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Quantifying production losses due to drought and submergence of rainfed rice at the household level using remotely sensed MODIS data

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ABSTRACT

Combining remotely sensed Moderate Resolution Imaging Spectroradiometer (MODIS) data with Bangladesh Household Income and Expenditure Survey (HIES) data, this study estimates losses in rainfed rice production at the household level. In particular, we estimated the rice areas affected by drought and submergence from remotely sensed MODIS data and rice production from Household Income and Expenditure Survey (HIES) data for 2000, 2005 and 2010. Applying two limit Tobit estimation method, this study demonstrated that both drought and submergence significantly affected rice production. Findings reveal that on average, a one percent increase in drought affected area at district level reduces *Aman* season rice production by approximately 1382 kilograms per household on average, annually. Similarly, a one percent increase in drought area reduces rainfed *Aus* season rice production by approximately 693 kilograms per household, on average, annually. Based on the findings the paper suggests disseminating and developing drought and submergence tolerant rice and also short duration rice varieties to minimize loss caused by drought and submergence in *Aus* and *Aman* rice seasons.

1. Introduction

Drought and submergence stresses[1] are two of the major limiting factors that substantially reduce rice yield and production in the rainfed ecosystem (Bernier et al., 2008; Devereux, 2007; Dey and Upadhyaya, 1996; Evenson et al., 1996; Gauchan and Pandey, 2012; Grover and Minhas, 2000; Khush and Toenniessen, 1991; Pandey and Bhandari, 2007, 2009; Pandey et al., 2007; Widawsky and O'Toole, 1996). More importantly, 50% of the total rice farmland in South Asia is rainfed in nature (Dawe et al., 2010), where the incidence of income poverty is also high. The frequent occurrences of submergence and drought are the major causes of crop failure, income volatility and the persistent poverty among the small and marginal rice farmers. The question arises as to what extent drought and submergence stresses affect economics of rice production at the household level in the rainfed rice ecosystem.

Unfortunately, despite the importance of the issue, existing studies seldom focus on the impacts of drought and submergence stresses on rice production and income at the household level in the rainfed ecosystem; however, such losses have mostly been approximated at the national- or regional-level, under aggregate scenarios and using aggregated data (e.g., Dey and Upadhyaya, 1996; Evenson et al., 1996; Garrity et al., 1996; IRRI, 2010; Pandey et al., 2007). For example, IRRI (2010) reported that over 20% of rice land in Bangladesh is prone to floods which occur every year and paddy loss due to flooding in Bangladesh and India alone amounts to an estimated four million tons of rice per year, which is enough to feed 30 million people. However, it is unknown how these effects can affect rice production at the farm household level. This article attempts to quantify the economic impacts of drought and submergence stresses on rice production of the rice farmers in the rainfed ecosystem. We used wet-season *Aus* and *Aman* seasons rice production in Bangladesh as a case study.

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[1] While submergence refers to the shallow type of flooding as compared to partial flooding and deep water flooding, in this paper in general, the excess water referred to as submergence and policies are drawn accordingly.

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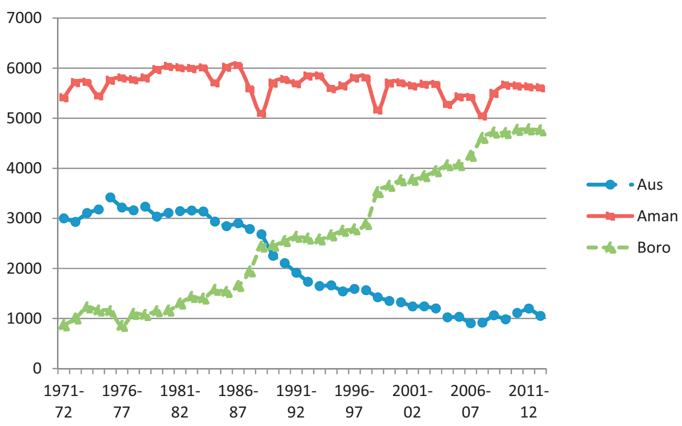

Fig. 1. Total rice area in Bangladesh by seasons during 1971–2010 (000 hectares). Sources: Online: http://www.brri.gov.bd/images/stories/RiceDatabase/Rice_data_1971-2013_14.pdf, accessed on May 14, 2014.

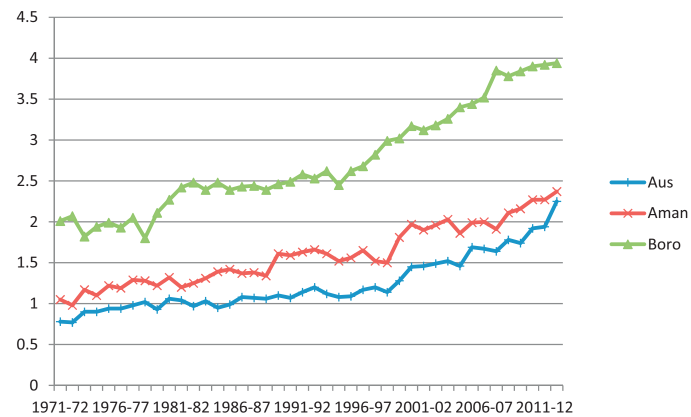

Fig. 2. Rice yield (t) per hectare in Bangladesh by rice seasons during 1981–2010. Source: Online: http://www.brri.gov.bd/images/stories/RiceDatabase/Rice_data_1971-2013_14.pdf, accessed May 14, 2014.

Aus, Aman and *Boro* are the three rice seasons grown in wet season (Kharif 1), summer season (Kharif 2) and dry season in Bangladesh, respectively (Hossain and Jaim, 2012). Kharif 1, often called Pre-kharif, starts from the last week of March and ends in May and Kharif 2 ends in September . The entire Kharif season is characterized by high temperature, rainfall and humidity. The moisture supply from rainfall plus soil storage is enough to support rainfed crops. Consequently, rainfall and temperature can have greater impacts on productivity of rainfed *Aus* and *Aman* seasons rice production in Bangladesh. *Boro*, on the other hand, is a dry season rice that is cultivated from mid-November to mid-February (BBS, 2011) and relies on irrigation, fertilizer and modern high yielding rice varieties.

In the case of Bangladesh, rice is cultivated on 75% of the total cropland (Ganesh-Kumar et al., 2012) and is the primary source of income and employment for nearly 15 million farm households. Second, rice is the staple food of 149.8 million people and supplies 76% of the total calorie intake, and more than 65% of the protein intake of the people of Bangladesh (Dey and Upadhyaya, 1996). Importantly, farm households in Bangladesh are predominantly small and marginal farmers with an average farm size of 0.53 hectare (Hossain et al., 2007). Because of the strategic importance of rice, Bangladesh has always been pursuing a policy of self-sufficiency in rice production (GOB, 2006). In fact, Bangladesh has achieved remarkable success in paddy rice production: from 13.63 million tons in 1981–1982 to 31.97 million tons in 2009–2010 (BBS, 1999, 2011), mainly through the rapid expansion of the modern input-intensive and irrigation-based dry-season "*Boro*" rice cultivation (Hossain et al., 2007; Islam et al., 2012). *Boro* also contributed to a remarkable success in achieving higher yield from 3.0 t/ha in the 1990s to 4.05 t/ha in 2008 (Hossain et al., 2007). *Boro* rice now occupies 42% of the net rice farmland in Bangladesh (Fig. 1), and it contributes more than 55% of the total rice production because of its higher yield (Fig. 2).Consequently, the country has been highly successful in averting any severe food shortages since 1974 when a famine occurred.

Finally, the diffusion of small-scale private irrigation facilities[2] enabled a rapid adoption and diffusion of modern rice varieties among small and marginal farmers in Bangladesh (e.g., Hossain et al., 1994), which challenges the popular perception that small farm households have typical disadvantages in adopting input-intensive modern varieties. Despite this, self-sufficiency in rice is yet to be achieved. Bangladesh is still a net rice-importing country. For example, in 2010–2011, Bangladesh imported 1.5 million tons of milled rice (GOB, 2012). However, land in *Boro* season rice has already been exhausted and further expansion of land in *Boro* season is difficult. To meet the increasing demand for rice, additional rice has to come from rainfed *Aus* and *Aman* rice seasons. *Aus* and *Aman* rice seasons, which are mostly rainfed and cultivated from mid-March to September (BBS, 2011), occupy more than 58% of the net rice farmland (Fig. 1), but contribute less than 45% to total rice production because of their relatively lower yields and weather related problems such as seasonal flash floods, drought and submergence (Fig. 2).

A novelty of this research is that it combines remotely sensed MODIS[3] data on drought and submergence with farm level data. Remote sensing has long been used to provide an alternative, quick, and independent approach for the estimation of cropping intensity, area, and changes in a country (Badhwar, 1984; Gumma et al., 2014; Lobell et al., 2003; Thenkabail, 2010; Thenkabail et al., 2009; Thiruvengadachari and Sakthivadivel, 1997). For example, Sakamoto et al. (2005) use MODIS, normalized difference vegetation index (NDVI), and monthly maximum value composite (MVC) data with spectral matching techniques (SMTs) to map rice areas in South Asia. In this study we use MODIS, MVC, and NDVI data and apply spectral matching techniques in the rice areas in Bangladesh for the years 2000–2001, 2005–2006 and 2010–2011 to identify drought and submergence stress-prone rice areas in Bangladesh in *Aus* and *Aman* rice (Kharif) seasons. The information generated can potentially guide rice scientists and planners in developing technologies suited to drought/submergence conditions and other rice ecosystems as well as in targeting technologies to local needs. Additionally, the similarities in the rice ecosystem in the major rice-growing countries, and the economic importance of rice in South Asia and Southeast Asian countries, provide a good indication of the general applicability of policies that the present paper intends to suggest based on the case of Bangladesh. For example, similar to Bangladesh, 50% of the total cropland in Nepal and more than 33% of the total cropland in India are dedicated to rice cultivation only (Gumma et al., 2011; Pandey and Bhandari, 2007; Pandey et al., 2007). In Cambodia, most of the 85% of the total population who live in rural areas depend on rice cultivation for their livelihoods (Ly et al., 2012).

Interestingly, similar to Bangladesh, more than 20 million hectares of rainfed rice area in India and seven million hectares of rainfed

[2] Government policy was favorable in importing small diesel engines for irrigation initially from China in the 1980s with an ambition to achieve rice self-sufficiency.

[3] One advantage of MODIS data is that it uses 250-m normalized difference vegetation index (NDVI) to classify drought and submergence on the sampled land area.

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rice area in northwestern Thailand and Laos are frequently affected by abiotic stresses such as drought (Huke and Huke, 1997; Pandey et al., 2007). In Cambodia more than 58% of the harvested rice comes from rainfed area (FAO, 2004). Thus, vast areas of rainfed rice farmlands in these countries greatly depend on weather for good harvest. Moreover, the Intergovernmental Panel on Climate Change (IPCC) and recent scientific literature warn that, because of global warming, some areas will receive more rainfall, others less. Both situations could potentially lead to increases in drought and submergence (IPCC, 2007; Emanuel, 2005; Wassmann et al., 2009). This will increase the risk of more drought and submergence stresses; consequently, this may also cause more losses in rice production and income in the major rice-growing areas of the world (Vaghefi et al., 2011; Wassmann and Dobermann, 2007; Adams et al., 1998; IFPRI, 2010). In fact, Bangladesh has been recognized as one of the most climate vulnerable countries in the world due to its geographical position, which is mostly a low-lying delta along with a long coastal area, and also its high dependence on agriculture for income and livelihood of millions of people (IPCC, 2007). So, it is important to understand the impacts of drought and submergence on production of rice in the rainfed ecosystem in Bangladesh, where farmers are already vulnerable to abiotic stresses, and may be more vulnerable in the future due to changes in the global climate.

The rest of the article is organized as follows. Section 2 presents materials and methods, Section 3 describes households and farm characteristics. Section 4 specifies the model to be estimated and discusses the variables and subsection 4.1 presents the results and details of the findings. Section 5 presents conclusions and policy implications.

2. Materials and methods

This article uses three sets of data in which we combined remotely sensed data with ground level weather data and farm and household level information. The first set is weather-related data on monthly average maximum temperature (°C) and yearly total rainfall in 2000 and 2005 made available by the Bangladesh Agricultural Research Council (BARC) and the same information for 2010 from the Bangladesh Bureau of Statistics (BBS, 2011) as 2010 data were not available in the BARC website. Note that station-level information on temperature and rainfall[4] from BARC and BBS was converted into sub-district-level information by applying an inverse distance weighting algorithm, which was used to create climate surfaces of each weather variable providing estimates on a 25-km resolution grid. These estimates were then averaged to provide climate values for each sub-district and were then assigned to each household in its respective sub-district. All spatial data processing and analysis were done using the ArcGIS v 10.0 computer program. However, from the government weather data, it is not possible to get the areas affected by drought and submergence for all districts.

Therefore, the second set of data on drought- and submergence-affected rice areas in *Aus* and *Aman* rice seasons in Bangladesh in 2000, 2005 and 2010 at the district level are extracted from MODIS normalized difference vegetation index (NDVI) 250-m satellite remote-sensing time-series data. In this study using MODIS data, a comparison between total rice area and yearly rice area was made (Gumma et al., 2014). If the rice class was identified as 'other class', then observed monthly rainfall was compared with normal monthly rainfall using spectral matching techniques (SMTs). SMTs match the rice class spectra extracted from a good year with rice with other class spectra extracted from a water-deficit (drought) or submergence year. We identified the duration, magnitude, and peak of NDVI. A higher value of NDVI was noticed during the kharif (rainy season) season (with the peak of NDVI observed during September) compared with the rabi season for land use changes. For Bangladesh, the highest value of maximum mean NDVI was 0.80 during the *Aus* and *Aman* rice seasons, but the value of NDVI was never above 0.5 in any of the months during drought/submergence years. Based on the information we defined drought and flood affected areas at the district level. We particularly define that an area is affected by drought if NDVI was below 0.3 and an area is affected by flood if NDVI was less than 0.2. Fig. 3 presents the drought and submergence maps over the sampled periods. In calculating the drought-affected rice area, we considered mild to severely drought-affected rice areas in the sampled years. Note that, under mild drought, yield loss can reach 10 percent; under moderate drought, yield loss can reach 50 percent. Yield loss can reach 100 percent under severe drought. In the case of submergence, yield loss can be 0 to 100 percent, depending on the time of submergence.

Fig. 4 on the other hand, using government data, is displaying the loss in *Aus* and *Aman* rice areas and *Boro* rice area separately in Bangladesh only due to floods during 2002–2007. The figure shows that floods have become a regular cause of damage of *Aus* and *Aman* season rice in Bangladesh, while damage of *Boro* rice due to flood is negligible, because in the case of *Boro* rice water related stress is highly controlled artificially by irrigation. By contrast, *Aus* and *Aman* rice are highly dependent on natural rainfall and weather, thus natural calamity can easily damage these crops. For example, in 2002, 0.20 million hectares of *Aus* and *Aman* rice were damaged by flood while the damage was only 0.12 million hectares in the case of *Boro* rice during the same period. Similarly, in 2007, while 1.14 million hectares of *Aus* and *Aman* land were damaged due to flood, the damage of *Boro* rice area was only 0.04 million hectares in the same year. It would be interesting to see how the damage in *Aus* and *Aman* rice due to floods and drought affect production of *Aus* and *Aman* rice at the household level.

The third set of data is the farm and households' demographic, rice production and income-related data from Household Income and Expenditure Survey (HIES), which were made available by the Bangladesh Bureau of Statistics (BBS). In the 2000 HIES survey, a total of 7440 households were randomly selected from six divisions, 64 districts, 303 sub-districts and 360 *mauzas* (consisting of a few or parts of villages with a separate land jurisdiction). In the 2005 HIES, a total of 10,080 households were randomly selected from 6 divisions, 64 districts, 364 sub-districts and 389 *mauzas*. Finally, in the 2010 HIES, a total of 12,240 households were randomly selected from 6 divisions, 64 districts, 384 sub-districts and 454 *mauzas*. In this article, however, as we are particularly interested in examining the impacts of drought and submergence on rainfed rice production in rural Bangladesh, we considered only households with strictly positive income from rice during the sampled years. Thus, essentially, we considered only 10,283 sampled farm households, of which 2641 are from 2000 HIES, 3543 are from 2005 HIES and the rest, 4099, are from the 2010 HIES.

3. Households and farm characteristics

Table 1 presents the distribution of the sampled households and other basic demographic information, including the location of the sampled households over the periods sampled. Table 1 shows that more than 80% of the sampled households are located in rural areas. It further shows that, on average, a spouse of a household head has 1.95 to 2.42 years of formal education, and, on average, a household consisted of nearly 5 members. As rice cultivation is a highly labor-intensive work and as family members can be a source of high-quality labor, we have empirically demonstrated that the number

[4] In Bangladesh, there are 35 weather stations that collect rainfall data and of which 23 weather stations collect temperature data and 18 weather stations collect humidity data (e.g., BBS, 2011).

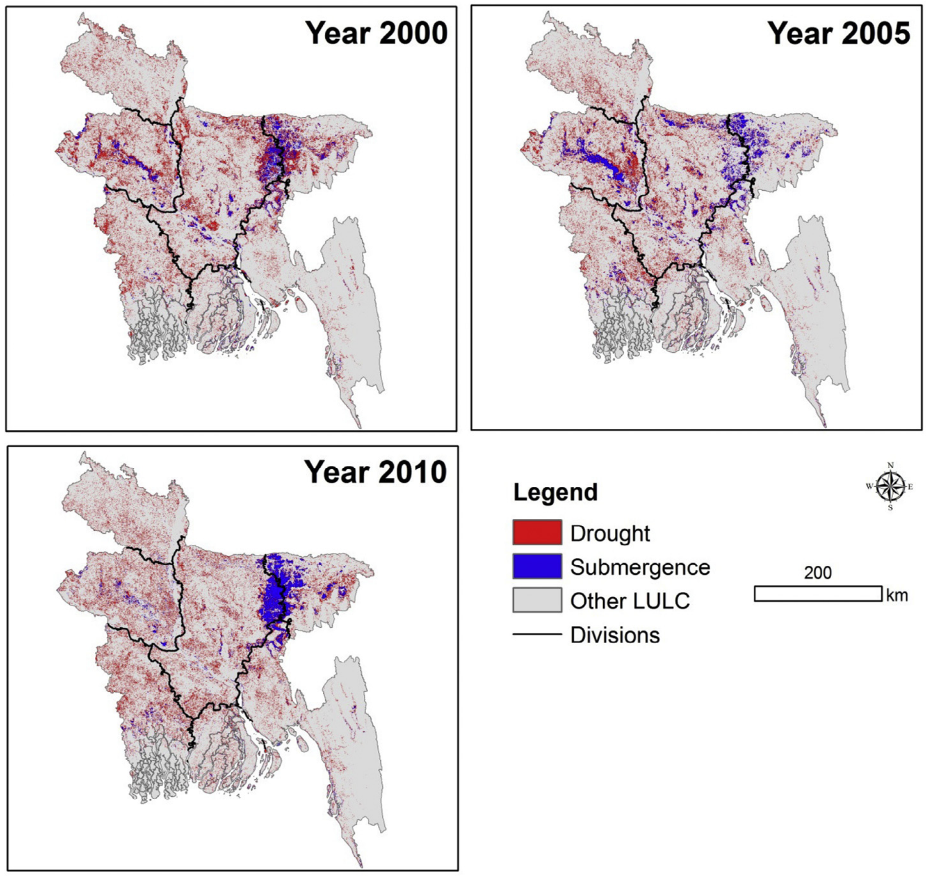

Fig. 3. Mapping drought and floods in Bangladesh using remotely sensed MODIS data over the period sampled. Source: MODIS 500 m MOD09A1 data.

of family members positively and significantly affects rice production of a household.

Table 2 shows the size of the total farmland, the farmland under the rice crop and the share of rainfed *Aus* and *Aman* season rice and irrigated *Boro* rice in total rice farmland at the farm household level in 2000, 2005 and 2010. The table shows that, on average, a household in 2010 cultivated 0.83 hectare of land, of which more than 75% was devoted to only rice farming. In the case of rice farmland, *Boro* rice occupied the highest proportion of land, followed by *Aman* rice. Alarmingly, Table 2 shows that the average size of the total farmland at the household level in Bangladesh has declined over the years, from 1.52 hectares in 2000 to 0.83 hectare in 2010. This finding strongly supports the findings of the World Bank (2012) that per capita arable land in Bangladesh declined from 0.17 hectare in 1960 to 0.05 hectare in 2008, mainly because of the enormous population pressure.

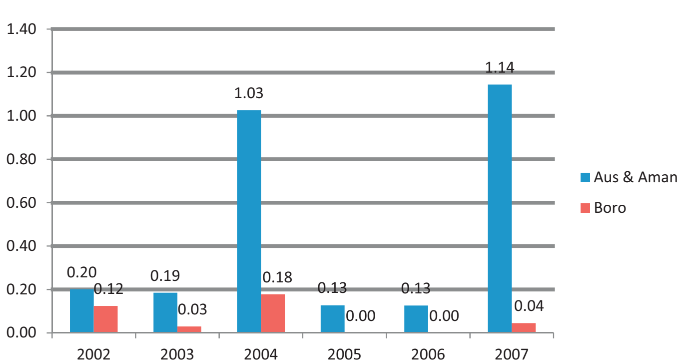

Fig. 4. Damaged area of *Aus* + *Aman*, and *Boro* rice crop (million hectares) due to flood over years. Sources: GOB (Government of Bangladesh). *Bangladesh Economic Review, 2005 & 2008*. Dhaka: Ministry of Finance. Online: http://www.mof.gov.bd/en/budget/er/2005/c7.pdf, accessed June 24, 2014, and http://www.mof.gov.bd/en/budget/er/2008/c7.pdf, accessed June 24, 2014.

Table 1
Demographic characteristics of the sample households (per household level average).

Year	2000	2005	2010
No. of sample households	2641	3543	4099
Age of HH head	45.8	47.1	47.5
HH head's years of schooling	3.1	3.3	3.2
Years of schooling of spouse	2.0	2.4	2.4
% Households from rural areas	93.2	83.1	82.2
% Male HH heads	96.5	95.7	93.2
No. of family members	6	5	5

Sources: BBS, Household Income and Expenditure Surveys, 2000, 2005 and 2010.

Table 2
Information on the use of cropland of the sample households (per household level average).

Year	2000	2005	2010
Total cropland (hectares)	1.52	1.02	0.83
Rice cropland (hectares)	1.024	0.82	0.644
% Rice cropland	67.2	80.7	77.8
% *Aus* land	13.3	9.8	11.2
% *Aman* land	45.3	45.4	41.6
% *Boro* land	41.4	44.9	47.2

Sources: BBS, Household Income and Expenditure Surveys, 2000, 2005 and 2010.

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Table 3
Information on the sources of crop income of the sample households per household level average (000 BDT).

Year	2000	2005	2010
Income from all crops	21.06	22.39	26.82
Income from rice	15.63	16.56	16.67
Value of produced rice consumed	7.94	7.41	10.40
Value of rice sold in the market	5.85	6.80	6.27
% Income from rice to total income from crop (%)	74.22	73.96	62.16
Income from *Aus* to total rice income (%)	8.38	6.58	6.24
Income from *Aman* to total income from rice (%)	41.71	36.11	32.51
Income from *Boro* rice to total income from rice (%)	49.84	57.25	61.25

Note. Values computed in terms of real BDT using general price index 1995–1996 = 100.Sources: BBS, Household Income and Expenditure Surveys, 2000, 2005 and 2010.

Table 3 presents the average income from all crops in the sampled years of a household, the share of rice income in total crop income and also the shares of *Aus, Aman* and *Boro* in total rice income in 2000, 2005 and 2010. Note that, using the 1995–1996 general price index, all nominal values have been deflated and converted into real values. It shows that, on average, the total crop income of a sample household ranged between BDT 21.06 thousand and BDT 26.82 thousand during 2000 to 2010 and income only from rice ranged between BDT 15.63 thousand and BDT 16.67 thousand during the same period. This means that only rice constituted 62% to 74% of the total crop income of a sample household during the sampled period. Table 3 further presents the average share of *Aus, Aman* and *Boro* rice income in a household's total income from the rice crop only. It shows that the shares of *Aus* and *Aman* rice in total rice income declined from 42% in 2000 to 33% in 2010, whereas the share of *Boro* rice in total rice income increased from 50% in 2000 to more than 60% in 2010. Importantly, Table 3 shows that, on average, *Boro* rice that occupied only 47% of the total rice farmland of a sampled household contributed more than 60% to total household rice income. By contrast, rainfed *Aus* and *Aman* rice that jointly occupied more than 52% of the total rice farmland of a sampled household contributed only 38% to the total rice income of a household.

The frequent occurrences of climate-related drought and submergence stresses have been identified as the major reason for lower yields in rainfed *Aus* and *Aman* season rice (Fig. 2), and therefore lower contribution of rainfed rice income to total crop income at the household level in Bangladesh (e.g., Ahmed, 2006; Dey and Upadhyaya, 1996; Khandker, 2007; Paul, 1998; Paul and Rashid, 1993). For example, floods in 1988 destroyed 2 to 2.3 million tons of only *Aman* rice in Bangladesh (Ahmed, 2006), and Paul and Rashid (1993) demonstrated that floods recurrently damaged at least four percent of the total rice crop in Bangladesh during 1967 to 1988. Paul (1998) and Benson and Clay (2004) also presented the number of major droughts and the fluctuation of agricultural value added caused by those droughts and floods in Bangladesh since its independence in 1971. Importantly, the severity of damage in rice production due to drought and submergence varies greatly among the districts because of the variation in the extent of drought- and submergence-prone rainfed *Aus* and *Aman* season rice areas among them (e.g., Murad and Islam, 2011; Paul, 1998). Figs. 3 and 4 demonstrate the fact. Table 4 also confirms it.

Table 4 presents total rice area (in 000 hectares) at the division level, and also the percentages of drought- and submergence-affected rice areas in Bangladesh in 2010. Table 4 shows that Dhaka, Rajshahi and Rangpur divisions are the major rice producing areas in Bangladesh. Importantly, Table 4 reveals that more than 3% to more than 5% of the rice area in Chittagong, Dhaka, Khulna, Rajshahi and Sylhet divisions was affected by drought in 2010, and 55% of the rice area in Sylhet, nearly 12% of the rice area in Dhaka and more than 3% of the rice area in Rajshahi division were affected by submergence in 2010 (Fig. 3). Table 4 also presents the share of total rice income in crop income and the share of rainfed *Aus* and *Aman* season rice in total rice income at the division level. This shows that the contribution of *Aus* and *Aman* season rice income ranged between 28% and 80% among the households at the division level in Bangladesh in 2010. In the coastal divisions such as Barisal, *Aus* and *Aman* are the major rice crops, while *Boro* is the major rice crop in the Rajshahi and Rangpur divsions. As the rainfed *Aus* and *Aman* season rice harvest greatly depends on climate (e.g., Fukaia et al., 1999; Hossain, 1995), there is a high correlation among drought and submergence stresses and the production of *Aus* and *Aman* rice at the farm household level.

One can observe an important fact from Table 4: in Barisal division, only 21 percent of the area is covered by *Boro* rice while 79% of the area is covered by rainfed *Aus* and *Aman* rice. As a result, even a smaller effect of drought and submergence can have higher impacts on rice production in this area. As rice is the major source of income of farmers in this division, this is probably one of the reasons for the highest incidence of extreme poverty in the division.

4. Model specification

To quantify the effects of drought and submergence on rainfed *Aus* and *Aman* production at the household level, we formulate and estimate the following equation:

$$Y_i = a_0 + (Z)_i \varphi i + (X_i)\phi i + a_1(\%DAA)_i + a_2(\%SA)_i + a_3(Year2005dummy) + a_4(Year2010dummy) + \theta_i + \omega_i$$

where **Y** is a vector of dependent variables that includes the production of *Aus* and *Aman* rice in thousand kilograms produced at the household level in 2000, 2005 and 2010; **Z** is a vector of variables that includes age, a sex dummy that assumes a value of 1 if a household head is a female or 0 otherwise, years of schooling of the household head, a dummy for the household's location that assumes a value of 1 if a household is located in a rural area or 0 otherwise, years of schooling of the spouse and the number of family members; **X** is a vector of variables that includes monthly average maximum temperature, and yearly total rainfall at the sub-district level, and six division dummies for seven divisions where Barisal

Table 4
Total rice area (000 ha), drought- and submergence-affected rice areas and rice income at the division level in 2010.

	No. of HH	MODIS rice area	% Drought-affected	% Submergence-affected	% Rice in total crop income	Total rice income (000 BDT)	% *Aus* and *Aman* rice	% *Boro* rice
Barisal	266	103.56	1.2	1.2	81.2	13.34	79.0	21.0
Chittagong	620	84.28	4.4	9.0	74.6	13.97	51.3	48.7
Dhaka	1047	116.03	5.0	11.6	74.9	15.87	28.6	71.4
Khulna	672	73.83	3.9	1.6	58.7	14.90	39.7	60.3
Rajshahi	615	110.26	3.2	3.3	63.9	18.68	35.8	64.2
Rangpur	586	115.65	0.6	0.1	76.7	20.05	45.4	54.6
Sylhet	293	89.92	12.9	55.5	85.9	21.43	47.0	53.0

Note. Values computed in terms of real BDT using general price index 1995–1996 = 100 .Sources: BBS, Household Income and Expenditure Surveys, 2010.

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Table 5
Estimated functions bit estimation method explaining *Aman* and *Aus* rice production at the household level.

Dependent variables	*Aman* season production (000 kilograms)			*Aus* season production (000 kilograms)		
Columns[a]	1	2	3	4	5	6
Share of rice area affected by drought[b]	−12.92*** (−7.08)	−13.82*** (−7.83)	–	−3.64 (−1.50)	−6.93*** (−2.81)	–
Share of rice area affected by floods[b]	−0.39 (−1.14)	–	−1.33*** (−3.94)	−1.28*** (−2.77)	–	−1.57*** (−3.53)
Yearly total rainfall[c] (000 mm)	−0.07 (−0.82)	−0.07 (−0.78)	−0.09 (−0.96)	−0.06 (−0.58)	−0.06 (−0.55)	−0.07 (−0.65)
Monthly average maximum temperature[c] (C^0)	−0.12 (−1.56)	−0.11 (−1.49)	−0.14* (−1.88)	0.01 (0.13)	0.04 (0.39)	0.0003 (0.00)
Education of head of household	0.04*** (5.84)	0.04*** (5.78)	0.04*** (5.78)	0.01 (0.77)	0.01 (0.56)	0.01 (0.81)
Age of head of household	0.01*** (6.47)	0.01*** (6.45)	0.01*** (6.36)	0.003 (1.38)	0.003 (1.39)	0.003 (1.41)
Female head of household	−0.03 (−0.26)	−0.03 (−0.31)	0.002 (0.02)	0.03 (0.27)	0.02 (0.14)	0.04 (0.30)
Rural location of household	0.01 (0.08)	−0.002 (−0.01)	0.08 (0.60)	0.07 (0.36)	0.03 (0.14)	0.09 (0.52)
Education of spouse	0.04*** (4.33)	0.04*** (4.37)	0.04*** (4.41)	0.001 (0.11)	0.003 (0.27)	0.001 (0.11)
No. of family members	0.15*** (9.63)	0.15*** (9.60)	0.14*** (9.17)	0.09*** (5.71)	0.09*** (5.65)	0.09*** (5.72)
Dhaka division, dummy	−1.10*** (−4.28)	−1.10*** (−4.28)	−1.38*** (−5.03)	−0.69*** (−3.49)	−0.66*** (−3.35)	−0.77*** (−3.73)
Chittagong division, dummy	−1.17*** (−5.11)	−1.18*** (−5.17)	−1.52*** (−6.32)	−1.80*** (−8.29)	−1.82*** (−8.44)	−1.91*** (−9.55)
Khulna division, dummy	−0.63** (−2.32)	−0.60** (−2.22)	−1.02*** (−3.63)	−0.80*** (−4.12)	−0.72*** (−3.66)	−0.91*** (−5.07)
Rajshahi division, dummy	−0.754*** (−2.79)	−0.744*** (−2.75)	−1.011*** (−3.63)	−1.461*** (−6.64)	−1.411*** (−6.35)	−1.552*** (−7.43)
Rangpur division, dummy	−0.370 (−1.62)	−0.370 (−1.62)	−0.311 (−1.32)	−3.862*** (−10.60)	−3.876*** (−10.60)	−3.854*** (−10.56)
Sylhet division, dummy	0.365 (1.05)	0.275 (0.80)	−0.646** (−1.99)	0.595* (1.73)	0.415 (1.12)	0.318 (1.10)
Year 2005, dummy	−0.34*** (−2.82)	−0.34*** (−2.85)	−0.32** (−2.57)	−0.29** (−2.03)	−0.29** (−2.03)	−0.29** (−2.02)
Year 2010, dummy	−0.44*** (−3.93)	−0.44*** (−3.96)	−0.42*** (−3.62)	−0.44*** (−3.34)	−0.45*** (−3.37)	−0.44*** (−3.32)
Constant	4.004* (1.71)	3.804 (1.64)	4.678** (1.97)	−0.714 (−0.23)	−1.445 (−0.46)	−0.368 (−0.12)
Sigma	2.121*** (151.29)	2.121*** (152.69)	2.137*** (157.08)	1.713*** (128.85)	1.721*** (129.49)	1.715*** (129.08)
No. of observations	10,283	10,283	10,283	10,283	10,283	10,283
Left censored	3395	3395	3395	8085	8085	8085
Right censored	1	1	1	1	1	1

[a]Six columns correspond to different models of Tobit, 1 with *Aman* rice full model and 2 and 3 are the restricted models in which we sequentially included drought and submergence variables separately. Similarly column 4 is the full model for *Aus* rice and 5 and 6 are the restricted models; [b]At the district level; [c]At the sub-district level. Numbers in parentheses are t statistics based on standard error that allows for intragroup correlation. *$P < 0.05$, **$P < 0.01$ and ***$P < 0.001$.

division is the base; DAA and SA are the percentages of MODIS rice area affected by drought and submergence; a_0 is the scaler parameter; ϕ and φ are the vectors of parameters, including $a_1, a_2, a_3,$ and a_4 as parameters to be estimated; i stands for individual household; t stands for year (t = 2000, 2005, 2010); and ω is the random error term. It is important to mention here that, as the data are cross-sectional in nature, we could not apply the household-level fixed-effect estimation method to estimate the equation. Moreover, information on *Aus* and *Aman* production on all sampled items (dependent variables) is not available for a number of households. This is because quite a few households did not produce rainfed *Aus* and *Aman* rice in the sampled years; hence, *Aus* and *Aman* production are zero for some households. The data are therefore clearly censored data in nature, which suggests applying a tobit model for estimation purposes (Gujarati, 1995). To deal with this situation we apply the two limit tobit estimation process to estimate the equation.

4.1. Results and discussion

Table 5 presents the estimated functions explaining the production of *Aus* and *Aman* rice at the household level. Note that in order to avoid the problem of multicollinearity (if any) between the drought and submergence events and rainfall and temperature, we run separate regressions, in which first we include both variables, and later include one at a time. Table 5 shows that the years of schooling and age of the head of the household is positive but insignificant in the function explaining *Aus* production; however, these variables have positive and statistically significant impact on production of *Aman* rice. A plausible explanation is that although both *Aman* and *Aus* seasons mostly rely on rain, production in *Aman* seasons use relatively more inputs and more high-yielding varieties (Hossain and Jaim, 2012).[5] As a result, for *Aman* season rice, the scope of the application of new information and knowledge in deciding modern agronomic practices, chemical fertilizers, seeds and varieties is wider, compared to *Aus* rice season.

Columns 1 and 4 in Table 5 present estimated functions explaining production of rice in *Aman* and *Aus* seasons at the farm household level that includes all of the explanatory variables. The estimated function in column 1 shows that while drought (share of rice area affected by drought) has a negative and significant impact on *Aman* season rice production, the impact of submergence (defined as share of rice area affected by floods) is negative and statistically insignificant. By contrast, the estimated function in column 4 shows that only submergence has a negative and statistically significant impact on *Aus* season rice production; the impact of drought is negative but statistically insignificant. This finding is not surprising since it has been noted that drought and submergence problems are not mutually exclusive events in Bangladesh (Paul, 1998). In fact, in most cases, one event follows another in the same place. It indicates a

[5] *Aus* rice usually follows more traditional cultivation method compared to *Aman* rice as yield in *Aus* rice is lowest among all other rice yields in Bangladesh. A simple proof is that while Bangladesh Rice Research Institute (BRRI) has developed 19 different types of HYV rice for *Boro* rice and 28 for *Aman* rice, for *Aus*, so far, it has developed nine varieties. For details: Online: http://www.knowledgebank-brri.org/brri-rice-varieties.php, accessed August 8, 2014.

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strong correlation between the two variables.[6] Therefore, to isolate the effects of drought and submergence stresses on rainfed rice production season, *Aus* and *Aman*, we report columns 2, 3 and 5 and 6. In columns 2 and 5 we only estimate the impact of drought (share of rice area under drought) on production of rice in the *Aman* and *Aus* season; in columns 3 and 6 we only estimate the impact of submergence (share of rice area under submergence) on production of rice in *Aman* and *Aus* season.

Findings in columns 2, 3, 5 and 6 show that both drought and submergence have a significantly negative impact on the rainfed rice production in *Aman* and *Aus* seasons in Bangladesh. For example, based on the estimated coefficient in column 2, on average, a one percent increase in drought affected area[7] reduces rainfed rice production in *Aman* season, at the farm household level, by approximately 1382 kilograms per household on average, annually. Similarly, the coefficient on drought in column 5 indicates that a one percent increase in drought area reduces rainfed rice production in *Aus* season by approximately by 693 kilograms per farm household on average, annually. Also, columns 3 and 6 show that a one percent increase in submergence-affected area reduces rainfed rice production in *Aman* rice season at the farm household level by about 133 kilograms on average, annually. It also reduces the rainfed rice production in *Aus* season by about 160 kilograms per household on average annually. Finally, findings in Table 5 show that after controlling for farm household level demographics and drought and submergence problems, climate-related variables, such as rainfall and maximum temperature, have less significant effects on rainfed rice production of *Aus* and *Aman* seasons in Bangladesh. This finding is in contrast with Sarker et al. (2012) who found that the rainfall and temperature have major influences on rice production in Bangladesh.

Human capital and experience variables were also found to have a significant impact on the rainfed rice production in *Aman* and *Aus* seasons in Bangladesh. Schultz (1975) notes that education and experience enhances individual's ability to absorb and apply new information and knowledge into productive activities. Results in Table 5 indicate that educated and experienced head of households allocate more land for *Aman*, thereby increasing rainfed rice production in *Aman* season. Interestingly, spouse's educational attainment (years in school) was also positive and statistically significant across the estimated functions for *Aman* season rice production. It is plausible that an educated spouse is more likely to be employed in off farm income generating earning activity, which can ease credit constraints for rice farm families (Mottaleb and Mohanty, 2014). Therefore, in general, years of schooling of the spouse may have a direct influence on rice production in *Aman* season which is relatively more modern than *Aus* rice, and thus it has higher scope application of fertilizer and modern management practices. However, it should be noted that all three variables were insignificant in the case of rainfed rice production in the *Aus* season. A possible explanation is that *Aus* production is more traditional and modern management practices may lessen significant differences in production. Thus, it warrants an introduction of improved rice varieties with modern management packages to break the ceiling of low production of *Aus* rice in Bangladesh.

The coefficient of the number of family members is positive and highly statistically significant across the estimated functions (Table 5). In general, rice farming is highly labor intensive and family members can be a source of free labor that can be used in rice production. Finally, location of the farm also plays an important role in rainfed rice production. Estimated functions in Table 5 reveal that compared to the farm households in Barisal division (base division), households in other divisions are less likely to produce rainfed rice in *Aman* and *Aus* seasons. It is worth mentioning here that the highest incidence of income poverty in Bangladesh was observed in Barisal division in 2010, which was 26.7% (BBS, 2011a). In the Barisal division nearly 80% of the total rice income came from rainfed rice production in *Aman* and *Aus* seasons. As the rainfed *Aus* and *Aman* harvest is highly dependent on the whims of nature, a link between the highest incidence of income poverty, in Barisal, and the dependence on rainfed rice production in *Aman* and *Aus* season for the livelihoods of farm households cannot be denied.

5. Conclusions and policy implications

Drought and submergence are two major stresses that cause substantial yield and income losses to rice farmers in rainfed areas of Asia (e.g., Fukaia et al., 1999; Pandey and Bhandari, 2009; Widawsky and O'Toole, 1996). In 50% of the total rice farmland in South Asia, which is rainfed in nature, is unfortunately where one can find the highest incidence of income poverty. Recurring loss in rice production caused by drought and submergence stresses, particularly in South Asia, added vulnerability to the poor rice farmers and deteriorated the overall poverty rate, in particular. Alarmed by the predicted changes in the global climate caused by global warming could cause more frequent and severe drought and submergence stresses – a phenomenon that will only exacerbate losses in rice production and income of poor farmers.

Using rainfed rice production data in *Aman* and *Aus* seasons in Bangladesh as a case study, this study quantifies the extent of losses in production at the farm household level. In particular, we used remotely sensed MODIS 250-m NDVI data and HIES data, 2000, 2005 and 2010, to estimate the losses in rainfed rice production for *Aus* and *Aman* seasons at the farm household level. Applying two limit tobit estimation method, we demonstrated that both drought and submergence stresses can have a significant impact on rainfed rice production in *Aman* and *Aus* seasons in Bangladesh. We found that in drought affected areas, on average, losses could range between 700 and 1300 kilograms, per farm household, on average annually, in case of rice production in *Aman* and *Aus* seasons. However, losses in rice production from submergence are significant but lower, ranging from 128 to 160 kilograms per farm household, annually.

Based on the findings, this paper suggests that production losses in rainfed *Aus* and *Aman* rice caused by drought and submergence stresses can be reduced substantially in a variety of ways. For example, artificial water control in the form of irrigation substantially increases *Boro* rice production which is the major rice crop in Bangladesh. Thus, wherever possible, artificial floodwater control should be introduced to protect *Aus* and *Aman* rice crops and supplementary irrigations should be introduced in the case of drought. Secondly, through the development and dissemination of improved rice varieties that are more tolerant to abiotic stresses, combined with the provision of modern management practices, such as changing sowing dates, using shorter duration varieties to avoid drought periods and the application of scale appropriate agriculture machinery for rapid harvesting, losses in *Aus* and *Aman* season rice production can also be minimized. Finally, development and dissemination of drought and submergence tolerant modern rice varieties can reduce losses in *Aus* and *Aman* season rice production substantially. Note that the International Rice Research Institute (IRRI) in collaboration with Bangladesh Rice Research Institute (BRRI) has already developed drought and submergence tolerant rice varieties in Bangladesh (e.g., Hossain et al., 2013).

However, the scientific community has been working still along the development of appropriate germplasm, because abiotic stresses

[6] It is found the coefficient of correlation between drought and submergence affected areas is +0.54 and it is significant at 1% level.

[7] Recall that the drought and submergence variables are measured at the district level.

are different in different countries, depending on topography of place/county. International donor agencies in collaboration with national government can facilitate rapid dissemination of the abiotic stress tolerant modern rice varieties. Importantly, this type of technology would not only allow farmers to adapt to current losses in rainfed rice production but would also allow poor rice farmers in the abiotic stress prone areas to adapt to worsening global climate and allow them to minimize the adverse effects of climate change in the future (e.g., Gumma et al., 2014; Mottaleb and Mohanty, 2014, Mottaleb et al., 2012). Consequently, in the long run, the returns to investment in developing abiotic stress tolerant rice variety would be very high. Thus, we strongly encourage policymakers and donors to fund research, development and dissemination of new rice varieties that are more tolerant to drought and other abiotic stresses.

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