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Agricultural Diversity and Sustainability: General Features and Bangladeshi Illustrations

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Abstract: Many scientists have expressed concern that declining agricultural diversity threatens agricultural sustainability. We draw on the available literature to outline and examine mechanisms that reduce agricultural diversity and identify the at-risk attributes of agricultural sustainability. Using a three-pillar concept embodying ecological, social and economic dimensions, this article provides a comprehensive general assessment of the sustainability of agricultural systems. It pays particular attention to consequences for agricultural diversity and sustainability of the increasing dependence of agriculture on the market system and new agricultural technologies. As an illustrative example, it examines changes in the diversity and sustainability of Bangladeshi agriculture by applying a novel index of the diversity of cropping land use, an output decomposition method, and statistical techniques. Crop diversity in Bangladesh is very low and dominated by the cultivation of rice, which now depends very heavily on a limited number of high yielding varieties (HYVs). Higher rice yields in Bangladesh and seasonal changes in rice cultivation have resulted in land sparing, which make room for greater crop diversity. Nevertheless, Bangladesh's food dependence on its rice output is very high and is critically dependent on groundwater irrigation. We recommend that Bangladesh consider increasing the diversity of its crops as a food security measure and as a hedge against a decline in its agricultural sustainability.

Keywords: agricultural diversity; agricultural sustainability; Bangladesh; crop diversification index; decomposition of sources of agricultural growth; food security; rice biodiversity; three-pillar sustainability concept

1. Introduction

Ever since the beginning of the Agricultural Revolution, about 10,000 years ago, most societies that have adopted agriculture to support their existence and economic growth and have had to struggle to sustain and increase their agricultural production. Several ancient agricultural societies collapsed because they were unable to sustain their agricultural production. Sometimes this was because their agricultural practices resulted in the ecological unsustainability of their agriculture (see for example [1,2]). Tisdell has hypothesized that following the Agricultural Revolution, agricultural diversity tended to increase at all geographical levels during a very long time period but that more recently, it has declined [3,4]. However, at the same time, new agricultural genetic resources and new agroecosystems continue to be developed [5], (Section 10.2). New genetic resources and new agroecosystems play a major role in the loss of pre-existing genetic resources and agricultural systems and create new challenges for the sustainability of agriculture. These challenges have been reviewed recently in Lemaire et al. [6]. The purpose of this article is to explore these trends and related challenges.

After outlining materials and methods used in this research this article briefly discusses the scope and measurement of the concept of agricultural diversity and then considers the consequences for agricultural diversity and sustainability of the increasing reliance of agriculture on off-farm inputs for its production. The three-pillar concept of sustainability is introduced to integrate the discussion and is related to agricultural diversity and sustainability issues. Particular attention is paid to the consequences for agricultural diversity and sustainability of the increasing dependence of agriculture on the market system and on new agricultural technologies. This general overview and analysis provides a useful backdrop for examining changes, which are occurring in the diversity and sustainability of Bangladeshi agriculture. This is the focus of the latter part of this article.

2. Materials and Methods

The first part of this article (Sections 2–6) draws on the available literature to specify the multidimensional nature of agricultural diversity and agricultural sustainability. Again, drawing on the available literature (see for example, References [7,8] for detailed overviews of this literature), it outlines and suggests mechanisms that have resulted in reduced agricultural diversity in modern times and considers the consequences of this loss of diversity for agricultural sustainability. The second part (Sections 7–10) utilizes secondary statistics to identify the extent of national crop diversity in Bangladesh to specify its trends by applying a novel index of crop diversity.

Rice dominates crop production in Bangladesh. Official data are used to determine trends in rice yields in Bangladesh and to account for seasonal changes in the cultivation of rice in Bangladesh. It explores the implications of these factors for land sparing and crop diversification. In addition, taking into account trends in Bangladesh's rice yields, and ecological and environmental constraints on its rice production (including data on its high-level of dependence on two HYVs and the presence of its narrow genetic resource base), we consider whether Bangladesh's high dependence on rice is sustainable. Indications are that it should try to increase its crop diversity as a hedge against the possibility of its high dependence on rice production becoming unsustainable.

3. The Scope and Measurement of the Concept of Agricultural Diversity

It has been claimed that no single measure of biodiversity is able to capture all of the many dimensions of biodiversity [9,10]. This is because biodiversity encompasses a diversity of diversities. The same is true of agricultural diversity. It involves a multitude of different diversities in different dimensions. These dimensions include.

- The extent of agricultural diversity at different geographical scales, e.g., on-farms, locally, regionally and nationally, as well as globally;
- The diversity of different types (species) of crops and categories of livestock;
- The extent of genetic diversity within each species of crop and within each species of livestock, that is the extent of variety of each type of crop and livestock breed; and
- The degree of variation in the types of agroecosystems used.

Of interest is not only the extent of agricultural diversity at any single point of time, but also how much agricultural diversity is exhibited during longer periods, for example, the extent to which crop rotation is practised and whether or not catch cropping—a fast-growing crop grown between successive plantings of a main crop—is adopted.

Another aspect of interest at the farm level is the prevalence of monocultures or polycultures. The latter, for example, may involve inter-cropping. The variety of crops grown on individual farms and the variety of domesticated animals kept is also relevant. Another important dimension of diversity at the farm level is the extent to which integrated on-farm agroecosystems are adopted. Such systems integrate cropping, the keeping of livestock and aquaculture. 'Wastes' from each of these activities are recycled for utilization in on-farm biological production, e.g., crop residues and animal wastes may be composted and used for fertilizing crops. Integrated agricultural systems are usually associated with greater on-farm agricultural diversity and are believed to enhance the sustainability of the level of on-farm agricultural production.

4. Increasing Reliance of Agriculture on Off-Farm Inputs and Its Consequences

Modern agroecosystems are more reliant on off-farm inputs for their output than are traditional farming systems. Consequently, the sustainability of agricultural production using modern agricultural systems depends more heavily on the continuing availability of off-farm inputs (such as artificial fertilizers, pesticides, improved varieties of seeds, water for irrigation, energy supplies, e.g., electricity and fuel, and so on) than do traditional systems. The availability of these inputs reduces the motivation of farmers to conserve and recycle on-farm resources in order to maintain agricultural production. Consequently, the incidence of integrated farming and crop rotation tends to decline.

4.1. Increasing Dependence of Agriculture for Its Sustainability on Off-Farm Resources

As a result of the adoption of contemporary agricultural practices, examination of the sustainability of agricultural production requires that increasing attention be paid to the sustainability of the supplies of external material resources used in agriculture, the implications of their continuing on-farm use for the maintenance of this production, e.g., the implications of this for soil fertility, for pest resistance to pesticides, and for changes in pest populations. It is also pertinent to note that agriculture's sustainability is increasingly subject to the effects of other external forces as economic growth occurs, for example, the consequences of climate change.

4.2. Increased Availability of Off-Farm Resources Tends to Reduce Agricultural Diversity

The increased availability and use of material inputs external to farms tends to reduce agricultural diversity. This is because they can be utilized to reduce the heterogeneity of the natural resource base of farms in different locations. Greater decoupling from the local environment occurs [4]. As a result, crops (and breeds of livestock) do not have to be as varied as otherwise to prosper in areas having different natural environmental conditions [4]. Consequently, agricultural genetic diversity declines, and this reduction becomes profitable. Furthermore, greater conformity in the adoption of agricultural practices (agroecosystems) can be expected.

5. The Three-Pillar Concept of Sustainability and Its Application to Diversity and Sustainability in Agriculture

5.1. Different Aspects of Agricultural Sustainability

Agricultural sustainability can be examined from several points of view. The three-pillar concept [11,12] focuses on the following sustainability aspects:

- Ecological sustainability;
- Social sustainability; and
- Economic sustainability.

These aspects can be considered from a normative or from a positivist point of view. The following normative questions are important:

- Should agricultural development be such that each of these goals are satisfied?
- What if it is impossible to achieve these goals simultaneously?
- If this is the case, what trade-offs should be made?
- To what extent is it ever acceptable to forgo any of these goals?

Apart from these normative questions, several positivist aspects of agricultural sustainability can be explored. These aspects are the focus of this article rather than normative questions. These positivist aspects include the extent to which the three pillars of sustainability listed above are interdependent.

In addition, one can examine the extent to which each of the above pillars of agricultural sustainability are capable of being met or whether trade-offs are required. For example, in order to achieve social and economic sustainability, it may be necessary to forgo some existing ecological diversity.

This raises the question of whether the changed regime of ecological diversity is sustainable and to what extent this is so. This should be investigated taking into account the possibility of systems having multiple stable equilibria, each of which exhibits different degrees of resilience. However, it should also be borne in mind that agricultural sustainability does not depend only on the nature of ecological diversity, but also on prevailing economic and social conditions in agriculture. This is made clear in Section 6. It is contended that assessments of agricultural diversity simultaneously govern all of the three pillars of sustainability to be examined.

5.2. The Treadmill of Agricultural Scientific and Technological Advances

Furthermore, it is important to consider how the economic sustainability of modern agriculture is being maintained. It is clear that it depends heavily on continuing scientific and technological advances, which help to increase and sustain agricultural yields, but most of the advances do so for only a limited period of time. For example, new plant varieties that are initially very successful in boosting agricultural yields often become victims of disease and pests, which multiply rapidly when the new varieties are widely adopted. Consequently, they become wasting assets and scientific breakthroughs are needed to find suitable replacements for them. Therefore, the sustainability of agricultural production becomes a 'treadmill' operation [13,14]. No one knows how successful scientists will be in maintaining the continuing cycle of genetic agricultural renewal. If they are unable to successfully sustain this cycle, the chances of agricultural collapse are high.

5.3. Reduced Agricultural Diversity in Production and Sustainability Problems

It might also be observed that the more widely a new crop variety is adopted, the greater are the chances of some diseases or pests increasing in incidence or evolving to attack it. This type of problem is discussed by Tisdell [4], Ch. 9. Therefore, the more widely a particular variety of a crop is adopted, the shorter is likely to be the length of its economic life. It may also be true of individual species of crops and domesticated animals that are more prone to epidemics and plagues, when their density and their aggregate populations increase.

Moreover, the way in which plants are cultivated and livestock are managed influences their susceptibility to diseases and pest infestations. For example, if new varieties of cereals are able to be planted at greater density to increase their yields (as a result of the increased use of chemical fertilizers, irrigated water and the genetic qualities present in these new varieties) these cereals are likely to be more susceptible to fungal attacks, especially when monoculture is practised. Transmission of animal diseases (by contagion) is likely to be easier, other things being equal, when the density and homogeneity of domesticated animals increases. These factors all influence the sustainability of agricultural production.

6. The Development of Markets as Well as Technologies and Their Impacts on Agricultural Diversity and Sustainability

The development of the market system has influenced the diversity of agriculture [4] and has presented farmers with new challenges for sustaining their incomes.

Market development:

- Fosters greater specialization in agricultural production and less diversity in this production [7];
- Results in the increased adoption and development of agricultural technologies, the application of which is specific to particular crops and the specific purposes for which livestock are used; and
- Changes the economic environment in ways that 'force' farmers to reduce the diversity of their farming operations in order to meet market competition or prosper economically.

As a result, the attainment of the three pillars (goals) of agricultural sustainability are less likely to be achieved or can only be achieved by increasing the level of human intervention in the development of agroecosystems. We consider each of these matters in turn.

6.1. Market Development and Reduced Agricultural Diversity

The extension of markets and a reduction in barriers to the involvement of farmers in making market transactions contribute to a reduction in agricultural diversity at all geographical scales. Two main mechanisms operate simultaneously to bring this about. These are (1) the occurrence of the environmental decoupling phenomenon (discussed above) as far as individual farms are concerned, and (2) the fact that increased marketability fosters greater economic specialization. While these developments add to economic efficiency and agricultural productivity for an indefinite period of time, they create new challenges for sustaining farm incomes and agricultural production, for example, because they result in a reduction in the size of the heritage genetic stock of potential value for sustaining agricultural production.

The size of the heritage agricultural genetic stock is reduced by market mechanisms, which include the following ones. These and additional ones are discussed in Tisdell ([3,15] Chs. [5–8]).

1. Crops and crop varieties (as well as breeds of livestock) that supply more marketable commodities than others crowd out those that are less suitable for this purpose. This favours the conservation of those agricultural organisms which enable the production of commodities which have the following qualities: possess greater buyer acceptability than others, are more easily transported without damage, have a longer shelf-life and are superior in appearance.
2. The growing importance of supermarkets in many countries reinforces this trend. They have a strong demand for agricultural produce that is standardized and which can be supplied regularly in large volumes. Consequently, crop varieties and crops that are more varied in their attributes and for which the volume of their supplies is small and quite variable in volume tend to disappear.
3. Changes in the tastes of consumers (which affect market demand) can reduce agricultural genetic diversity. For example, the increased demand for low fat pork has adversely affected the commercial conservation of some pig breeds, for example, in Vietnam.
4. The increased availability of substitute agricultural products reduces the demand for some agricultural commodities. Hence, their production can become unprofitable and they may disappear, thereby reducing the genetic stock. For example, some varieties of millet have disappeared in northern China due to the increased availability of substitutes (such as rice, wheat and maize).
5. International specialization in economic production can also add to agricultural biodiversity loss. The development of cocoa plantations in Ghana has, for instance, has resulted in the disappearance of a breed of small-sized cattle because of changed agricultural land use.
6. The regional introduction of higher yielding varieties of crops and breeds of livestock from other parts of the world can also be instrumental in the disappearance of heritage varieties of crops and breeds of livestock.
7. The abandonment of some farming areas for economic (or ecological) reasons can contribute to the loss of heritage agricultural biodiversity. For example, varieties of crops, which are specific to marginal agricultural areas, are likely to be lost.

6.2. New Agricultural Technologies Favour Monoculture

As a consequence of the nature of market-driven economic growth, new agricultural technologies are developed in order to increase the profitability of agricultural specialization. They tend to increase the relative profitability of monoculture. In particular, a considerable amount of machinery is developed that is specifically designed for the cultivation of particular crops or varieties of these, e.g., the planting and harvesting of specific crops, for instance, cereals, cotton, sugar cane and so on. Crops and varieties of crops that are more suitable than others for cultivation using new machinery consequently tend to be favoured for conservation. This reduces the agricultural genetic stock. Furthermore, there is an economic incentive to develop, by means of R&D, varieties of crops that are increasingly amenable to the demands of mechanization or new technologies. This also tends to diminish the agricultural genetic base. The same is even true in relation to the genetic livestock pool.

6.3. Increased Capital-Intensity Contributes to Less Agricultural Diversity

A further consequence of the nature of economic growth (which is stimulated by the market system) is that farms become more capital-intensive and farms of increased size become more profitable due to increased economies of scale. Simultaneously, it also becomes more profitable to specialize at the farm level in the growing of specific crops on a greater scale. This means that overhead costs associated with specific technologies and methods of production can, therefore, be spread over a larger volume of agricultural production. The net effect of this development is to reduce agricultural diversity.

6.4. Increased Farm Incomes Due to Technological Advances Do Not Last

Although technological developments tend to initially raise the incomes of early adopters of these, in the long run, due to market competition, it is difficult or impossible for farmers to sustain these higher incomes. Continual technological advances and innovations are needed if more innovative farmers are to maintain their incomes. Laggards in adopting new technologies fall by the wayside once they are embedded in the market system. Competitive market embeddedness sets in motion forces that continually result in the reduction of agricultural diversity and make it more difficult to sustain farm incomes. It is well established in the economic literature that in highly competitive markets, above normal or high levels of income and profit disappear with the passage of time (see, for example, References [16,17]). Due to high capitalization (overhead costs), the economic vulnerability and risks facing farming enterprises become a serious problem (see also Reference [18], Ch. 10).

6.5. Once Embedded in the Market System, Individual Farmers Have Limited Ability to Escape from It and Reduce Their Economic Vulnerability

Once embedded in the market system, individual farmers have little ability to escape from the above-mentioned economic sustainability problem. Those farmers who do not adopt new initially more profitable (lower cost of production) economic technologies find that their incomes fall because the price received from their produce declines. They may no longer be able to earn an income sufficient for their needs and may find that they can only obtain a higher income by obtaining employment outside the agricultural sector, if such employment is available. In less developed countries, obtaining alternative avenues of employment can be difficult or impossible; and consequently, small-scale farmers on marginal farms are liable to suffer considerable economic hardship. Their economic sustainability is jeopardized.

This raises the question of why do farmers adopt new technologies that increase their overhead (fixed) costs and which at the same time, increase their income vulnerability? In the early stages of the availability of such technologies, the profitability of adopting these usually more than compensates for the extra economic risks and vulnerability involved. However, as more and more farmers adopt such technologies, profit margins from their use fall (as a result of falling prices for agricultural produce) but the risks and economic vulnerability associated with their use increase due to rising overhead costs. Nevertheless, farmers are now locked into the new agricultural system involved due to market competition. Sustaining farm incomes becomes more difficult. Demand for further technological advance increases and the cycle repeats itself once again. Therefore, a treadmill effect characterizes the development of modern economies.

6.6. The Consequences of the Above-Mentioned Forces for Agricultural Diversity and Sustainability

The consequences of all these forces (which reduce agricultural diversity) is that

- Agricultural ecological sustainability is at increasing risk;
- The rural social environment is inevitably altered; and
- Maintaining agricultural economic sustainability becomes more challenging and dependent on forces external to individual farms.

A complex web of interactions is involved, the nature of which is illustrated in Figure 1. Although it is widely accepted that reduced ecological diversity may diminish ecological resilience and therefore, the sustainability of ecosystems, it is not the only factor influencing agricultural sustainability. Economic and social factors are also important, as is made clear in Figure 1. All three pillars of sustainability need to be taken into account in assessing the sustainability of agricultural systems.

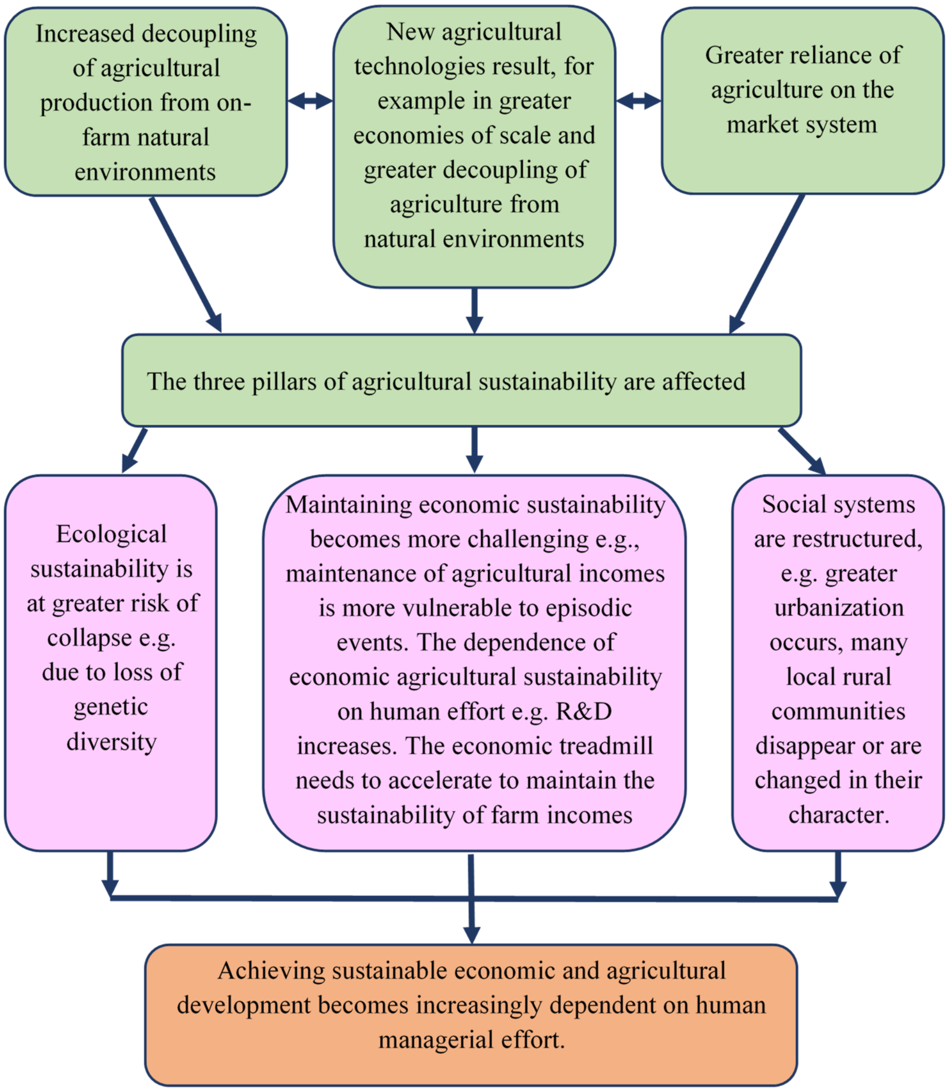

Figure 1. Indication of the complex interactions that influence the prospects of achieving agricultural sustainability (and sustainable development) given current patterns of economic growth.

As in many developing regions of the world, South Asia is characterized by an increasing transition from subsistence agriculture to semi-subsistence agriculture and thence, to commercial (market-driven) agriculture. This pattern of development is apparent in Bangladesh, for instance. Let us, therefore, consider the extent to which patterns of change in agricultural diversity and sustainability have occurred in Bangladesh and their likely consequences. The type of changes that have occurred in Europe and more developed countries [19] are occurring in Bangladesh in a much shorter time-frame, and also in China [20].

7. Linking the Two Parts

The first part of this article has provided information about the multidimensional nature of agricultural diversity, has outlined relevant concepts of sustainability, and has provided a general coverage of agricultural developments which have resulted in a reduction in agricultural diversity, especially at the farm level. The reduction in agricultural diversity has created concerns about the ecological and economic sustainability of agricultural activities, as well as the sustainability of rural communities. A follow-up case study of agricultural diversity has been completed by us, the results of which are reported in the second part of this article. In this case study, it is impossible to explore all aspects of agricultural diversity and sustainability raised in the first portion of this article.

Our case study explores the extent of crop diversity in Bangladesh and its change at the aggregate level (not at the farm level) and its potential implications for agricultural sustainability. It pays particular attention to the heavy dependence of Bangladesh on the production of rice and the changes in its rice sector following the Green Revolution. Changes in Bangladesh's on-farm agricultural diversity have yet to be studied by us empirically. Nevertheless, the aggregate relationships observed by us do have on-farm implications. For example, the increased dependence nationally of Bangladeshi agriculture on off-farm input (such as fertilizers and pesticides) has resulted in Bangladeshi farmers becoming more market dependent.

The slowdown in the pace of growth in rice yields in recent years (which we observe) is also no doubt replicated in the increased difficulties experienced by most Bangladeshi rice-growers in attempting to increase their rice yields using Green Revolution technologies. We also find that the genetic resource base of rice has declined considerably in Bangladesh and that its rice production now depends heavily on only two HYVs of rice. This has the potential of threatening the sustainability of Bangladesh's rice production, thereby lowering the incomes of most of its farmers and adversely affecting its food security.

The second part of this article also presents us with an opportunity to outline a novel index of crop diversity and apply it at the national level to the use of land for crops in Bangladesh, and to consider its application to changing crop diversity in Bangladesh.

Given this clarification of the connection between our case study and the first part of this article, let us now turn to the case study itself.

8. Background Information about Bangladeshi Agriculture

8.1. General Features

The interplay of complex socio-economic, natural and environmental factors characterizes Bangladeshi agriculture. Millions of small farm-households (12.8 m) with ≤1 ha of arable land constitute 84% of Bangladesh's total farm households (15.2 m) [21] (p. 457). Fifty nine percent of all Bangladesh's farm households cultivate land ≤0.4 ha while 25% have a farm size in the 0.4–1 ha range. Population density is close to 1200 people km^{-2} making Bangladesh one of the most densely populated countries in the world. This implies a very small amount of arable land per capita—one of the lowest in the world. Bangladesh is the most agriculture intensive (agricultural land as a percentage of total land area) and rice-intensive (rice area as a percentage of net-cropped area) country in South Asia [22]. It is characterized by seven distinct zones of climatic patterns ranging from extreme drought-prone areas in the west, northwest and northern parts to very high rainfall areas in the east [23].

Crop production dominates Bangladesh agriculture although of late livestock and aquaculture are making an increased contribution to labour absorption output and household incomes [24,25]. The latter trend is due to the demands of the increasing numbers of those belonging to the middle class or higher for animal protein. Nevertheless, Bangladesh agriculture is still dominated by grain production.

1. Bangladesh more than tripled its grain (rice plus wheat) production to 37.4 million tonnes in the year ending June 2018 from a meagre 11 m tonnes in the early 1970s. This represents an

increase of food grain production by about 240%. In this period, its population increased by about 136% (from 70 m to 165 m). In feeding its increasing population, Bangladesh has relied almost exclusively on increasing intensification of agriculture mainly by relying on dry season irrigation to produce rice. At the beginning of the Green Revolution, Bangladesh had a cropping intensity ([Gross cropped area (including multiple cropping)/Net-cropped area)] × 100.) of less than 150% [26]. This increased to about 195% in recent years [25], mainly due to an increase in annual multiple cropping, which has significantly contributed to the process of agricultural intensification in Bangladesh. Information from BBS [25,27] suggests that between the early 1970s and 2018:

- Fallow land in Bangladesh declined from 0.7 m ha to about 0.2 m ha—less than a third of what its level was 47 years ago.
- The area single cropped declined from about 5 m ha to <2.4 m ha.
- Area under multiple cropping registered a spectacular increase. The area double cropped increased from 3 m ha to 3.8 m ha. Of greater significance is the quadrupling of the area under triple cropping (from ≤0.450 m ha to ≈ 1.8 m ha).

8.2. Increasing Dependence on Groundwater

Increasing reliance on groundwater irrigation is characteristic of this process of agricultural intensification. In the early 1970s with less than 10% (just over a m ha) of the total cropped area irrigated, more than 80% originated from surface water sources. Today, 79.3% of irrigated cropland (6 m ha) utilizes groundwater [25], which is now becoming scarcer relative to the demand for its use.

As a result of this increased dependency, water tables are sinking because the withdrawal of water exceeds recharges. The current situation is unsustainable. Furthermore, water pollution is rising due to the increasing use of chemical fertilizers and agrochemical pesticides.

This average groundwater dependency for Bangladesh as a whole masks the significant regional variations. In some areas, especially those in the drought-prone areas, this dependency is considerably higher than elsewhere (around 95%, [28]). Note that South Asia, as a whole, is far more dependent on groundwater for supporting its population than any other region in the world [22,29]. Because of the high dependency on groundwater for irrigation, Bangladesh has one of the highest levels of groundwater dependency for sustaining its population of any nation.

8.3. Rising Use of Agrochemicals

Application of chemical fertilizers rose dramatically from less than 10 to 238 nutrient kg ha^{-1} of net-cropped area between early 1970s and 2016–17 [26,30]. The application of pesticides (including different types of insecticides, fungicides and herbicides) per net cropped ha over a 20-year period increased from 234 g in 1997–98 to 375 g in 2016–17. (Consistent data on pesticide use for earlier periods are not readily available.) The increased use of agro-chemicals is in response to the development of high yielding crop varieties, particularly rice. It has contributed to the increasing dependence of Bangladeshi farmers on external inputs and the market system. This process was discussed earlier in this article.

Increased use of chemical fertilizers for crop production has adverse consequences for water quality due to the leaching of nitrates into groundwater from chemical fertilizer use in crop production. There is substantial reduction in the stock of aquatic resources because of greater chemical use in agriculture associated with the adoption and diffusion of the Green Revolution technologies [31]. The use of agrochemicals also poses a significant risk to human health [32].

8.4. Changing Seasonal Patterns of Rice Production in Bangladesh

Rice is Bangladesh's major crop by far. In 2018, almost three-quarters of its cropland was allocated to rice (see Table 1). One key feature of the process of crop production in Bangladesh is that both the area and the output of dry season rice (*Boro*, exclusively irrigated, winter-early summer) now exceeds those of two other rice crops, *Aus* (summer-early monsoon) and *Aman* (monsoon-late autumn) (http://knowledgebank-brri.org/). The latter two crops are primarily rain fed.

Table 1. Area allocated in Bangladesh to major crops (yearly average in the triennium ending June 2018).

Type of Crops	Area (m ha)	Proportion of Gross Cropped Area Allocated to Crops
Rice	11.33	0.7378
Jute	0.725	0.0472
Potato	0.483	0.0315
Wheat	0.403	0.0262
Oilseeds (9 crops)	0.464	0.0302
Vegetables (40 crops)	0.410	0.0267
Spices (6 crops)	0.404	0.0263
Maize	0.375	0.0244
Fruits (28 crops)	0.302	0.0197
Pulses (10 crops)	0.368	0.0240
Sugarcane	0.093	0.0061
Total cropped area	15.357	1.000

Source: Based on data from BBS ([25], pp. 39–42). Diversification index, D = 0.4479.

The following changes are apparent from Table 2. Whereas in 1974–75, *Boro* rice made the smallest relative seasonal contribution to the total output of rice in Bangladesh from 2004–05 onwards, it became the major contributor to rice output. *Aus* output of rice slipped from 23.3% of annual rice output in 1974–75 to only 7.5% in 2017–18. The relative decline in the percentage contribution of *Aman* rice to total rice output was lower than for *Aus* rice (it fell from 58.4% of the total to 38.6%).

Table 2. Trends in percentage contribution to rice area and output of *Aus*, *Aman* and *Boro* crops of rice for selected years, Bangladesh 1974–75 to 2017–18.

Year (July–June)	Percentage Share of Total Crop					
	Aus Crop		*Aman* Crop		*Boro* Crop	
	Area	Output	Area	Output	Area	Output
1974–75	27.8	23.3	62.0	58.4	10.2	18.3
1984–85	25.6	17.5	60.6	57.8	13.7	24.6
1994–95	15.3	10.1	60.2	53.0	24.5	36.9
2004–05	9.4	5.6	53.2	42.6	37.4	51.8
2014–15	9.1	6.7	48.4	37.8	42.4	55.5
2017–18	9.3	7.5	48.9	38.6	41.8	54.0

Source: Based on data from Bangladesh Rice Knowledge Bank (http://knowledgebank-brri.org/) and BBS [25].

Nevertheless, the decline in this percentage (by 19.6%) for the *Aman* crop was higher than for the *Aus* crop (15.8%). Consequently, a major reversal occurred in the seasonal distribution of rice production in Bangladesh as the Green Revolution became more established.

This pattern is also reflected in the changed seasonal distribution of the amount of land used for rice cultivation. The percentage of total rice land used in the *Boro* season rose fourfold between 1974–75 and 201–18 whereas the relevant areal percentages shown in Table 2 declined in both the *Aus* and *Aman* seasons. Because the amount of land used for growing rice remained relatively steady between 11.2 and 11.6 m ha (see Table 3, presented in Section 10.1), extra land became available in the *Aus* and *Aman* seasons for growing crops other than rice.

9. Lack of Crop Diversification and the Measurement of Crop Diversity in Bangladesh

The changed seasonal pattern of rice production has made additional land available for the growing of crops other than rice. Between the financial year 1971–72 and 2017–18, about 2 m ha of land previously planted with rice in the *Aus* season and about 1.7 m ha of land previously allocated to rice in the *Aman* season were no longer used to grow rice. Thus, a total of about 3.7 m ha of land formerly devoted to growing rice in these seasons became available for growing crops other than rice. This provided an opportunity for diversifying the composition of the type of crops grown in Bangladesh. It was a significant factor enabling Bangladesh to diversify the composition of its aggregate agricultural production but was not the only influence on this process. An increase in incomes and the numbers belonging to the middle class also increased demand for a more diversified diet, i.e., a diet less dependent on rice [33]. This is so, despite rice still accounting for the major part of diets in Bangladesh, as can be inferred from Table 1.

Why has the *Boro* season now become the major rice-growing season? The basic reason appears to be that there is more control over water supplies in the *Boro* season than in the *Aus* and *Aman* seasons as a result of relying only (or almost entirely) on irrigated water in the *Boro* season (the dry season). Farmers have greater control of environmental conditions for growing rice in this season than in the other two seasons. HYVs of rice developed in Bangladesh give their highest yields when these are grown under ideal or almost ideal environmental conditions, but are intolerant to deviations from these conditions. This type of relationship is discussed by Tisdell [15] (pp. 82–83). It involves the application of the law of biological tolerance [34] according to which the success of an organism depends on a complex set of conditions with each organism having a certain minimum, maximum and optimum environmental factor(s) that determine its success [35]. As a rule, HYVs are less tolerant of adverse and variable environmental conditions than are traditional crop varieties but give much higher yields when grown under the environmental conditions which suit them.

9.1. Current Diversity of Crops Grown in Bangladesh

Table 1 presents the average area under various crops (and crop groups) for the triennium ending June 2018. The information contained in Table 1 indicates that Bangladeshi agriculture lacks crop diversification, with close to three-fourths of the gross cropped area allocated to rice. Thus, rice dwarfs all other crop growth by a wide margin even though a large number of different crops are grown. For example, jute (Despite jute being widely regarded as the best natural substitute for synthetics, e.g., nylon and polypropylene, its production and use of its products are declining globally due to competition from substitutes [36–38].), the second most important crop (in terms of area), occupied 0.725 m ha of land under cultivation compared to over 11.33 m ha under rice. However, jute is not a food crop, unlike potatoes and wheat. These two food crops account for the highest share of cultivated land in Bangladesh after jute. However, the amount of land allocated to these two crops is very small compared to that used for growing rice.

9.2. An Index of Aggregate Crop Diversity and Trends in It in Bangladesh

While the relative lack of aggregate crop diversity is obvious from Table 1, a measure of it would be useful for tracking its change with the passage of time. We propose a novel index of the diversity in land use based on the different types of crops grown. In the case considered here, it is applied at the national level, but it can also be applied at different geographical scales. This index is an adaptation of the Herfindahl–Hirschman index widely used in economics to measure the extent of business concentration in an industry.

The proposed index of the diversity of land use is sensitive, in this case, to the relative amounts of land used for different crops and the number of crops grown. We first define the index so it indicates lack of diversity in the allocation of land to different crops and then derive from this a land-use diversity index. Note that this index is only a partial indicator of crop diversity because as was pointed out earlier in this article, agricultural diversity (including crop diversity) is a multidimensional concept.

Let L represent the index of the lack of diversity of crops based on the allocation for land to the growing of different crops, and let p_i represent the proportion of land (expressed as a decimal) used for producing crop i or the ith category of crops. (This land-use lack of agricultural diversity index is an adaptation of the Herfindahl–Hirschman index, [39,40] used in economics as a measure of business and industry concentration [41]. The index is generally expressed as $HHI = \sum_{i=1}^{n} s_i^2$ where s_i is the market share as a percentage of the ith firm in the industry. This market share is expressed either as a proportion (decimal) or as a percentage. In the latter case, the value of this index is in the range $0 \leq HHI < 10{,}000$. The upper value corresponds to a situation in which a monopoly exists—a single firm accounts for all the sales in the industry.) Then

$$L = \sum_{i=1}^{n} p_i^2 \rightarrow 0 < L \leq 1 \tag{1}$$

The corresponding land-use diversity index is

$$D = 1 - L \rightarrow 0 \leq D < 1 \tag{2}$$

The larger is D the greater is the diversity of crops grown on cultivated land. When $D = 0$, only a single type of crop is grown. As the number of crops increases or the amount of land allocated to each becomes more equal, D approaches one.

The indices can also be expressed in percentage terms by multiplying their values by 100 or by calculating them using percentages. In the latter case, if for example, r_i represents the percentage of land allocated to growing crop i or the ith category of crops,

$$\hat{D} = 100 - \left(\sum_{i=1}^{r} r_i^2\right) \times 100 \rightarrow 0 \leq \hat{D} < 100 \tag{3}$$

Zero corresponds to a situation in which only one type of crop is grown. As land-use crop diversity increases, $\hat{D}$ approaches 100.

Our crop diversity index does not capture all aspects of crop diversity nor agricultural diversity. Its application is likely to be most valuable in countries or regions where monoculture of crops predominate, as in Bangladesh. In the case of mixed crops, it would theoretically be possible to estimate the percentage of land occupied by each crop in the mix and use this in the calculation but the data for this may not be readily available.

Regarding livestock and fish farming, it would be possible to adapt the index to consider diversity in each of these sectors but it would not be based on area. The relative populations of different breeds of livestock, e.g., pigs, could be substituted for area.

Our article, however, only focuses on the diversity of crop production.

Applying the diversity indices to the diversity of Bangladesh's cropland based on the yearly average of its land allocation in the triennium ending June 2018 (as shown in Table 1), $D = 0.4479$ and $\hat{D} = 44.79\%$. This implies low diversity of the type of crops grown in Bangladesh.

One cannot establish *a priori* a cut-off point for low crop diversity. Changes in the index, D, signal the direction of change in crop diversity. Therefore, it is most useful for indicating trends in this diversity, as is shown in our Figure 2. Nevertheless, it is true that as D approaches zero, crop diversity declines and that crop diversity increases as D approaches its upper limit of unity. In this regard, it is similar in nature to the IUCN Red List Index (RLI) which provides an indication of the nature of the change in wild biodiversity.

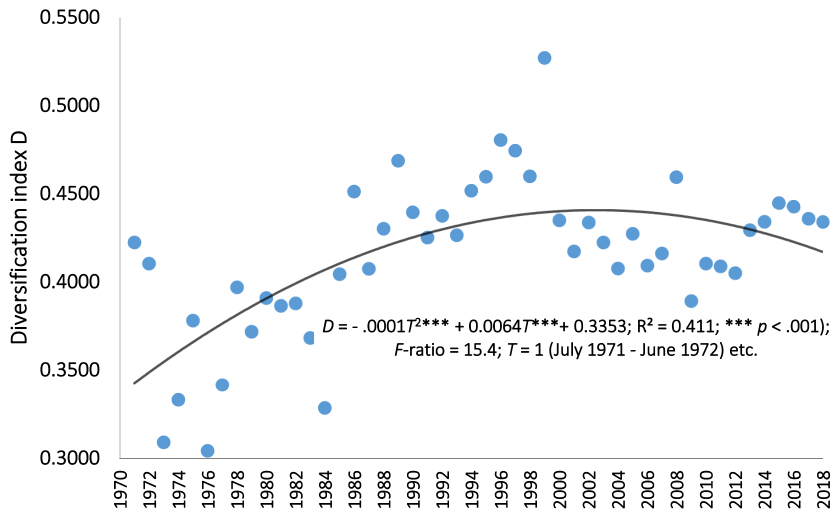

Figure 2. Trends in four-crop D (diversification) index of land used for cropping since 1971–72 to 2017–18 (Source: Based on data from Reference [25] BBS, 2019).

We do not have sufficient data at present to determine the trend in D taking account of all crops shown in Table 1. However, we can calculate the trend in this index taking into account the four major crops grown in Bangladesh.

D was calculated for each year based on land use by four crops (rice, jute, potato and wheat) utilizing their shares (in decimals) since 1971. Given the nature of the D-value and movement over time, we tried several functional forms including linear, quadratic and cubic. The linear function displayed a significant positive trend but generated a low R^2 value of 0.258. On the other hand, a cubic function produced results with none of the coefficients statistically significant but had an R^2 value of 0.415. However, the quadratic functional form produced results with an R^2 value of 0.411 and all coefficients are significant at $p < 0.001$. Figure 2 illustrates the movement of D over time with the quadratic functional form. Both the observed and fitted values of D suggest an increasing trend up to around the year 2000. In the last two decades, it appears to have declined slightly. The estimated regression equation illustrated in Figure 2 suggests that there might now be a long-term declining trend given the significant negative value of the coefficient of T^2. Note, however, that the negative value of the coefficient of t^2 is very small in magnitude compared to the relatively much larger numerical value of the coefficient of T. Therefore, one needs to exercise caution in interpreting this regression model as providing definitive evidence of a future decline in the crop diversification index. Additionally, it only accounts for four crops.

Overall, low values of the D index typify lack of diversification within crop agriculture in Bangladesh, even though a very slow trend toward diversification appears to be in evidence. Although no significant diversification has occurred in areas planted to 'staple' crops, at the national level, it seems highly likely that the relative area of cultivated land planted with 'non-staples' has increased. Therefore, some increase in crop diversification at the national level has occurred since the Green Revolution. This must be so since the area sown to staples has been relatively constant but the total cultivated area has risen (by one-third) due to the rise in multiple cropping. As more rice has been grown in the *Boro* season and less in the other seasons, there has been an increase in other crops including fruits and vegetables cultivated in the *Aus* and *Aman* seasons. This is due to their profitability [36] and more land being available in those seasons as well as the low risk due to the availability of supplementary irrigation. (Personal communications with Dr Mahbubur Rahman, a Bangladesh Agricultural University academic staff member). These crops also use much less water than rice.

10. Land Sparing and the Intensification of the Cultivation of Bangladesh's Rice Crop. Is this Process Sustainable?

Rising yields of rice in Bangladesh have made it possible to save land for the growing of other crops. Furthermore, using decomposition analysis, it is found that the massive increase in Bangladesh's output of rice is overwhelmingly due to rising rice yields particularly since the Green Revolution.

In this section, we apply decomposition analysis to determine the percentage change in Bangladesh's rice output which is due to increased yield and the percentage difference arising from the changed amount of land allocated to rice cultivation. (A variant of this formula was used by Tisdell [42] to decompose the growth in Vietnam's pork production by that attributable to the increased average carcass weight of pigs and the number of slaughtered pigs. This formula can also be easily adapted to decompose changes in the level of output obtained from other livestock attributable to changed yield (of a specific animal product) and the level of population of the type of livestock being considered, or the numbers slaughtered.) We also examine the trend in the yield of rice in Bangladesh and analyse this, to consider the likelihood of yields continuing to increase in the same way as in the past.

10.1. The Relative Contribution of Land Use and Yield to the Total Output of Rice in Bangladesh

We use the formula presented in Equation (4) to decompose the changed aggregate production of rice in Bangladesh into the component due to altered yield and the component arising from the variation in land use.

$$z_t - z_{t-n} = (x_t - x_{t-n})\, y_{t-n} + (y_t - y_{t-n})\, x_{t-n} \tag{4}$$

where

1. $z_t - z_{t-n}$ = change in the level of production of crop between year t and year $t - n$.
2. $x_t - x_{t-n}$ = change in the area of the crop between year t and $t - n$.
3. $y_t - y_{t-n}$ = change in the (aggregate average) yield of crop between year t and $t - n$.

The first term on the right hand side of Equation (4) is the absolute change in output due to a change in the area planted of the crop, assuming yield is constant at level y_{t-n}.

The second term in Equation (3) is the absolute change in the output of the crop due to the change in its yield.

Let Δz, Δx and Δy represent the variables defined respectively in (i), (ii) and (iii) above. Then,

$\Delta x z_{t-n}/\Delta z$ is the percentage change in the total output of the crop attributable to the alteration in the total area planted of the crop.

$\Delta y x_t/\Delta z$ is the percentage change in the total output of the crop attributable to the change in its yield.

In view of the decomposition formula presented in Equation (4), Table 3 presents the changes in area, production and yield of rice between the five-year average ending June 1975 (beginning of the Green Revolution) and five-year average to June 2018 with decomposition of sources of output growth. The total rice output and yield respectively increased by about 22 m tonnes and about 2000 kg ha^{-1} while the gross area under rice cultivation declined marginally by 0.384 m ha. The increase rice output between the two end-points is due entirely to the increase in yield (by 101.9%) which counterbalances the negative area effect (−1.9%). Thus, the overall growth in output is exclusively dependent on the growth in yield.

Table 3. Change in area, production and yield of rice between the five-year average ending June 1975 (beginning of the Green Revolution) and five-year average to June 2018 with decomposition of sources of output growth.

Time Period (July–June)	Gross Cropped Area (000 ha)	Output (000 tonnes)	Yield (kg ha^{-1})
1971–75	11,608	12,419	1070
2014–18	11,224	34,335	3059
Changes between 1971–75 and 2014–18			
	Area	Output	Yield
	−384	21,916	1989
Percentage change in rice output due to			
	Area	Yield	Total
	−1.9	101.9	100

Source: Based on data from Bangladesh Rice Knowledge Bank (http://knowledgebank-brri.org/) and BBS [25].

10.2. Trends in Rice Yields

The substantial rise in the yield of rice in Bangladesh, especially since the beginning of the Green Revolution, has added significantly to food availability in Bangladesh and has contributed to the increased diversity of its domestic food supplies by increasing the amount of land available for the cultivation of crops other than rice. The following question arises: How sustainable is Bangladesh's rice yield and to what extent is it likely that this yield can be increased further by more intense cultivation of rice and continuing genetic improvements in HYVs of rice? Trends in rice yields may provide a tentative answer to the first question. This section considers this trend. The declining biodiversity of rice in Bangladesh is an additional related concern and is discussed in the next section.

Figure 3 provides a scatter plot of observed rice yields in Bangladesh over the 47-year period to June 2018. There is a jump in yield in the year beginning July 1998. This is due to a rise in the *Boro* rice area by 0.638 m ha over the previous year. More than 93%, this increased area was planted with HYVs. On the other hand, *Aman* and *Aus* areas (lower yielding) declined by 0.997 m ha resulting in an overall decline of 0.359 m ha in overall rice area but an increase in yield by 135 kg ha^{-1} in the year beginning July 1998.

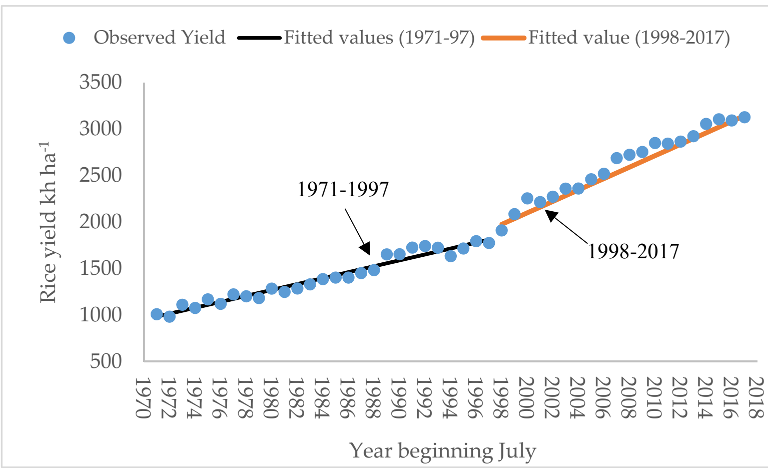

Figure 3. Trends (as discussed in the text) in overall rice yields in Bangladesh (*T* = July 1971–June 1972 = 1, to July 2017–June 2018 = 47). Source: Based on data from Bangladesh Rice Knowledge Bank (http://knowledgebank-brri.org/) and BBS [25].

The trajectory of rice yields suggests that two lines might best approximate the observed relationship. Using ordinary least squares, we fitted the lines represented by Equations (5) and (6) to observed rice yields for the two periods (July 1971–June 1998, first 27 years; and July 1998–June 2018, last 20 years). The lines are illustrated in Figure 3.

$$\hat{Y}(1971\text{–}1997) = 951.541^{***} + 31.829\ Time^{***}\ (^{***}\ p < 0.001)\ R^2 = 0.96,\ F\ (1,\ 25) = 568.8\ (^{***}\ p < 0.001) \quad (5)$$

$$\hat{Y}(1998\text{–}2017) = 318.689^{***} + 61.379\ Time^{***}\ (^{***}\ p < 0.001)\ R^2 = 0.98,\ F\ (1,\ 18) = 723.8\ (^{***}\ p < 0.001) \quad (6)$$

These equations indicate that, overall, the annual increase in yield occurred at a faster absolute rate in the (1998–2017) period than in the (1971–97) period but the percentage rate of growth tapered off. Note that the second series starts with a yield of about 2000 kg ha^{-1} in 1998.

In order to see if the yield growth shows any sign of tapering off (as the observations shown in Figure 3 suggest) we fitted a logistic curve to the observed values of overall rice yields over a 47-year period to June 2018. Figure 4 presents the scatter plot and the fitted logistic function Equation (7).

$$\text{(Estimated) Rice Yield} = \frac{1}{\left(\frac{1}{3500} + \left(0.001\left(0.937^{Time}\right)\right)\right)} \quad (7)$$

where 3500 kg ha^{-1} is the assumed upper boundary of rice yield. [R^2 = 0.939, F (1, 45) = 687.2 ($p < 0.001$); t-ratio = 406.6 ($p < 0.001$)]. Note that the upper boundaries of yield values of 4000 and 4500 kg ha^{-1} were also tried with very similar diagnostics. Therefore, we report the results with the assumed upper boundary of 3500 kg ha^{-1} for illustrative purposes.

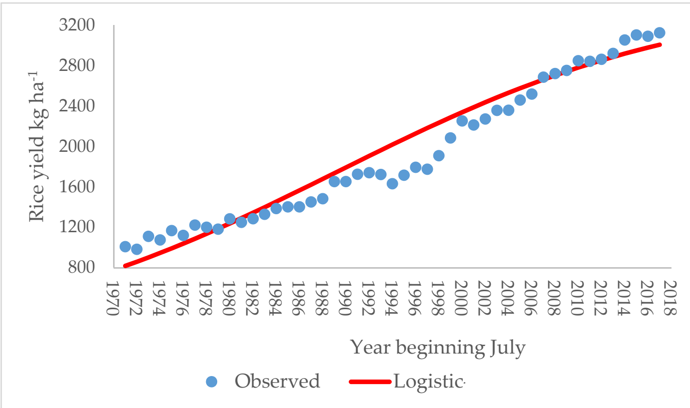

Figure 4. The logistic trend (as stated in the text) in overall rice yields in Bangladesh (T = July 1971–June 1972 = 1, to July 2017–June 2018 = 47).

The logistic function specified in Equation (7) provides a reasonably good fit to the observations shown in Figure 4. This suggests that the ability of Green Revolution packages to further increase Bangladesh's aggregate rice yields might now be limited. It is therefore unclear whether the current high yields of rice can be sustained.

The effectiveness of the Green Revolution packages could be tapering off. Greater intensification of rice cultivation appears to be becoming less effective as a means for increasing rice yields. Thus, Bangladesh's dependence on rice for further increasing its food supply and leaving room for greater crop diversification appears to be in doubt. Furthermore, the erosion of Bangladesh's genetic rice base may threaten the sustainability of its rice yields.

11. Declining Biodiversity of Rice

11.1. Background Information

Historically, Bangladesh has been well known for extensive rice biodiversity. For centuries, farmers have been growing a large number of rice varieties characterized by different quality, resistance to many diseases and insects and with adaptability to varying growing conditions. The International Rice Research Institute Gene Bank apparently contains over 8000 rice varieties collected from Bangladesh [37] (p. 1).

With the introduction of the seed-fertilizer-irrigation technology popularly known as the Green Revolution, significant transformation in crop production has taken place. (At the beginning of the Green Revolution IR-5, IR-8 and IR-20 varieties of rice were introduced through direct imports of seeds (*material transfer*) with subsequent adaptation (*design transfer*) and indigenous development of different strains of rice by the Bangladesh Rice Research Institute (*capacity transfer*) [43,44].) Data from the Bangladesh Rice Knowledge Bank (http://knowledgebank-brri.org/), indicate that:

- HYVs of rice are grown over 87% of all rice lands in 2017–18 compared to less than 25% in 1994–95. By 2004–05, the spread of HYVs grew to more than 66% and to more than 84% by 2014–15. Spread of *Aus* and *Aman* HYVs of rice broadly reflects the pattern for overall rice—slower pace of adoption in the first two and half decades of the Green Revolution (up to mid-1990s) followed by a rapid pace since.
- Adoption of *Boro* HYVs proceeded at a very rapid pace. By the mid-1970s, it reached 50% even though the total area under this rice crop was just over a m ha. Subsequently, however, both area and HYV adoption rate expanded. By the mid-1990s, *Boro* rice was grown in about 2.7 m ha of land of which more than 90% was under HYVs. By 2017–18, *Boro* rice cultivation expanded to about 4.9 mha almost all of which were planted with HYVs.
- Growth in rice output and yield of three rice crops followed a path similar to that of their area under cultivation. Penetration of HYVs propelled rice yields, which further propelled overall rice production. The combined effect of these changes resulted in tripling of overall output and more than tripling the yield of rice.

Over the last five decades, rice has experienced significant loss of diversity, especially after the start of the Green Revolution. HYVs of rice have replaced the local varieties particularly in the *Aus* and *Boro* seasons. Because of the introduction of HYVs, many traditional rice varieties have completely disappeared or are on the way to extinction. Prominent *Aman* varieties that face extinction include among others, *Nazir Shail*, *Lati Shail*, *Raja Shail*, *Balam*, *Binni*, *Digha* and *Kartik Shail* while the important *Aus/Boro* varieties include *Haitta*, *Kotoktara*, *Goria*, *Porangi*, *Kala Manik*, *Hasi Kalmi*, *Balam*, *Vaduri*, and *Aguli* [37].

This has resulted in the genetic erosion of rice. The replacement of local varieties, which narrowed the genetic base, could increase genetic vulnerability [45,46]. Over one hundred rice varieties have been developed by the Bangladesh Rice Research Institute (BRRI) and the Bangladesh Institute of Nuclear Agriculture (BINA). However, their genetic base became narrowed because few local varieties were used in the breeding program [47]. Genetic uniformity causes resistance or susceptibility to disease and insects [48], which results in poor performance of some HYV rice varieties.

The introduction of HYVs not only changed cropping patterns but also the rice ecosystem. For example, (local variety) *Broadcast Aus* (*B. Aus*) and (local variety) *Broadcast Aman* (*B. Aman*) were grown as mixed crops. With time, this practice has all but disappeared. In Bangladesh, HYVs which were cultivated extensively were found after 10–15 years to be susceptible to diseases and insects, and became obsolete. For example, in the mid-1970s BR3 was the most popular variety in the *Boro* season but has now been replaced by BRRI*Dhan*28. The same happened with *Aus* and *Transplanted Aman (T. Aman*). Replacement of new varieties also depends on farmers' needs, i.e., in the mid-1970s, farmers preferred coarse grains but at present they prefer medium to fine grains due to changing preferences of customers.

The Bangladesh Rice Research Institute (BRRI) released its BR3 commercial rice variety in 1973 and it was the major variety cultivated during the *Boro* season until 1990. It was developed from a local variety *Latishai*. It has a coarse grain with a high amylose content. After 1990, in order to satisfy consumers' preferences, BRRI released BR28 and BR29 in 1994. These two varieties remain popular due to their medium fine grains, better adaptability and shorter growth duration relative to BR3. BR28 was developed from one popular local variety *Purbachi*. Subsequently, BRRI developed a range of varieties improving on BR3, BR11, BR28 and BR29 for wider adaptability and both biotic and abiotic stress tolerance [49].

With the introduction of HYVs of rice, many local varieties have completely disappeared or are on the way to extinction. This situation is alarming and is reminiscent of the Irish potato famine and the leaf blast of maize due to widespread cultivation based on a few varieties. While BRRI developed 91 modern varieties of rice, only a few of them have a local genetic base. Although several local varieties were used in the breeding program only a few of them were successful in giving higher yields. *Latisal, Nazirshail, Badshahbhog*, and *Khaskani* demonstrated the potential for higher yields. Local rice varieties are adapted to adverse eco-environmental conditions including drought, salinity and tidal submergence. Due to their poor yield, they were replaced by modern varieties with higher yields. Some of the modern varieties are also suitable for adverse conditions. For instance, BR22 and BR23 are suitable for late planting while BR28 and BR81 are early maturing and suitable for *haor* areas (a *haor* is a wetland ecosystem, which is physically a bowl, or saucer shaped shallow depression in the greater districts of Mymensingh and Sylhet in the north-eastern part of Bangladesh). BR34 is an aromatic and fine grain variety which became popular to the farmers. BR51 and BR52 are submergence tolerant while BR47 is salinity tolerant. All these varieties have become popular with the farmers.

11.2. Narrow Genetic Base of Modern Rice Varieties

Table 4 presents the parentage of some popular rice varieties developed by BRRI. Note the narrow genetic base of the new varieties and the lack of reliance on a wide range of local genetic resources.

Table 4. Parentage of some popular rice varieties developed by Bangladesh Rice Research Institute (BRRI).

Variety	Parentage	Season	Released	Genetic Base
BR3	IR506-1-133/*Latisail* *	Boro	1973	Primarily local
BR11	IR5/IR20	*T. Aman*	1980	Exotic
BR22	*Nizersal* */BR51-46-5	*T. Aman*	1988	Primarily Local
BR23	DA-29 */BR4	*T. Aman*	1988	Local
BR26	IR183618/IR25863	*T. Aus*	1993	Exotic
BR28	B6/*Purbachi* *	*Boro and Aus*	1995	Local
BR29	BG90-2/ BR51-46-5	*Boro*	1995	Local
BRRIDhan34	Selection from *Khaskani* *	*T. Aman*	1997	Local
BRRIDhan48	IR515-11-2B-343/TCCP266	*T. Aus*	2008	Exotic
BRRIDhan49	BR1543-9-2-1 */IR13249	*T. Aman*	2008	Primarily Local
BRRIDhan51	IR81213/Swarna */IR67684B	*T. Aman*	2008	Primarily Exotic
BRRDhan62	*Jirakatari* */BRRIDhan39	*T. Aman*	2013	Primarily Local
BRRIDhan87	Amol */BRRIDhan28	Boro	2017	Primarily Local

* Local genetic base. Source: Compiled from BRRI ([49], Table 2, pp. 7–9).

The main reason for growing HYVs of rice is due to substantially higher yields and profitability relative to (low local yielding) local varieties. Furthermore, some of the local varieties take longer to mature. This notwithstanding, farmers still grow some special varieties including *Kalijira* and *Kataribhog* for their aroma and grain quality, and *Motadhan* in the environmentally stressed coastal areas.

11.3. HYV Adoption and Lack of Diversification of Rice Varieties

Information presented in Table 5 typifies the high dependence of Bangladesh on a narrow range of rice varieties. This is especially the case for *Boro* rice crop with BR28 and BR covering more than 60% of the area (about 3 m ha). Furthermore, BR28 covers more than 15% of the area of the *Aus* crop (0.161 m ha). Thus, in the *Boro* and *Aus* seasons combined BR28 grows on 1.852 m ha of land. The *Aman* crop is more diversified—no single rice variety is overwhelmingly dominant.

Table 5. Coverage of rice land by selected HYVs by crop season: Bangladesh 2017–2018.

Variety	**% Coverage (area m ha)**	**Variety**	**% Coverage (area m ha)**	**Variety**	**% Coverage (area m ha)**
Boro Crop		*Aus* Crop		*T.* (Transplanted) *Aman* Crop	
BRRIDhan28	34.80 (1.691)	BRRIDhan48	17.28 (0.186)	BRRIDhan49	11.41 (0.648)
BRRIDhan29	26.25 (1.275)	BRRIDhan28	14.98 (0.161)	BR11	7.11 (0.404)
BRRIDhan58	2.14 (0.104)	BR26	6.86 (0.074)	BR22	4.21 (0.239)
BRRIDhan50	1.78 (0.086)	BR21	4.74 (0.051)	BRRIDhan34	4.04 (0.229)
BR16	1.25 (0.061)	BR27	3.81 (0.041)	BRRIDhan52	3.11 (0.177)
		BRRIDhan43	2.69 (0.029)	BR23	2.75 (0.156)
		BR2	2.00 (0.022)	BRRIDhan51	2.08 (0.118)
		BR2RIDhan55	1.69 (0.018)	BRRIDhan41	1.66 (0.094)
Other BRRI	3.76 (0.183)	Other BRRI	11.93 (0.128)	Other BRRI	11.39 (0.647)
Total BRRI *Boro*	69.98 (3.400)	Total BRRI *Aus*	65.98 (0.709)	Total BRRI *T. Aman*	47.76

Source: Based on data from BRRI (2018b, pp. 166–168) [50].

12. Discussion and Conclusions

This article has demonstrated the complex nature of analysis of the relationship between agricultural diversity and agricultural sustainability. This is partly because the concepts of agricultural diversity and agricultural sustainability are multidimensional in nature. The general analysis (Sections 3–5) identified important factors which have reduced agricultural diversity in recent times, particularly at the farm level, and these can have potentially adverse impacts on each of the three pillars of agricultural sustainability encapsulated in Figure 1.

The case study on Bangladesh investigated agricultural diversity at the national level and its implications for agricultural sustainability. We had sufficient national data for that purpose but not for farm-level studies. The latter ought to be the subject of future research.

Our case study (Sections 8–11) revealed that:

- The extent of crop diversification in Bangladesh is very low, mainly because of its extremely high dependence on rice as a food source. Nevertheless, by applying a novel index of crop diversity and additional analysis, we discovered that crop diversification has increased in Bangladesh since the Green Revolution. This has occurred partly because higher rice yields and changes in the seasonal cultivation of rice have resulted in land sparing. Land sparing has provided extra land for growing crops other than rice. Furthermore, as incomes have risen in Bangladesh, this has increased the demand for foods other than rice.
- Despite this development, Bangladesh remains heavily dependent on rice for its food supply. Indications are that new technologies are less able to sustain the growth in Bangladesh's rice yield than in the past given that cultivation of HYVs of rice creates significant environmental damage [51]. The rate of growth in its rice yield has tapered off and these yields appear to be approaching a stationary or a near stationary state. One cannot rule out the possibility that they will decline in the near future because of ecological and environmental factors.
- The most important rice crop (*Boro*) is critically dependent on two varieties, BRRI*Dhan*28 and BRRI*Dhan*29 with >60% land area (3 m ha) under cultivation that typify its shrinking genetic rice-resource base. Any outbreak of any plant diseases and/or pest epidemics can result in a significant loss or collapse of the rice crop output similar to the collapse of Bangladesh's wheat output between the late 1990s and early 2000s, and then again in 2016 [52,53].
- Bangladesh's high dependence on its *Boro* rice output has resulted in the over-use of its underground water supplies. Its use of underground water exceeds its recharge in many areas of Bangladesh. Its current water use is, therefore, unsustainable. Consequently, given the high dependence of Bangladesh on rice for its food supplies, its future food security is under threat. While we recognise that the issue of water use requires further investigation, it is beyond the scope of this paper.

This issue has been investigated in some detail by Alauddin and Sharma [28], Hasan et al. [52] and Shah [29].

- In addition, a very high proportion of Bangladesh's farm families depend heavily on rice for most or all of their incomes. Consequently, their income levels are threatened given that the ecological and environmental sustainability of rice yields are in doubt.

The nature of agricultural crop production in Bangladesh does not signify a great deal of sustainability nor does it represent a significant extent of diversification. As a hedge against the possibility of falling rice yields and output, Bangladesh should investigate the desirability of increasing the diversification of its crops both at the national level and at the farm level. Switching to non-rice crops, e.g., vegetables, fruits, pulses, non-rice grains (e.g., wheat) compatible with land suitability will reduce groundwater usage significantly and therefore be environmentally ameliorating and ecologically sustainable. Cropping diversification can also be a key element in reducing income variability and, therefore, risk at the farm level [54] for millions of small farmers. This is likely to promote social and economic sustainability. (Lock in (and associated path dependence) in the use and development of dominant agricultural species (and in some cases breeds of livestock and varieties of crops) can occur for several reasons, some of which are considered in Tisdell [55]. These include R&D being skewed in their favour, the development of technologies that are relatively specific to them and the persistence of consumer food preferences for them. Producers of major agricultural commodities may also form strong political lobby groups and be relatively numerous. Therefore, they are likely to be successful in obtaining more support from governments than producers of less established minor agricultural products.) We recognise that the impact and opportunity cost of the switch from rice to non-rice crops on farm incomes, the environment, storage and risks including biotic, abiotic and market risks warrant a thorough investigation. However, this is beyond the scope of the present study.

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References

1. Diamond, J.M. *Collapse: How Societies Choose to Fail or Succeed*; Viking Press: New York, NY, USA, 2005.
2. Tisdell, C.A.; Svizzero, S. The economic rise and fall of the Silesian Únětice cultural populations: A case of ecologically unsustainable development? *Anthropologie* **2018**, *56*, 21–38. [CrossRef]
3. Tisdell, C.A. Genetic loss in food crops in the Pacific: Socio-economic causes and policy issues. *J. Pac. Stud.* **2016**, *36*, 23–40.
4. Tisdell, C.A. *Economics and Environmental Change: The Challenges We Face*; Edward Elgar Publishing: Cheltenham, UK, 2017.
5. Tisdell, C.A. *Resource and Environmental Economics: Modern Issues and Applications*; World Scientific: Singapore, 2009.
6. Lemaire, G.; Carvalho, P.; Kronberg, S.; Recous, S. (Eds.) *Agroecosystem Diversity: Reconciling Contemporary Agriculture and Environmental Quality*; Academic Press: Cambridge, MA, USA, 2019.
7. Abson, D.J. The economic drivers and consequences of agricultural specialization. In *Agroecosystem Diversity: Reconciling Contemporary Agriculture and Environmental Quality*; Lemaire, G., Carvalho, P., Kronberg, S., Recous, S., Eds.; Academic Press: Cambridge, MA, USA, 2019; pp. 301–312.
8. Leterme, P.; Nesme, T.; Regan, J.; Koreaav, H. Environmental benefits of farm-and-district-scale livestock integration: A European perspective. In *Agroecosystem Diversity: Reconciling Contemporary Agriculture and Environmental Quality*; Lemaire, G., Carvalho, P., Kronberg, S., Recous, S., Eds.; Academic Press: Cambridge, MA, USA, 2019; pp. 335–349.
9. Juhász-Nagy, P. Notes on compositional diversity. *Hydrobiologia* **1993**, *249*, 173–182. [CrossRef]

10. Magurran, A.E. *Measuring Biological Diversity*; Blackwell Publishing: Oxford, UK, 2003.
11. Barbier, E.B. The concept of sustainable economic development. *Environ. Consers.* **1987**, *14*, 101–110. [CrossRef]
12. Brodt, S.; Six, J.; Feenstra, G.; Ingels, C.; Campbell, D. Sustainable Agriculture. 2011. Available online: https://www.nature.com/scitable/knowledge/library/sustainable-agriculture-23562787/ (accessed on 26 August 2019).
13. Cochrane, W.C. *Farm Prices: Myth and Reality*; University of Minnesota Press: St Paul, MN, USA, 1958.
14. Levins, R.A.; Cochrane, W.W. The Treadmill Revisited. *Land Econ.* **1996**, *72*, 550–553. [CrossRef]
15. Tisdell, C.A. *Sustaining Biodiversity and Ecosystem Functions: Economic Issues*; Edward Elgar: Cheltenham, UK, 2015.
16. Marshall, A. *Principles of Economics*, 1st ed.; Macmillan: London, UK, 1890.
17. Chamberlin, E.H. *The Theory of Monopolistic Competition*, 6th ed.; Harvard University Press: Cambridge, MA, USA, 1950.
18. Tisdell, C.A. *Competition, Diversity and Economic Performance: Processes, Complexities, and Ecological Similarities*; Edward Elgar Publishing: Cheltenham, UK, 2013.
19. Mazoyer, M.; Roudart, L. *A History of World Agriculture: From the Neolithic Age to the Current Crisis*; Membrez, J.H., Translator; Earthscan: London, UK, 2006.
20. Brown, C.G.; Waldron, S.A.; Wilkins, J.F. Specialisation and intensification of farming systems in Western China. J. Agribus. *Dev. Emerg. Econ.* **2017**, *7*, 69–80. [CrossRef]
21. BBS (Bangladesh Bureau of Statistics). *Statistical Yearbook of Bangladesh*; Bangladesh Bureau of Statistics: Dhaka, Bangladesh, 2016.
22. Alauddin, M.; Quiggin, J. Agricultural intensification, irrigation and the environment in South Asia: Issues and policy options. *Ecol. Econ.* **2008**, *65*, 111–124. [CrossRef]
23. Rashid, H.E. *An Economic Geography of Bangladesh*; University Press Ltd.: Dhaka, Bangladesh, 1991.
24. Alauddin, M.; Tisdell, C.A. Labor absorption and agricultural development: Bangladesh's experience and predicament. *World Dev.* **1995**, *23*, 281–297. [CrossRef]
25. BBS (Bangladesh Bureau of Statistics). *Yearbook of Agricultural Statistics Bangladesh 2018*; Bangladesh Bureau of Statistics: Dhaka, Bangladesh, 2019.
26. Alauddin, M.; Tisdell, C.A. *The 'Green Revolution' and Economic Development: The Process. And Its Impact in Bangladesh*; Macmillan: London, UK, 1991.
27. BBS (Bangladesh Bureau of Statistics). *Statistical Yearbook of Bangladesh 1997*; Bangladesh Bureau of Statistics: Dhaka, Bangladesh, 1998.
28. Alauddin, M.; Sharma, B.R. Inter-district rice water productivity differences in Bangladesh: An empirical exploration and implications. *Ecol. Econ.* **2013**, *93*, 210–218. [CrossRef]
29. Shah, T. *Taming the Anarchy: Groundwater Governance in South Asia*; Resources for the Future and International Water Management Institute: Washington, DC, USA, 2009.
30. GoB (Government of Bangladesh). *Bangladesh Economic Review*; Government of Bangladesh, Ministry of Finance: Dhaka, Bangladesh, 2018.
31. Asuduzzaman, M.; Toufique, K.A. Rice and fish: Environmental dilemmas of development in Bangladesh. In *Growth or Stagnation? A Review of Bangladesh's Development 1996*; Sobhan, R., Ed.; Centre for Policy Dialogue and University Press Ltd.: Dhaka, Bangladesh, 1997; pp. 447–494.
32. Akter, M.; Fan, L.; Rahman, M.M.; Geissen, V.; Ritsema, C.J. Vegetable farmers' behaviour and knowledge related to pesticide use and related health problems: A case study from Bangladesh. *J. Clean. Prod.* **2018**, *200*, 122–133. [CrossRef]
33. BBS (Bangladesh Bureau of Statistics). *Preliminary Report of Household Income and Expenditure Survey*; Bangladesh Bureau of Statistics: Dhaka, Bangladesh, 2017.
34. Tisdell, C.A. The biological law of tolerance, average biomass and production in a variable uncontrolled environment. *Int. J. Ecol. Environ. Sci.* **1983**, *9*, 99–109; Reprinted in Tisdell, C.A. In *Economics and Ecology in Agriculture and Marine Production*; Edward Elgar Publishing: Cheltenham, UK, 1983.
35. Shelford, V.E. Some concepts of bioecology. *Ecology* **1931**, *12*, 455–467. [CrossRef]
36. Kazal, M.M.H.; Rahman, S.; Alam, M.J.; Hossain, S.T. Financial and Economic Profitability of Selected Agricultural Crops. 2013. Available online: http://fpmu.gov.bd/agridrupal/sites/default/files/ToR%205-Final%20Technical%20Report_MAFI,%20SAU_Dr.Kazal_Submit.pdf (accessed on 28 August 2019).

37. Hossain, M.; Jaim, W.H.M.; Alam, M.S.; Rahman, A.N.M. *Rice Biodiversity in Bangladesh: Adoption, Diffusion and Disappearance of Varieties. A Statistical Report from Farm-survey in 2005*; BARC (Bangladesh Agricultural Research Council) Research and Evaluation Forum: Dhaka, Bangladesh, 2013.
38. Rahman, S.; Kazal, M.M.H.; Begum, I.A.; Alam, M.J. Exploring the future potential of jute in Bangladesh. *Agriculture* **2017**, *7*, 96. [CrossRef]
39. Hirschman, A.O. *National Power and the Structure of Foreign Trade*; University of California Press: Berkely, CA, USA, 1945.
40. Herfindahl, O.C. *Concentration in the US Steel Industry*; Columbia University: New York, NY, USA, 1859.
41. Matsumoto, A.; Merlone, U.; Szidarovszky, F. Some notes on applying the Herfindahl–Hirschman Index. *Appl. Econ. Letts* **2012**, *19*, 181–184. [CrossRef]
42. Tisdell, C.A. Trends in Vietnam's pork supply and structural features of its pig sector. *Open Area Stud. J.* **2009**, *2*, 52–71. [CrossRef]
43. Alauddin, M.; Hossain, M. *Environment and Agriculture in a Developing Economy: Problems and Prospects for Bangladesh*; Edward Elgar: Cheltenham, UK, 2001.
44. Hayami, Y.; Ruttan, V.W. *Agricultural Development: An International Perspective*; Johns Hopkins University Press: Baltimore, MA, USA, 1985.
45. Marshall, D.R. The advantages and hazards of genetic homogeneity. *Ann. N. Y. Acad. Sci.* **1977**, *287*, 1–20. [CrossRef]
46. Simolders, H. *Enhancing Farmers' Role in Crop Development. Framework Information for Participatory Plant Breeding in Farmers Field Schools*; Centre for Genetic Resources, Wageningen University and Research Centre: Wageningen, The Netherlands, 2006.
47. Kabir, M.A.; Sarkar, H.C.; Salam, M.A.; Hoque, M.; Miah, N.M. Genetic composition of improved rice varieties in Bangladesh. *Bangladesh Rice J.* **1994**, *5*, 95–110.
48. Hargrove, T.R.; Coffman, W.R.; Cabanilla, V.L. Ancestry of improved cultivars of Asian rice. *Crop Sci* **1980**, *20*, 721–727. [CrossRef]
49. BRRI (Bangladesh Rice Research Institute). *Adhunik Dhaner Chash*; Bangladesh Rice Research Institute: Gazipur, Bangladesh, 2018.
50. BRRI (Bangladesh Rice Research Institute). Annual Report of the Bangladesh Rice Research Institute 2017–2018. 2018. Available online: http://brri.portal.gov.bd/sites/default/files/files/brri.portal.gov.bd/page/9728b868_efc7_4f0f_926b_bbd4dc7638e3/Annual%20Report%28administration%29-18.pdf (accessed on 28 August 2019).
51. Sabiha, N.-E.; Salim, R.; Rahman, S.; Rola-Rubzen, M.F. Measuring environmental sustainability in agriculture: A composite environmental impact index approach. *J. Environ. Manag.* **2016**, *166*, 84–93. [CrossRef]
52. Hasan, M.M.; Alauddin, M.; Rashid Sarker, M.A.; Jakaria, M.; Alamgir, M. Climate sensitivity of wheat yield in Bangladesh: Implications for the United Nations Sustainable Development Goals 2 and 6. *Land Use Policy* **2019**, *87*, 104023. [CrossRef]
53. Mottaleb, K.A.; Singh, P.K.; He, X.; Hossain, A.; Kruseman, G.; Erenstein, O. Alternative use of wheat land to implement a potential wheat holiday as wheat blast control: In search of feasible crops in Bangladesh. *Land Use Policy* **2019**, *82*, 1–12. [CrossRef]
54. Heady, E.O. Diversification in resource allocation and minimization of income variability. *J. Farm. Econ.* **1952**, *34*, 482–496. [CrossRef]
55. Tisdell, C.A. Socioeconomic causes of loss of animal genetic diversity: Analysis and assessment. *Ecol. Econ.* **2003**, *45*, 365–376. [CrossRef]