for downstream uses. We are not aware of an estimate of the volume that might be potentially saved for productive use, nor of the consequent reduction in returns to the river system in Pakistan.

An increase in the area of crops also implies that the land is available. The growth of large cities such as Lahore is reducing the area available for cropping in some parts of Pakistan (Riaz, 2013). At the same time, some of the greater area of land could come from a greater cropping intensity (more double cropping). Ahmad et al. (2014) point out that the cropping intensity in Sindh is quite low, at 67%. Furthermore, irrigation occupies only a small fraction of the overall land in Pakistan, even with mountainous areas excluded. Thus, while some prime agricultural land may be disappearing under urban developments, overall there does not seem to be a constraint on the expansion of cropping areas.

2. The yields of crops – particularly the yield per unit of water used – increases at a rate greater than in the past (Planning Commission, 2009). There is scope for increased yields, as already noted, but there is no evidence to suppose that the rate is likely to increase. To induce an increase in the rate of yield increase would presumably require greater commitment to research, extension and institutional factors such as market (financial) incentives for farmers (Ahmad and Farooq, 2010). Zhu et al. (2013) also suggested that increased agricultural research with other adaptations be pursued to reduce the impacts of climate change.

3. The mix of crops is changed such that more food is grown with the available resources. Qureshi et al. (2010) suggest that replacing high water use crops such as rice and sugarcane with other crops, including more drought resistant crops, would reduce groundwater use and allow a greater overall production of (food) crops. Replacement with high value crops such as sunflower, pulses, vegetables and orchards would also boost farm incomes (Qureshi et al., 2010). Presumably, the current mix of crops is in some sense optimal (whether by maximising profit or minimising risk) for farmers, so a change in the mix of crops implies a change in (market) incentives and risks.

4. Less food is exported and/or more is imported. The trend for many years is for more exports of rice, and more imports of pulses and oils. Conceivably, if domestic food production were to stall at current levels (perhaps because of limits to the sustainable use of groundwater), the ensuing adjustment of food prices would lead to lowered food exports and/or increased food imports. However, as pointed out by Ahmad and Farooq (2010), domestic food production in Pakistan is regarded as fundamental to economic development, poverty reduction and national security. On this perspective, not only is the prospect undesirable, but the poorer state of the economy would lead to balance of payments difficulties in purchasing the food.

5. Although somewhat beyond the scope of this paper, we note for completeness that in principle the rate of population growth could be slowed more rapidly than is currently projected. However, the decline in the fertility rate is weak and may have stalled in the first decade of the present century (Sathar, 2011). This, combined with recent upward revisions of the Pakistan's projected population in 2050, as discussed in the Introduction, raise doubts about the prospect. Moreover, even if fertility were lowered immediately to replacement levels, the population would continue to grow to about 260 million as today's young become adults and have children of their own (Bongaarts et al., 2013). Even if it were achievable, it would therefore be only a small part of the overall solution to 2050, though it would be more important beyond then.

The impact of climate change on water availability is uncertain (e.g. Archer et al., 2010). However, climate change is projected to reduce crop yields (e.g. Iqbal et al., 2009; Zhu et al., 2013; Ahmad et al., 2015; Shakoor et al., 2015), though the reductions may be partially offset by adaptation such as changed planting dates. If yields are reduced, greater change will be required in the options noted above than would be the case in the absence of climate change. That is, water use, crop yields, changes to crop mix, food imports, or some combination thereof, would have to grow at a faster rate. Zhu et al. (2013) showed that several adaptations could reduce the impacts of climate change, and suggested that the best outcomes could be achieved by increased investment in agricultural research (to raise yields) combined with increased water use efficiency.

The changes to water use, yields and/or imports and exports implied by these possibilities is considerable, and yet the calculations are based on current levels of food availability per capita. Unless access and distribution become more equitable, even more food will be required to alleviate food insecurity amongst the poorer half of the population. It should be noted that the same level of food insecurity in a larger population would result in more people suffering from lack of food.

Pakistan thus has several supply and demand side options for maintaining or improving food availability at the national level. Ahmad and Farooq (2010) recommend a range of measures that include crop research and development, extension, financial institutions for agricultural credit; they emphasise the importance of poverty reduction as an aim of all policies. The Water Sector Task Force (2012) emphasises surface water infrastructure development and increasing agricultural yields by improving various aspects of water management. Qureshi (2015) argues for a range of policies for sustainable groundwater use, including conjunctive surface and groundwater management, increasing the economic productivity of groundwater, and improved governance. All note that agreement on the measures is likely to be difficult but, with agreement, considerable improvements in food availability are possible (Water Sector Task Force, 2012).

We note further that options involving increased water use imply undesirable environmental impacts, either through unsustainable groundwater use or through increased surface water use leading to less water for the environment. Importing more food or exporting less may be economically and politically undesirable. Other measures such as increased agricultural productivity (particularly productivity per unit of water used) and changing crop mixes imply that policies are put in place to increase research and extension, and to provide incentives for farmers to change cropping.

Our analysis has proceeded from an assessment of past trends of agricultural production, food availability and water use, to an examination of the consequences for a growing population of a continuation of those trends. Other studies have examined aspects of these linked issues, but none that we know deals with the overall problem. Several studies deal with food security with little mention of water, other than to note its scarcity or the need for new dams. These include Ahmad and Farooq (2010), who assess past and future trends of food availability and calorie intake, and suggest several policies for addressing the challenges including promoting greater crop yields. Khan and Shah (2011) and Bashir et al. (2012) assess food security mainly in terms of past trends. Muhammad and Asghar (2012) assess future food security in Pakistan in terms of wheat only. On the other hand, Briscoe and Qamar (2005), the Water Sector Task Force (2012), Condon et al. (2014) and Laghari et al. (2012) assess adaptations in water infrastructure and institutions, including improving crop yields, without quantifying the food security implications. Zhu et al. (2013) linked crop models, water supply models and economic models to assess the food and water implications of climate change. However, while their models do account for the demand for groundwater, they present future water requirements in terms of total water use only, and make no assessment of the potential implications for groundwater. Furthermore, their scenarios all project an increase in availability of about 440 kcal per capita per day from 2010 to 2050 due to assumed increases in crop yields and imports (as shown in Fig. 13 of Zhu et al.), whereas the past 40 years has seen an increase of about 120 kcal (shown in Fig. 4 of this paper). Thus, they appear to have assumed yields and imports that increase at rates well above those suggested by past trends, without a detailed analysis of other, less optimistic, assumptions. Our analysis therefore offers a more complete picture of the groundwater implications than does the study of Zhu et al., and also sets future prospects more firmly in the context of historical performance.

5. Conclusion

We conclude that while maintaining the current level of food availability to 2050 in Pakistan appears achievable, it will involve some combination of: using increasing volumes of groundwater from already overused aquifers; building more dams and other irrigation infrastructure, thereby increasing the availability of surface water; increasing crop yields (especially yields per unit of water used) at a much greater rate than in the past; swapping to crops that use less water, thereby increasing the amount of food that can be grown with the available water; and, exporting less food and importing more. Some options may not be economically desirable choices for farmers or the country, and some appear to require political agreements that are difficult within Pakistan. It appears likely that, at least in the short to medium term, there will be increasing use of groundwater, with risks to both the quantity and quality of water available in the future.

Acknowledgements

The Pakistan Mission of the Australian Department of Foreign Affairs and Trade provided funds for this study through the Sustainable Development Investment Portfolio Indus project. CSIRO provided additional support through its Land and Water portfolio.

Appendix A. potential yields of some major crops in Pakistan

Potential yields of major crops in Pakistan have steadily increased for several decades as newer crop varieties have been introduced (Fig. A1). The current potential yields are greater than the current actual average yields. The current average yield of wheat is about 2.5 T/ha (data sources in Table 2, and can also be estimated by inspection of Fig. 3), whereas the potential yield is about 7 T/ha (Fig. A1). For Basmati rice, the figures are about 1.7 and 6 T/ha; for coarse rice, about 2.4 and 10 T/ha; for maize, about 4 and 8–12 T/ha; for sugarcane, about 55 and 140 T/ha; and for chickpea, about 0.7 and 3 T/ha.

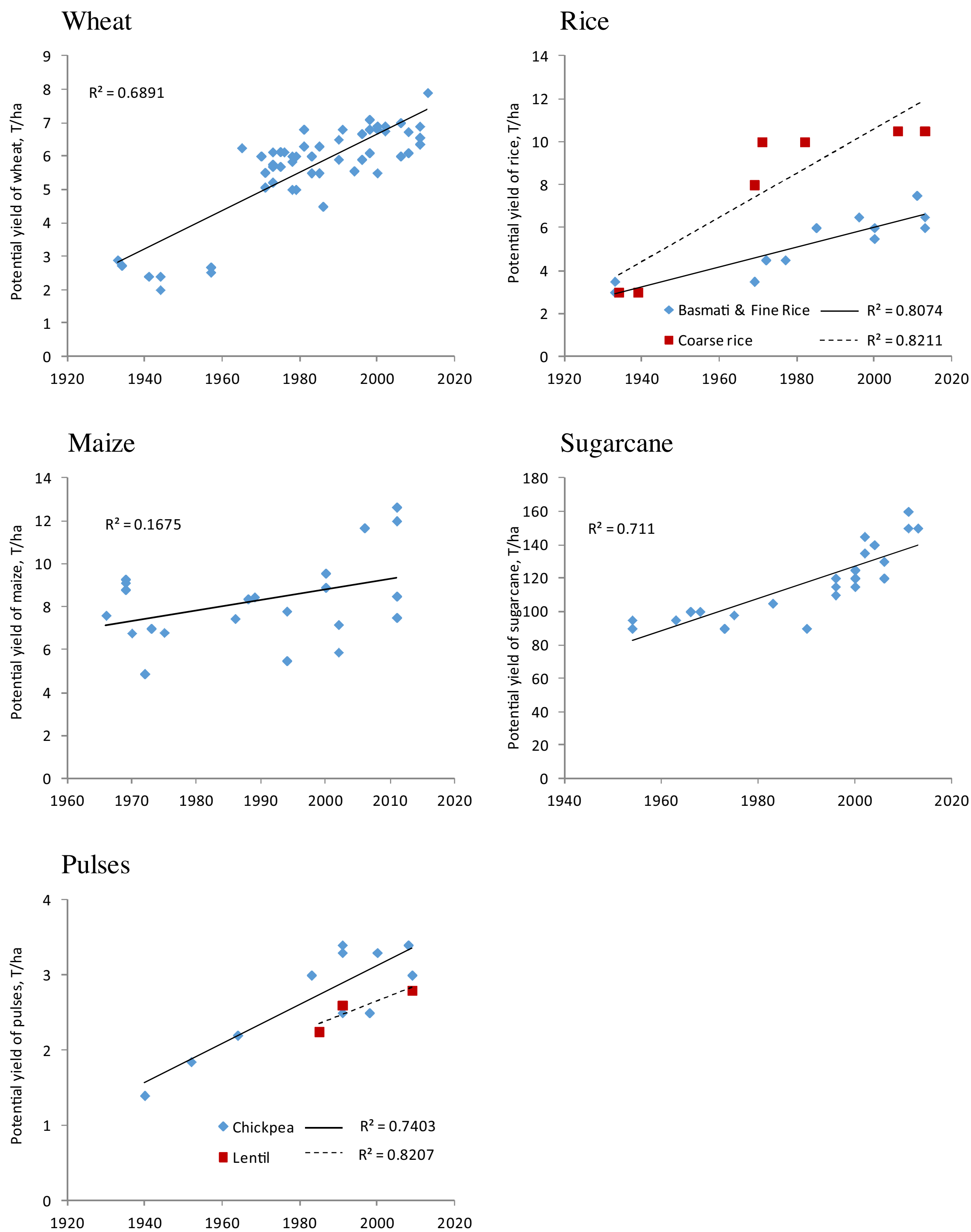

Fig. A1. Potential yields of some major crops. Data sources: http://www.aari.punjab.gov.pk/research/verities; for rice, also Mushtaq and Akram (2007).

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