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Impacts of climate change, agroecology and socio-economic factors on agricultural land use diversity in Bangladesh (1948–2008)

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ABSTRACT

The paper examines the impacts of climate change, agroecology and socio-economic factors on agricultural land use diversity (ALUD) using a panel data of 17 regions of Bangladesh covering a 61 year period (1948–2008) by applying a dynamic panel GMM estimator. Results revealed that ALUD and total rainfall have actually increased @ 0.19% and 0.02% per year whereas variability in temperature has declined @ 0.06% with significant differences across agroecological zones (AEZs). Among the climatic factors, total rainfall significantly increases ALUD. ALUD is also significantly influenced by agroecological characteristics. ALUD is significantly higher in Ganges River Floodplains but lower in Meghna River Floodplains and Chittagong Coastal Plain. Among the socio-economic factors, ALUD increases significantly with increase in the prices of vegetables, jute and phosphate fertilizer and R&D investment. ALUD significantly decreases with increase in the prices of lentil, onion, sugarcane, nitrogen and potassium fertilizers and extension expenditure. Policy implications include price policies to improve vegetable and jute prices, stabilise/reduce fertilizer prices and investments in R&D to develop crops that are suitable for high rainfall areas as well as specific AEZs in order to promote ALUD in Bangladesh.

Key Words: Agricultural land use diversity, climate change, agroecology, socio-economic factors, dynamic panel GMM estimator, panel data, Bangladesh.

1. Introduction

While the influences on the levels of agricultural production are multiple, inter-related and varied across different spatial scales, the impacts of climate change are increasingly recognised as a significant factor affecting livelihoods globally (Bharwani et al, 2005; Kurukulasuriya and Rosenthal, 2003). Nonetheless limitations remain in understanding the effects of global climate change on agriculture (Lobell et al., 2011). Land cover and land use changes are acknowledged to be related to environmental factors, including climate change, in complex ways (Dale, 1997; Lepers et al, 2002). While many have attempted to predict likely future impacts of climate change on food production (e.g., Benhin, 2008; Jackson, 2011), fewer studies addressed the relationship between climate change in the recent past and agricultural production over time at the regional scale – despite observed temperature increases over past decades (Lobell and Field, 2007). Similarly, very little attention has been paid to the ways in which climate change over the past may have impacted on land cover and agricultural land use. Instead, studies tend to examine the contribution of changing land use (e.g., de-forestation) to climate change (Gao and Liu, 2011). Where the question of agricultural land use is addressed, if often obliquely, is limited to the discussion of farm-level adaptation to climate change (e.g., Mercer et al, 2012; Manandhar et al., 2011). This increasingly rich and spatially-diverse literature examines the changes made by farmers in recent past in order to address perceived climate change at the local level. Although these studies provide a valuable description of the heterogeneity of approaches to climate change adaptation by farmers and an exploration of the complex weave of social, economic, political, cultural and environmental factors influencing adaptation and how these vary across diverse geographical milieu, they do not provide a measure or quantitative evidence of the level and nature of influence of climate change on agricultural land use and/or agricultural productivity. As Gao and Liu (2011) explain, "… few have studied the impact of climate change on land cover change, especially benign land cover change … nobody has explored the causal relationship between climate change and land use change except at the conceptual level" (p477). Similarly, Salvati et al. (2013) explain that "up to now relatively few studies examine the changes in both land cover and selected climate variables over large areas at an adequate detailed spatial scale and over a long period of time" (p402).

Furthermore, studies examining land use and land cover changes do not even mention climate as a significant factor. For example, Lambin et al. (2003) briefly mention climate as one aspect of natural variability affecting land use but climate is not listed in the authors' five fundamental high level causes of land-use change which include: resource scarcity; changing opportunities created by markets; outside policy intervention; loss of adaptive capacity and increased vulnerability; and changes in social organisation, in resource access and in attitudes. Similarly, Leper et al. (2005) while identifying land-use changes over a period of 1981-2000, the relationship between land-use change and climate change was not explored. Similarly, Qasim et al. (2013) examining land use change in the Swat District of Pakistan briefly mentioned the expansion of off-season vegetable production due to mild temperatures but there was no further discussion of the impact of global climate change.

Given such a dearth of information in the existing literature, the present paper is an attempt to examine the impacts of climate change, agroecology and a range of socio-economic factors on agricultural land use change or diversity (ALUD) at the regional scale over a 61 year period (1948–2008) using a panel data of 17 regions of Bangladesh, a country most vulnerable to climate change, increased flooding and other vagaries of nature.

We undertake this task by estimating a model of crop choice based on a theoretical framework of the farm household model applying a micro-econometric approach. This is because, we conceptualize that the observation of ALUD at a regional level is an aggregate response of individual farmers' crop choice decisions and subsequent allocation of their farm area to chosen crops in response to a host of factors. In general, in these decision making processes, socio-economic and policy factors dominate and climate change is seen as either an additional factor or an enabler to observed land use change. For example, Reid et al. (2000) noted that the most significant factors influencing land use change during 1957–1993 in Ghibe Valley in Ethiopia are the socio-economic and political factors although climate was only attributed to influx of migrants in the area following drought. Similarly, Liu et al. (2010) noted that land use change across China between 2000 and 2005 are due to national land strategies (e.g., reforestation policy) whereas climate warming is mentioned as enabling factor for conversion of grassland to arable lands. Otwald and Chen (2006) noted strong correlation of policies and reforms than climate change on land use change in Loess Plateau, China since the early 2000s. In this study, we explicitly include climate change variables and agroecological characteristics in addition to a wide range of socio-economic factors to identify their individual influences on ALUD at the regional level covering a long 61 year period (1948 – 2008).

The rest of the paper is structured as follows. Section 2 presents the analytical framework of the study, develops the empirical model, and describes the data. Section 3 presents the results. Section 4 provides conclusions and draws policy implications.

2. Methodology

2.1 The Theoretical Model

First, we develop a general model of farm production to examine the determinants of land use diversity and or area allocated to different crops following Rahman (2008). The farmer produces a vector Q of farm outputs using a vector of inputs X. The decision of choice, however, is constrained by a given production technology that allows combination of inputs (X) and an allocation of a fixed land area ($A = A^0$) among j number of crops, given the characteristics of the farm (Z). The total output of each farmer i is given by a stochastic quasi-concave production function:

$$Q_{ij} = f(X_{ijk} ....X_{ijk}, \varepsilon \mid A_i, Z_i) \qquad (1)$$

where ε is the stochastic variable indicating impacts of random noise. It is assumed that $f_{Xk}>0$ and $f_{XXk}<0$. Each set of area shares (α_j) among j crops sums to 1, $\sum_j^J \alpha_j = 1, j = 1,2,....J$, which maps into the vector Q through physical input-output relationships. The choice of area shares implies the level of farm outputs. The profit of each farm i is given by:

$$\pi_i(Q, X, p, w \mid A_i, Z_i) = \sum_{j=1}^{J} p_j Q_{ij} - \sum_{k=1}^{K} w_j X_{ijk} \qquad (2)$$

where p is the vector of output prices and w is the vector of input prices.

The farmer is assumed to have a von Neuman-Morgenstern utility function, $U(W)$ defined on wealth W with $U_W>0$ and $U_{WW}<0$. The wealth is represented by the sum of initial wealth (W_0) and the profit generated from farming (π). Therefore, the objective of each farm is to maximize expected utility as (Isik, 2004):

$$EU(W_0 + \pi(Q, X, p, w \mid A_i, Z_i) \qquad (3)$$

where E is the expectation operator defined over ε. The choice variables in (3), the farm's input levels X_{ijk}, are characterized by the first-order conditions

$$\frac{\partial EU}{\partial X_{ijk}} = EU_w(p_j * f_{Mijk} - w_k) = 0 \qquad (4)$$

The second-order conditions are satisfied under risk aversion and a quasi-concave production function (Isik 2004). The optimal input mix is given by:

$$X_{ijk}^* = X_{ijk}^*(p_j, w_k, U \mid A_i, Z_i) \qquad (5)$$

And the optimal output mix, depending on (X^*_{ijk}) is defined as:

$$Q^*_{ij} = f(X^*_{ij1},......X^*_{ijk}) \mid A_i, Z_i) \qquad (6)$$

2.2 Determinants of the choice of crops

To determine the factors affecting a farmer's choice of crops, we derive the equivalent wealth or income from the expected utility (Rahman, 2008):

$$E_i = E(W_0 + \pi_i(Q, X, p, w \mid A_i, Z_i) \qquad (7)$$

This equivalent wealth or income in a single decision making period is composed of net farm earnings (profits) from crop production and initial wealth that is 'exogenous' to the crop choices (W_0), such as farm capital assets and livestock resources carried over from earlier period.

Under the assumption of perfect market, farm production decisions are made separately from consumption decisions and the household maximizes net farm earnings (profits) subject to the technology and expenditure constraints (Benin et al. 2004). Therefore, production decision of the farms, such as crop choices, are driven by net returns (profits), which are determined only by input and output prices, farm physical characteristics and socio-economic characteristics of the farm household (Benin et al., 2004). Therefore, the optimal choice of the household can be re-expressed as a reduced form function of input and output prices, market wage, farm size, initial wealth, and socio-economic characteristics of the farms (Rahman, 2008):

$$h^*_i = h^*_i(p_j, w_k, Z_i, A_i, W_{0i}) \qquad (8)$$

Eq. (8) forms the basis for econometric estimation to examine the factors affecting diversity of crops on individual farms, an outcome of choices made in a constrained optimization problem.

After developing the model for individual farmers, we extend the model to regional level. The key assumption is that the factors affecting choice of crops at the individual farm household level in a given period of time can be applied to identify the determinants of land area allocated to various crops at the regional level (which essentially represents combined action of individual farmer's responses in each region):

$$S_{rt} = S_{rt}(\alpha^{*}_{rjt}(p_{jrt}, w_{krt}, Z_{rt}, A_{rt}, W_{0rt})) \qquad (9)$$

where *S* represents the Shannon index of ALUD at the regional level, r represents the rth region (r = 1, 2, 3, …. 17) and t represents time (t = 1, 2, … 61).

2.3 Data

The data used for the analysis were constructed from various sources. The principal data on Bangladesh agricultural sector is taken from the special issue of Statistical Yearbook of Bangladesh which reports land area, production and yield of all major crops covering the period 1948-1972 (BBS, 1975), various issues of the annual Statistical Yearbook of Bangladesh covering the period 1975 to 2008 (BBS, various issues), agricultural databases covering the period 1948-1990 compiled and published by Hamid (1991, 1993), agricultural censuses of Pakistan 1960 (PMFA, 1960) and Bangladesh 1983/4, 1996 and 2008 (BBSa, various issues) and Ahmad (1958), population censuses of Pakistan 1951 and 1961 (PSO, various issues) and Bangladesh 1974, 1981, 1991, 2001, and 2011 (BBSb, various issues), Bangladesh Water Development Board (2012), Bangladesh Meteorological Department, Bangladesh Bank (various issues), Quddus (2009), FAOSTAT, USDA-ERS, Barker et al, (1985), USDA, Tripathi and Prasad (2009), and Agricultural Statistics of India (2004)[1].

[1]Although Bangladesh now has 64 districts, most time-series data are largely available at the greater district level (which was the original districts prevailed until 1981) and we are naming them as regions in this study.

2.3.1 Dependent Variable: Shannon index of Agricultural Land Use Diversity

The dependent variable is the Shannon index which was adapted from the ecological indices of spatial diversity in species. Evenness, which combines both richness and relative abundance concept, is measured by a Shannon index. It is a commonly used diversity index that takes into account both abundance and evenness of species present in the community. The Shannon Index is defined as: $S = -\sum_{j=1}^{N} \alpha_j * \ln \alpha_j, S \geq 0$, where α_j = area share occupied by the *j*th crop in GCA, and N is the number of crops. Higher value of index denotes higher diversity (Dusek and Popelkova, 2012). A value of 0 would represent a community with just one species (Beals et al., 2000). Typically the value of Shannon Index in a real ecosystem ranges between 1.5 and 3.5 (Macdonald, 2003). On the other hand, Shannon's Equitability (E_S) can be calculated by dividing S by $S_{\max}$ (here $S_{\max} = \ln J$). Equitability assumes a value between 0 and 1 with 1 being complete evenness (Beals et al., 2000).

Shannon's diversity index is frequently used in the determination of landscape diversity (e.g., Rahman, 2010; Benin et al., 2004) because of its indisputable advantage in obtaining numeric values that can be easily compared (Dusek and Popelkova, 2012). One limitation of Shannon index is its inability to express spatial distribution of patches within an area (Dusek and Popelkova, 2012) which in our case is not a major issue as we are using data at the regional level.

For the purpose of comparison of ALUD across agroecology, we have also constructed another commonly used diversity index, the Transformed Herfindahl Index (THI). The concentration of crop type is measured by a Herfindahl Index and is defined as: $HI = \sum \alpha_j^2, 0 \leq HI \leq 1$. The value of 0 denotes perfect diversification whereas the value of 1 denotes perfect concentration, i.e., only one crop (Islam and Rahman, 2012). THI is simply defined as $THI = 1 - HI$. Its value increases with the increase in diversification and assumes a value of 0 in case of perfect concentration and a value of 1 for perfect diversification (Islam and Rahman, 2012).

2.3.2 Explanatory variables: agro-ecology, climate change and socio-economic factors

Independent variables are operational measurements of the vectors shown on the right hand side of Eq. (9). A wide range of variables were incorporated representing agroecology, climate change and socio-economic factors. These are: prices of major crops, fertilizer prices, labour wage, literacy rate, average farm size, labour stock per farm, animal power per farm, irrigation, R&D investment per farm, extension expenditure per farm, total annual rainfall, temperature variability, flood proneness and agroecology. Table 1 presents brief definition, descriptive statistics and hypothesized direction of influence of these variables on ALUD while the construction details of these variables are delegated to the appendix (see Appendix A). We expect that the signs of the variables which are expected to hold at the farm household level will also hold at the regional level. That is positive influence of non-cereal crop price rises on ALUD, reduction of input prices (i.e., fertilizers and labour wage) to trigger shift in cropping portfolio that are fertilizer use intensive (e.g., vegetables), positive influence of farm size, labour stock, infrastructure and services (e.g., extension and R&D expenditures), and wealth (e.g., livestock resource) on ALUD. We also expect positive influence of total rainfall and negative influence of flood proneness on ALUD. However, we cannot a priori determine the influence of agroecological characteristics on ALUD.

Apart from incorporating input and output prices and agricultural labour wage, the justification for including other variables are as follows: Land and livestock are both scarce and major sources of wealth in rural Bangladesh. Larger farm areas can be allocated among more crops (Benin et al., 2004). Rahman (2008) noted that a reduction in livestock resources is positively related to crop diversity at the farm level because growing non-cereal do not require extensive draft power support. Hence, the average farm size and livestock stock were incorporated to test their independent influences on decisions regarding ALUD. Irrigation is included because lack of access to modern irrigation facilities has been identified as one of the principal reasons for stagnation in the expansion of HYV rice area in Bangladesh (Rahman and Thapa 1999; Mahmud et al., 1994). Also, irrigation may decrease diversity through uniform moisture conditions (Benin et al., 2004). The education variable was used because it serves as a proxy of access to information as well as capacity to understand the technical aspects and profitability related to different crops which may influence crop production decisions (Rahman, 2009). R&D is an important element in disseminating modern technology and production knowhow to farmers and potential of agricultural growth hinges largely on its effectiveness. A total of 131 improved varieties of various cereal and non-cereal crops have been developed and released by Bangladesh Agricultural Research Institute (BARI). Agricultural extension is another important element and significant influence of extension education on adoption of land-improving technologies was reported in the literature (e.g., Solis et al., 2007). Therefore, R&D and total extension expenditure per farm were incorporated to account for their influences on ALUD.

Bangladesh is earmarked as the country most vulnerable to climate change and flooding is another environmental hazard. Therefore, two climate change variables (i.e., total annual rainfall and variability in annual temperature) and the share of area flooded each year are included to determine their independent influences on ALUD. Finally, agroecology is another important feature that either limits or opens up opportunities for farmers to choose their cropping portfolio which remains largely ignored in the literature. A total of 11 dummy variables representing agroecological characteristics (or AEZs) were incorporated in the model to identify their independent influence on ALUD, leaving the remaining 12th AEZ subsumed in the intercept/constant term.

2.4 The empirical model

In order to identify the determinants of ALUD, we use the Dynamic Generalised Methods of Moment (GMM) estimator for panel data (for details, see section 3.2). The basic model is specified as follows:

$$S_{rt} = a_{rt} + b_{rt} S_{r,t-1} + c_{rt} p_t + d_{rt} w_t + g_{rt} Z_t + h_{rt} G_t + e_{rt} \quad (10)$$

where S represents the Shannon index of ALUD, p is a vector of output prices, w is a vector of input prices, S_{t-1} is the lagged Shannon Index of ALUD, Z is a vector of socio-economic characteristics of the regions, G is a vector of climate change and agroecological variables, e is the error term controlling for the unobserved factors and/or random noise, and *a, b, c, d, g* and *h* are the parameters to be estimated and ε_{rt} is the error term. We use this approach because a number of econometric problems may arise in a panel data framework. For instance: (a) a number of explanatory variables, such as, the price variables may be endogenous, and may be correlated with the error term; (b) the time-invariant characteristics (fixed effects) such as regions may be correlated with the explanatory variables. The fixed effects are contained in the error term in equation (10), which consists of the unobserved region-specific effects, v_r and the observation-specific errors, u_{rt} ($\varepsilon_{rt} = v_r + u_{rt}$); and (c) the presence of the lagged dependent variable (i.e., ALUD of the previous year, $S_{r,t-1}$) gives rise to autocorrelation (Mileva, 2007). Parameters were estimated using a user written program 'xtabond2' by Roodman (2009) for

STATA V10 software program (Stata Corp 2010). The routine 'xtabond2' estimates the Allerano-Bond Dynamic Panel GMM estimator (Allerano and Bond, 1991) and is more flexible than the original Allerano-Bond GMM estimator using 'xtabond' command.

3. Results

3.1 Agricultural land use diversity, climate change and land type by agroecology

Since the focus of this study is to highlight the influence of agroecology and climate change on ALUD, we first provide evidence of differences with respect to selected indicators including ALUD amongst 12 composite AEZs (see Figures 1 and Table 2). The Bangladesh Agricultural Research Council (BARC) created a database of area and proportion of major land elevation types in each of the 30 AEZs. The land elevation data in Bangladesh is classified according to flooding depth of the landscape. These are: High Land (HL, no flooding); Medium High Land (MHL, flooding depth of 0.10–0.90 m); Medium Low Land (MLL, flooding depth of 0.91–1.83 m); Low/Very Low Land (LL, flooding depth of > 1,83 m). We used this information and constructed a complete set of the proportion of HL, MHL, MLL and LL for each of the 12 composite AEZs (see Figure 1). It is clear from Figure 1 that there are large differences with respect to land elevation types for each AEZ. For example, the proportion of HL is highest in EH and DHAKA AEZs, GTF has the highest proportion of MHL and MMREF has the highest proportion of LL. Quddus (2009) noted further differences with respect to qualitative features such as soil types (i.e., dominance of sandy loam, loamy, silt loam, clay loam and heavy clay soils), fertility conditions (i.e., low, medium, and high), and levels of organic materials (i.e., low, moderate, medium, and high) for each of the 12 composite AEZs.

Table 2 presents the level of ALUD and other selected indicators by AEZs. Significant differences exist amongst AEZs with respect to all of the selected indicators which further complements trends observed in Figures 1 through 4 (see bottom of Table 2). Overall, ALUD (measured by Shannon Index) has actually increased @ 0.19% per year in Bangladesh with seven AEZs experiencing increases from its initial level of diversity whereas remaining five AEZs have experienced declines. For example, LGRF experienced the highest level of increase in diversity whereas SBSKF experienced highest level of decline. Quddus (2009) reported that cropping intensity has increased by 20% in LGRF between 1980 and 2003 but it has declined by 3.0% in SBSKF. Consequently, per capita food production increased by 3.2% annually in LGRF as compared to a decline of 0.5% annually in SBSKF between 1980 and 2005. Islam and Rahman (2012) also noted higher level of crop diversification in Kushtia, Faridpur, Jessore, Dhaka and Pabna regions, which belong to our HGRF, LGRF, and DHAKA AEZs, and attributed this phenomenon to favourable soil composition and agro-climatic conditions.

The other measure of ALUD, i.e., the THI, also showed similar results. The correlation coefficient between Shannon Index and THI is estimated at a high ρ = 0.99 ($p<0.01$), thereby confirming that the choice of diversification index will not alter the results. Islam and Rahman (2012) also demonstrated strong correlation between different measures of crop diversity for the regions of Bangladesh. Therefore, to analyse the determinants of ALUD, we have used Shannon Index because it considers two elements: species richness and evenness while THI considers only diversification. The overall annual maximum temperature, minimum temperature and total rainfall grew at an annual compound rate of 0.02% ($p<0.05$), 0.05% ($p<0.01$) and 0.02% ($p<0.10$), respectively over this 61 year period with significant differences across AEZs which confirms warming of temperature and rainfall over time although at a very low rate (results not shown).

3.2 Determinants of agricultural land use diversity

This section examines the determinants of ALUD at the regional level in Bangladesh. Table 3 presents the parameter estimates of Eq (10) using the Dynamic Panel GMM estimator. Prior to reporting the results, we discuss various hypothesis tests conducted to confirm validity of the model. We have specified all prices, climate change (excluding flood share), farm size, and R&D and extension expenditure variables as endogenous and used the second lag of these endogenous variables as instruments using system GMM estimator. The lower panel of Table 3 shows the results. The Sargan's test has the null hypotheses of 'instruments as a group are exogenous'. Therefore, the higher is the p-value of Sargan statistic the better (Mileva, 2007). Table 3 clearly shows that p-values of Sargan's test for overidentified restrictions, GMM instruments and IV instruments are large as required. The Allerano–Bond tests for autocorrelation and has the null hypothesis of 'no autocorrelation' and is applied to differenced residuals. The AR(1) process in the first differences usually rejects the null hypothesis, but the important one is the AR(2) which will detect autocorrelation in the levels of the data (Mileva, 2007). Table 3 clearly shows that AR(2) test cannot reject the null of 'no autocorrelation'. We further checked for robustness by estimating the GMM model with collapsed instruments which sharply reduces the number of instruments but reduces statistical efficiency in large sample (Roodman, 2009). Both Sargan's test and AR(2) test failed to reject the null hypotheses as required (see last two columns at the lower panel of Table 3). Therefore, taking results of all these tests altogether, we can consider that the specified model is valid and robust.

Next we present validity tests the variable choices in the model. First, the F-statistic which tests the null that 'the coefficients on the prices, climate change, agroecology and socio-economic factors are jointly zero' is strongly rejected at 1% level of significance, thereby justifying inclusion of these wide range of variables to explain change in ALUD which also holds for the collapsed instrument GMM model (Table 3). Furthermore, hypothesis tests of each group of variables as jointly zero are also strongly rejected (Table 4). We also conducted pairwise t-test for the equality of the coefficients on the 11 agroecology variables, in order to check whether we can aggregate them further. The null of ‘equality of coefficients’ was strongly rejected for 48 out of the total 55 possible pairs, implying that the impact of these AEZs on ALUD are significantly different.

Since the study uses a long panel data of 61 years, we computed both the short-run and long-run elasticities[2] of ALUD with respect to the regressors (see last two columns of Table 3). It is clear from Table 3 that the values of the long-run elasticities are substantially larger than the short-run elasticities as expected. Among the crop prices, increase in the relative price of vegetables will significantly increase ALUD with long-run elasticity value of 0.51. This is expected as revenue earned from vegetables is significantly higher than producing cereals (Rahman, 2009). This may explain the observed increase in the area allocated to various vegetables in GCA over time with corresponding rise in the revenue earned from exporting vegetables from Bangladesh in recent years (Rahman, 2010). Similarly, increase in the relative price of jute will significantly increase ALUD (long-run elasticity value of 0.54). With the rise in awareness against plastic use, demand for jute is on the rise in the international market. Bangladesh contributes nearly 39% of total raw jute supply cultivated in 39% of total jute area of the world with an average maximum yield of 1.53 mt ha^{-1} during the 1961–2002 (Gupta et al., 2009). Therefore, large positive response of jute price on ALUD is an effect in the right

[2] The long-run effect in a GMM Dynamic Panel Data framework can be defined as: $\beta\hat{}/(1-\rho)$, where $\beta\hat{}$ is the coefficient on X_{rt-1} and ρ is the coefficient on the lagged-dependent variable S_{rt-1} (Holmlund and Soderstrom, 2007) . After some manipulation, the long-run elasticity can be written as $(\beta\hat{}/(1-\rho))*(X_{rt-1}/S_{rt-1})$.

direction. Negative influence of onion, lentil and sugarcane price on ALUD is contrary to expectation. Area under sugarcane recorded significant decline at variable rates in most regions of Bangladesh over time and also processing facilities of sugarcane is concentrated in few areas of Bangladesh. However, negative influence of a rise in lentil price on ALUD is a source of concern. This is because pulses are leguminous crops and improve soil quality by fixing nitrogen. But yield levels of pulses in Bangladesh are very low and hence fail to compete with other non-cereals, even with price rises perhaps.

Among the input prices, we see that a rise in the prices of urea and potassium fertilizers significantly reduce ALUD with long-run elasticity values of –0.56 and –0.71, respectively. The implication is that if urea and potassium prices increase over time, then the farmers will switch away from non-cereal crops and concentrate on producing cereals because non-cereal crops are fertilizer intensive. On the other hand, a rise in the price of phosphate fertilizer will increase ALUD with a very high long-run elasticity value of 1.13. The influence of agricultural labour wage has no effect on ALUD.

The influence of the socio-economic factors in determining ALUD is not very strong. We see that only R&D investment per farm significantly increase ALUD (long-run elasticity value 0.14) whereas extension expenditure per farm reduces it although the effect is very small in the short-run (elasticity value –0.008). The significantly positive impact of R&D investment on ALUD reinforces the notion to continue investment in research in order to promote growth in agriculture. Rahman and Salim (2013) also reported significant influence of R&D investment on agricultural productivity growth in Bangladesh. However, the negative impact of extension expenditure on ALUD is puzzling. It may be argued that since the thrust of extension activities in

Bangladesh was to promote widespread diffusion of a rice-based Green Revolution technology implying cereal monoculture, this may have worked against improving ALUD.

Coming to our variables of interest, i.e., climate change and agroecology, we see that the total rainfall significantly increases ALUD (long-run elasticity value 0.38). High rainfall over time enables farmers to diversify their cropping portfolio requiring varying levels of water. Temperature variability has a negative influence on ALUD but is not significant. Agroecology has significant and varied influences on ALUD. For example, ALUD is significantly higher in HGRF and LGRF whereas it is significantly lower in GTF, MMRF, LMREF and CCPSI. Both HGRF and LGRF have a good mix of HL, MHL and MLL and also average farm sizes are higher as compared to MMRF, MMREF and CCPSI. Quddus (2009) reported that HGRF and LGRF have a mixture of silt loam and silt-clay loam soils (most suited for agriculture) and MMRF, MMREF and CCPSI have a mixture grey, grey silt loam and silt clay loam soils. Also, the ratio of agricultural workers to population increased by 11.2% and 15.8% in HGRF and LMRF between 1980–2005 as compared to only 6.5%, 3.5% and 1.6% in MMRF, MMREF and CCPSI, respectively (Quddus, 2009). In summary, agroecology significantly influences ALUD which was previously ignored in the literature.

4. Conclusions and policy implications

The aim of this study is to examine the impacts of climate change, agroecology and socio-economic factors on ALUD in regions of Bangladesh regions covering a 61 year period (1948–2008). Results revealed that ALUD has actually increased @ 0.19% per year overall, the total rainfall grew @ 0.02% and variability in temperature declined @ 0.06% per year with significant differences across AEZs. ALUD has increased in seven AEZs and declined in five AEZs where important limitations exist in terms of natural and socio-economic constraints.

A host of climate change, agroecology and socio-economic factors significantly influence ALUD in the long run. Among the climatic factors, total rainfall significantly increases ALUD. Agroecological characteristics exert significant but variable influences on ALUD. ALUD is significantly higher in Ganges River Floodplains but significantly lower in Meghna River Floodplains and Chittagong Coastal Plain. Among the socio-economic factors, an increase in the relative prices of vegetables and jute significantly increase ALUD. In other words, a rise in relative prices of these crops will shift farmers to diversify their cropping portfolio to cash crops. R&D investment significantly increases ALUD as expected.

A number of policy implications can be drawn from the findings of this study. The government should increase investment in R&D as this policy amenable instrument will significantly increase ALUD. First, the focus of research effort should be geared towards two main areas: (a) development of crop varieties of cereals and non-cereals that are responsive to high rainfall; and (b) developing a range of crops suited to specific AEZs. Second, modification of the message and the thrust of agricultural extension services from promoting rice monoculture to crop diversification in order to circumvent its existing negative influence on ALUD. Third, price policies aimed at increasing vegetable and jute prices in order to increase ALUD which in turn will increase foreign exchange earnings for the economy from export. Ali (2004) also highlighted that investment in research and extension system and policy incentives geared towards high value crops (e.g., vegetables) not only make them internationally competitive, but will also improve earnings and productivity of the sector which was also echoed by Joshi et al (2006). And fourth, price policies aimed at stabilising/reducing fertilizer prices. Bangladesh has undertaken market reforms to liberalise input markets, particularly fertilizers, since the 1990s (Alam et al., 2014) but is now reverting back to fertilizer subsidies to boost growth in the agricultural sector. Our results show that price policies to stabilise/reduce fertilizer prices (particularly widely used urea fertilizer) is essential to promote ALUD. While realizing all these policy options poses formidable challenges, targeted investments in these areas will significantly increase ALUD in Bangladesh which is a desirable goal.

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Table 1. Definition, measurement, descriptive statistics and expected signs of the variables used in the model

Variables	Definition	Unit	Mean	Stdev	Expected sign
Shannon index		Number	0.75	0.35	
Crop prices	National constant prices at 1984/85 level				
Paddy	Weighted average price of all varieties of rice	BDT/mt	4906.67	1289.57	+
Vegetables	Weighted average price of all major types of vegetables	BDT/mt	2796.39	596.85	+
Garlic	Garlic price	BDT/mt	9210.91	3464.29	+
Onion	Onion price	BDT/mt	4270.45	1521.14	+
Jute	Jute price	BDT/mt	7282.55	3219.37	+
Lentil	Lentil price	BDT/mt	8115.03	3369.13	+
Rapeseed	Rapeseed price	BDT/mt	10273.33	2300.07	+
Sugar	Sugarcane price	BDT/mt	796.63	356.13	+
Input prices	International constant prices at1984/85 level				
Urea fertilizer	Urea fertilizer price	BDT/mt	6393.30	1980.55	±
TSP fertilizer	Triple Super Phosphate price	BDT/mt	5691.53	2001.89	±
MP fertilizer	Muriate of Potash price	BDT/mt	3799.97	1483.18	±
Labour wage	Daily wage of agricultural labour at 1984/85 prices	BDT/manday	28.20	7.25	–
Socio-economic factors					
Literacy rate	Proportion of literate population aged 7+ years	%	29.75	12.15	±
Average farm size	Average farm size per farming households	ha	2.29	0.92	+
Labour stock per farm	Average number of rural labour force per farm	persons	3.11	2.13	+
Animal power per farm	Average number of cattle per farm	number	2.53	1.24	+
R&D investment per farm	R&D investment at constant 1985/85 prices	BDT/farm	9.48	14.55	+
Extension expenditure per farm	Average extension expenditure per farm	BDT/farm	2.74	5.82	+
Share of irrigated area	Proportion of irrigated area in Gross Cropped Area	%	0.14	0.13	±
Climate and environment					
Temperature variability	Difference between mean max and min annual temperature	^{0}C	9.53	0.96	±

Variables	Definition	Unit	Mean	Stdev	Expected sign
Total rainfall	Total annual rainfall	mm	2189.49	807.42	+
Flood proneness	Proportion of total flooded area in each region	%	0.009	0.009	–
Agroecology					
HPTF	Old Himalayan Piedmont Plain and Tista Floodplain	Dummy	0.12	--	±
KFAB	Karatoya Floodplain and Atrai Basin	Dummy	0.12	--	±
BJF	Brahmaputra- Jamuna Floodplain	Dummy	0.06	--	±
HGRF	High Ganges River Floodplain	Dummy	0.18	--	±
LGRF	Low Ganges River Floodplain	Dummy	0.06	--	±
GTF	Ganges Tidal Floodplain	Dummy	0.12	--	±
SBSKF	Sylhet Basin and Surma-Kushiyara Floodplain	Dummy	0.06	--	±
MMRF	Middle Meghna River Floodplain	Dummy	0.06	--	±
LMREF	Lower Meghna River and Estuarine Floodplain	Dummy	0.06	--	±
CCPSI	Chittagong Coastal Plain & St. Martin's Coral Island	Dummy	0.06	--	±
DHAKA	Greater Dhaka	Dummy	0.06	--	±
EH	Eastern Hills	Dummy	0.06	--	±

Table 2. Selected indicators of agricultural land use diversity, climate and socio-economic factors by agroecological zones of Bangladesh (1948-2008).

Agroecological zones	Shannon index 1948	Shannon index 2008	THI 1948	THI 2008	Average annual change Shannon (%)	Mean Shannon index	Mean total rainfall (mm)	Mean temperature variability (^{0}C)	Average farm size (ha)	Literacy rate (%)	R&D per farm (BDT)	Extension per farm (BDT)	Irrigation share (%)
HPTF	0.81	0.88	0.37	0.40	0.129	0.83	2063.66	10.27	2.85	27.05	6.93	2.01	0.12
KFAB	0.72	0.82	0.31	0.36	0.204	0.79	1621.13	10.15	2.61	27.55	7.82	2.26	0.20
BJF	0.79	0.58	0.37	0.22	-0.621	0.74	2125.02	9.31	2.15	23.55	3.63	0.96	0.18
HGRF	0.86	1.18	0.40	0.51	0.444	1.08	1792.90	9.94	2.70	25.87	10.48	2.94	0.16
LGRF	0.76	1.43	0.35	0.66	0.765	1.05	1872.97	9.17	2.02	25.64	8.20	2.58	0.08
GTF	0.41	0.34	0.16	0.12	-0.319	0.40	1890.90	9.23	2.20	37.70	7.96	2.35	0.06
SBSKF	0.22	0.11	0.08	0.03	-1.606	0.20	3813.80	9.70	2.57	29.28	7.59	2.40	0.21
MMRF	0.58	0.60	0.27	0.24	0.063	0.71	2275.41	9.30	1.32	30.71	4.61	1.42	0.15
LMREF	0.47	0.24	0.19	0.09	-1.532	0.35	2999.80	8.40	1.48	33.19	7.77	2.34	0.08
CCPSI	0.21	0.24	0.07	0.08	0.209	0.23	2849.80	8.61	1.45	37.19	8.68	2.61	0.01
EH	1.14	1.02	0.45	0.38	-0.199	1.17	2572.05	9.18	2.66	23.01	34.34	8.93	0.06
DHAKA	0.96	1.05	0.43	0.44	0.143	0.99	2182.30	9.19	1.81	41.00	9.49	3.24	0.17
Bangladesh	0.68	0.76	0.30	0.32	0.193	0.75	2189.49	9.53	2.29	29.75	9.48	2.74	0.14
Test for differences across agroecological zones (Generalized linear model with one way ANOVA)													
$F_{(11, 1025)}$	--	--	--	--	--	379.19***	86.09***	46.73***	38.6***	22.73***	22.98***	8.04***	14.08***

Note: *** = significant at 1% level (p<0.01)

Table 3. Determinants of agricultural land use diversity in Bangladesh (1948-2008).

Variables	Dynamic GMM estimator for panel data			
	Coefficients	t-value	Short-run elasticity	Long-run elasticity
Constant	0.1340**	2.08	--	--
Lagged Shannon index (t-1 year)	0.8246***	29.93	--	--
Crop prices (normalised by paddy price)				
Vegetables	0.0801***	2.89	0.066	0.506
Garlic	0.0040	0.90	0.011	0.086
Onion	-0.0282***	-2.45	-0.038	-0.285
Jute	0.0342***	5.85	0.067	0.535
Lentil	-0.0139*	-1.91	-0.036	-0.270
Rapeseed	-0.0009	-0.10	-0.003	-0.019
Sugar	-0.1655**	-2.26	-0.035	-0.284
Input prices				
Urea fertilizer	-0.0082***	-2.53	-0.069	-0.559
TSP fertilizer	0.0188***	2.52	0.143	1.134
MP fertilizer	-0.0176*	-1.73	-0.089	-0.708
Labour wage	-0.0001	-0.24	-0.005	-0.036
Socio-economic factors				
Literacy rate	0.0011	1.49	0.042	0.344
Average farm size	0.0018	0.28	0.005	0.041
Labour stock per farm	0.0044	1.27	0.018	0.138
Animal power per farm	-0.0062	-1.02	-0.021	-0.160
R&D investment per farm	0.0018***	3.93	0.023	0.143
Extension expenditure per farm	-0.0022**	-2.44	-0.008	-0.052
Share of irrigated area in Gross Cropped Area	0.0108	0.26	0.002	0.016
Climate and environment				
Temperature variability	-0.0054	-1.24	-0.069	-0.538
Total rainfall	0.0014**	2.35	0.042	0.377
Flood proneness	-0.2930	-0.86	-0.004	-0.031
Agroecology				
Old Himalayan Piedmont Plain and Tista Floodplain (HPTF)	-0.0042	-0.22	-0.001	-0.003
Karatoya Floodplain and Atrai Basin (KFAB)	-0.0098	-0.51	-0.001	-0.009
Brahmaputra- Jamuna Floodplain (BJF)	-0.0273	-1.29	-0.002	-0.012
High Ganges River Floodplain (HGRF)	0.0398**	2.42	0.009	0.039
Low Ganges River Floodplain (LGRF)	0.0353*	1.94	0.003	0.012
Ganges Tidal Floodplain (GTF)	-0.0988***	-3.95	-0.016	-0.177
Sylhet Basin and Surma-Kushiyara Floodplain (SBSKF)	-0.1526***	-4.79	-0.012	-0.260

Variables	Dynamic GMM estimator for panel data			
	Coefficients	**t-value**	**Short-run elasticity**	**Long-run elasticity**
Middle Meghna River Floodplain (MMRF)	-0.0425**	-1.95	-0.003	-0.021
Lower Meghna River and Estuarine Floodplain (LMREF)	-0.1303***	-4.82	-0.010	-0.132
Chittagong Coastal Plain & St. Martin's Coral Island (CCPSI)	-0.1459***	-4.87	-0.011	-0.225
Greater Dhaka (DHAKA)	-0.0056	-0.25	-0.001	-0.002
Model diagnostics		**p-value**		**p-value**
$F_{(33, 986)}$	579.79***	0.000	256.4***	0.000
Sargan's test for overidentified restrictions ($\chi^2_{500\ df}$)	501.62^{NS}	0.471	1.41^{NS} ($\chi^2_{6\ df}$)	0.376
Arellano-Bond test for AR(1) in first differences (z-statistic)	-6.59***	0.000	--	--
Arellano-Bond test for AR(2) in first differences (z-statistic)	0.87^{NS}	0.382	0.89^{NS}	0.376
Difference-in-Sargan's tests of exogeneity of instrument subsets:				
GMM instruments for levels (null: H = exogenous) ($\chi^2_{222\ df}$)	188.23^{NS}	0.952	--	--
IV instruments (null: H = exogenous) ($\chi^2_{16\ df}$)	23.42^{NS}	0.110	--	--
Number of instruments	534		40	
Number of observations	1020		1020	

Note: Instruments for first differences equation:
Standard D. (literacy labourfarm animfarm irrigshare floodshare hptf kfab bjf hgrf lgrf gtf sbskf mmrf lmref ccpsi dhakaeco);
GMM-type (Lag order 2 2, i.e., second order of the endogenous variables to be used as instruments (nvege ngarlic nonion njute nlentil nrapeseed nsugar urea1 tsp1 mp1 wage temprange rainfall1 rdevfarm extfarm farmsize))
*** = significant at 1% level (p<0.01)
** = significant at 5% level (p<0.05)
* = significant at 10% level (p<0.10)

Table 4. Test of hypotheses

Model specification tests	F-statistic	Decision
No influence of crop prices on ALUD H_O: Coefficients on the crop prices are jointly zero ($F_{7, 986\ df}$)	6.75***	H_O rejected (Crop prices significantly influence ALUD)
No influence of input prices on ALUD H_O: Coefficients on the input prices are jointly zero ($F_{4, 986\ df}$)	2.54**	H_O rejected (Input prices significantly influence ALUD)
No influence of climate on ALUD H_O: Coefficients on the rainfall and temperature variables are jointly zero ($F_{2, 986\ df}$)	5.29***	H_O rejected (Climate has significant influence on ALUD)
No influence of agroecology on ALUD H_O: Coefficients on the agroecology variables are jointly zero ($F_{11, 986\ df}$)	4.79***	H_O rejected (Agroecological characteristics have significant influence on ALUD)
No influence of socio-economic factors on ALUD H_O: Coefficients on the socio-economic factors are jointly zero ($F_{7, 986\ df}$)	3.31***	H_O rejected (Socio-economic factors have significant influence on ALUD)
Pairwise t-tests of the equality of the coefficients on the agroecology variables H_O: $g_{ri} = g_{rj}$ for all $i \neq j$		H_O rejected (48 pairs of coefficients are significantly different from each other at 10% level of significance at least out of a total of 55 possible combinations)

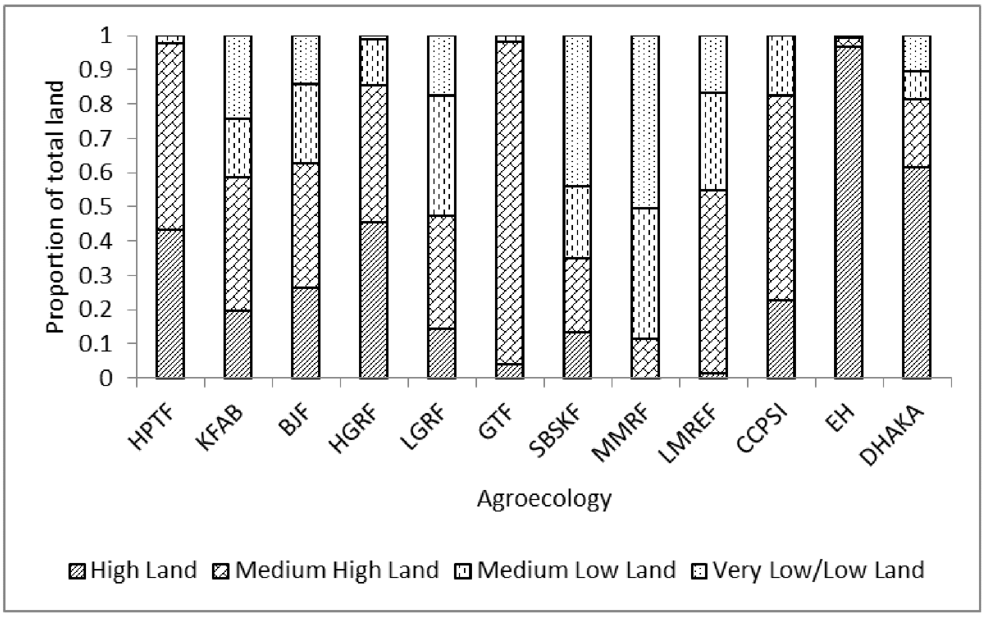

Figure 1. Land elevation types by agroecological zones in Bangladesh.

Appendix A: Definition and construction of variables used in the model

The various variables are defined and constructed as follows:

Variable name	Definition and construction details
Shannon index	To compute the Shannon Index of ALUD, area (in thousand hectares) under major nine crop groups is used. These are: (1) all seasons and varieties of rice (Aus, Aman, and Boro – the pre-monsoon, monsoon and dry winter seasons), (2) wheat (includes maize, barley, cheena, and other minor cereals), (3) jute, (4) sugarcane, (5) tubers (includes potatoes and sweet potatoes), (6) pulses (includes gram, mung, mashkalai, lentil, and khesari), (7) oilseeds (includes mustard and rapeseed), (8) vegetables (includes potatoes, arum, bean, cabbage, cauliflower, cucumber, jhinga, bitter gourd, brinjal, okra, patal, puisak, pumpkin, radish and water gourd), and (9) spices (chilli, garlic, ginger, onion and other minor spices) for each of the 17 regions (greater districts) for the period 1948-2008. The sum total of these areas provides the measure of Gross Cropped Area (GCA).
Labour stock per farm	Agricultural population (in thousands) for each region is used. Usable information on agricultural population appeared in agricultural censuses 1960, 1983/84, 1996 and 2008. Also, agricultural population by region was available for 1951 Population Census of East Pakistan. Although definitions of 'agricultural population' across periods may likely to vary but nevertheless this is a far closer measure of labour (both male and female) engaged in the sector rather than arbitrarily allocating all rural male population as labour input as done by previous studies. The data for the inter-census years were constructed using a standard linear trend extrapolation model. The series was then divided by number of farms available from census information which was constructed following the same procedure as above to create the time-series.
Animal power per farm	Number of draft animals (i.e., cattle and buffaloes) is estimated using linear trend extrapolation from actual counts available in the agricultural censuses of 1960, 1983/84, 1996 and 2008. The count for 1949 is taken from Ahmad (1958). The data for the inter-census years were constructed using a standard linear trend extrapolation model. The series was then divided by the number of farms derived above.
Crop output prices	Prices of major crop groups (defined above) were used. In order to avoid any potential endogeneity issues, use of national level price is preferred because in this case, prices faced by individual farmers or at the regional level are exogenous, as they are essentially price takers in the market. We have used prices of single or two dominant crops belonging to each major crop group, as prices of all individual crops covering such a long period of time were simply not available in any form. Specifically producer prices of paddy (representing cereals), garlic and onion (representing spices), jute and sugarcane (representing cash crop), lentil (representing pulses), rapeseed (representing oilseeds), and vegetables (representing vegetables constructed as an average price of green beans, cabbages, cauliflowers, broccoli, cucumbers, pumpkins, gourds, spinach and tomatoes) were utilized. Construction of price series proved quite difficult. FAOSTAT reports producer prices of a range of crops for Bangladesh in current prices from

Variable name	Definition and construction details
	1966 onward, which was readily used. Prices of crops prior to 1966 were unavailable in any proper form. Tripathi and Prasad (2009) used a database of value of agricultural outputs (66 individual crops) in current and constant 1999/2000 prices for India for the period 1951–2000. Dividing the value of output of current price series with constant price series, therefore, provided the deflator series. Then multiplying the harvest price of crops for West Bengal, India for the year 1999/2000 with the deflator series provided current prices of the selected crops in Indian Rupees for the period 1951-1965 (the 1951 prices are repeated for 1948, 1949 and 1950 in absence of any additional information). These prices are then converted to equivalent Bangladeshi taka using appropriate exchange rate. All price variables, thus constructed, are then converted into constant 1984/85 prices. All crop output prices were normalized by the paddy price. Hence, these are relative prices of other outputs. The reason for doing this is two-fold. First, it is assumed that the shift in the relative prices of other crops will induce farmers to diversify their crop portfolio from rice monoculture. Second, since the ratio is unit free, we have avoided collinearity that may arise from specifying close substitutes of crops (e.g., garlic and onion).
Fertilizer prices	Price of three major fertilizers, namely, Urea, Triple Super Phosphate (TSP) and Muriate of Potash (MP) were used. USDA-ERS (United States Department of Agriculture, Economic Research Service) reports current prices of Urea, Triple Super Phosphate and Muriate of Potash in US dollars from 1960 onward. These prices were converted to Bangladeshi taka using exchange rate and the 1960 prices were repeated for the period 1948-1959 in absence of any other information. International prices for fertilizer were used because fertilizer price in Bangladesh is highly distorted due to various subsidies applied by the government from time to time. All fertilizer prices, thus constructed, are then converted into constant 1984/85 prices.
Labour wage	Agricultural labour wage information was taken from Barker et al., (1985) and Statistical Yearbook of Bangladesh (various issues). The current prices are then converted into constant 1984/85 prices.
Irrigation	Proportion of GCA under irrigation. The total area (in acres or hectares) under irrigation always appears in various Yearbooks of Statistics of Bangladesh and is easy to compute.
Average farm size	Average farm size (ha per farm) is taken from Census of Pakistan 1951 and agricultural censuses of 1960, 1983/84, 1996 and 2008. The data for the inter-census years were constructed using a standard linear trend extrapolation model.
Average literacy rate	Average literacy rate of population aged 7 years and above is taken from Census of Pakistan 1951 and 1961 and Bangladesh Population censuses of 1974, 1981, 1991, 2001 and 2011. The data for the inter-census years were constructed using a standard linear trend extrapolation model.
R&D expenditure per farm	Research and Development (R&D) expenditure data is converted to a series involving a time-lag in order to take account of the time required for the technology generated by the research system to reach the farmers for adoption. In order to take the lag into account, the weighted sum of research expenditures over a period of 14 years is used. The research variable is

Variable name	Definition and construction details
	constructed as $\Sigma W_{t-i} R_{t-i}$, where W_i is a weight and R_{t-i} is research investment in year t-i measured at constant 1984-85 prices. The weight for the current year research expenditure is zero, for a one year lag the weight is 0.2, while for a 2 year lag it is 0.4, and so on (for details, see Dey and Evenson, 1991). The series was then divided by the number of farms.
Extension Expenditure per farm	Total extension expenditure incurred by the MoA and/or the Department of Agricultural Extension (in million taka) at constant 1984/85 prices is used. Data prior to 1972 were collected from Pakistan Planning Commission reports and few missing years were interpolated using a standard linear trend extrapolation model. The series was then divided by the number of farms.
Total annual rainfall	Total rainfall measured in mm for each region per month from a list of rainfall recording stations is available from 1948 onward (from Bangladesh Meteorological Department). The regional allocation of this rainfall information is made depending on the location of the rainfall station.
Temperature variability	Monthly maximum and minimum temperature is also available for each region from 1948 onward (from Bangladesh Meteorological Department). We then compute the difference between maximum and minimum average annual temperature each year for each region as a measure of temperature variability.
Flooded area	Data on the extent of area flooded in sq km and as percent of total Bangladesh area is available from 1954 onward. In absence of any further breakdown of this information, we have divided the total percentage of area flooded in Bangladesh evenly into 16 regions (excluding Chittagong Hill Tract). This will leave the total percent of area flooded in the country unchanged for the year it was reported, although dividing this measure evenly across region is rather simplistic. Nevertheless, this will allow us to examine the influence of an important climate variable on ALUD.
Agroecology	Bangladesh consists of 30 agroecological zones (AEZ) constructed by FAO in 1988 which overlaps amongst administrative boundaries, thereby, making regional classification very difficult. However, Quddus (2009) conducted an exercise by combining two or three AEZs together so that the new classification commensurate with district administrative boundaries. The result was 12 AEZs derived from original 30 AEZs that can be distributed into 64 new districts and are mutually exclusive (for details, see Table 1 in Quddus, 2009). We have created a set of 12 dummy variables representing these new12 AEZs and allocated them to 17 regions as appropriate.