The Application of Geographic Information Systems to Climate Change & Land Evaluation

A study of the effects of climate change upon crop productivity in a sub-tropical environment

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Doctor of Philosophy

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Summary

This research investigates the contribution that Geographic Information Systems (GIS) can make to the land suitability process used to determine the effects of a climate change scenario. The research is intended to redress the severe under representation of Developing countries within the literature examining the impacts of climatic change upon crop productivity.

The methodology adopts some of the Intergovernmental Panel on Climate Change (IPCC) estimates for regional climate variations, based upon General Circulation Model predictions (GCMs) and applies them to a baseline climate for Bangladesh. Utilising the United Nations Food & Agricultural Organisation's Agro-ecological Zones land suitability methodology and crop yield model, the effects of the scenario upon agricultural productivity on 14 crops are determined. A Geographic Information System (IDRISI) is adopted in order to facilitate the methodology, in conjunction with a specially designed spreadsheet, used to determine the yield and suitability rating for each crop. A simple optimisation routine using the GIS is incorporated to provide an indication of the 'maximum theoretical' yield available to the country, should the most calorifically significant crops be cultivated on each land unit both before and after the climate change scenario. This routine will provide an estimate of the theoretical population supporting capacity of the country, both now and in the future, to assist with planning strategies and research. The research evaluates the utility of this alternative GIS based methodology for the land evaluation process and determines the relative changes in crop yields that may result from changes in temperature, photosynthesis and flooding hazard frequency.

In summary, the combination of a GIS and a spreadsheet was successful, the yield prediction model indicates that the application of the climate change scenario will have a deleterious effect upon the yields of the study crops. Any yield reductions will have severe implications for agricultural practices. The optimisation routine suggests that the 'theoretical maximum' population supporting capacity is well in excess of current and future population figures . If this agricultural potential could be realised however, it may provide some amelioration from the effects of climate change.

Keywords: *Land-Evaluation, Climate Change, Agro-ecological Zones (AEZ), Application of Geographic Information Systems, Crop Productivity.*

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Dedication

It is to the memory of 'Doc' Collins that this work is dedicated -

His kindness, enthusiasm and friendship will never be forgotten.

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Abbreviations & Acronyms

AEZ	Agro-Ecological Zone
ALES	Automated Land Evaluation System
b.	Broadcast Rice Variety
BARC	Bangladesh Agricultural Research Council
BBS	Bangladesh Bureau of Statistics
BRRI	Bangladesh Rice Research Institute
CCC	Canadian Climate Centre
CDP	Crop Diversification Programme
CFC	Chlorofluorocarbon
CO_2	Carbon Dioxide
ET	Evapotranspiration
FAO	Food and Agricultural Organisation
FAP	Flood Action Plan
GCM	General Circulation Model
GFDL	Geophysical Fluids Dynamics Laboratory
GIS	Geographic Information System
HI	Harvest Index - economically useful fraction of net biomass of crop
HYV	High Yielding Variety
IBRD	International Bank for Reconstruction & Development
IIASA	International Institute for Applied Systems Analysis
IPCC	Intergovernmental Panel on Climate Change
LAI	Leaf Area Index - area of green leaves per unit of ground surface
LECS	Land Evaluation Computer System
LESA	Land Evaluation Site Assessment
LUT	Land Use Type/Land Utilisation Type
MB	Megabytes (1 million bytes)
PET	Potential Evapotranspiration
ppm	Parts Per Million
RAM	Random Access Memory
SODAPS	Soil Survey Data Processing System
t.	Transplanted Rice Variety
UKCCIRG	United Kingdom Climate Change Impacts Review Group
UKMO	United Kingdom Meteorological Organisation
UNDP	United Nations Development Program
UNEP	United Nations Environment Program
USAID	United States Agency for International Development
USDA	United States Department of Agriculture

Chapter 1

Introduction

1.1 Context & Problem Statement

Agriculture is fundamental to many third world economies. Climate change has the potential to significantly alter the ability of sub-tropical countries to support their expanding populations by affecting their agricultural systems. In Bangladesh, for example, 58% of the 120 million population were employed in agriculture in 1987 (BBS, 1988). When combined with the challenges of managing economic development in a country already blighted by natural disasters, lack of resources, political instability and over-population, the additional impacts of climate change could prove significant.

This study is intended to redress the imbalance of research in relation to the impacts of climatic change upon sub-tropical regions, using the Bangladesh agricultural system as an example. The few studies of the impacts of climatic change upon Developing countries have generally been specifically concerned with the effects of sea level rise whilst the broader implications, for agriculture for example, have generally been ignored. Detailed studies of the potential regional impacts of climatic change upon agricultural systems in the Developing world also remain scant.

Present knowledge is unable to suggest whether climate change is likely to increase or decrease the agricultural productivity in the sub-tropics, since current limitations to regional climate modelling techniques are inadequate for the detailed predictions necessary for this type of evaluation. This research intends to apply informed opinion and the suggestions of the Intergovernmental Panel on Climate Change's predictions of regional climate change, to the United Nations Food & Agricultural Organisation's Agro-ecological Zones Methodology (FAO, 1978a) and to assess the extent that a Geographic Information System (GIS) can facilitate this process.

1.2 Research Strategy

The study examines the various methods of climate prediction and modelling currently available and the main alternative methods used for land evaluation, detailing the rationale for choosing to adopt the FAO Agro-ecological Zones (AEZ) Land Suitability Methodology for the project (FAO, 1978a, 1988).

From the few regional climate prediction estimates suggested by the literature for the sub-tropics, a number of General Circulation Model (GCM) derived predictions from the IPCC (1992) for mean monthly temperature, solar radiation and the frequency of the hazard from flooding were identified for application to the study. These variables will be applied to the 1988 baseline climate of Bangladesh, at 26 climate stations across the country and the AEZ land suitability assessment will be used to quantify the changes in potential yields that may occur in 14 of the major crops of Bangladesh. The FAO AEZ methodology will be used to rate the land according to various land suitability 'classes' both before and after the chosen climate change 'scenario'. The suitability of the crops will be assessed by the presence, absence or levels of specified climatic requirements (temperature and rainfall, for example), internal soil requirements (soil temperature, depth etc.) and external soil requirements (slope, flooding etc.).The suitability will be determined by matching land qualities, through a process of overlaying maps of land information within the GIS and then assigning suitability classes to each category.

In order to undertake the suitability assessment process after applying the climate change scenario, it will be necessary to delimit new boundaries to the Climatic Resources zones originally designated by the FAO. No previous attempt has been made to modify these zone boundaries, so this will present the first attempt at achieving this.

The project aims to redesign the land evaluation methodology to incorporate a Geographic Information System (GIS) - IDRISI, and to evaluate the contribution that the GIS could make to improving the current land suitability process, which often relies upon manual map overlay techniques. These techniques have inherent limitations, detailed in Chapter 5, which the GIS may be able to reduce or eliminate. In addition, the availability of facilities within the GIS such as 'interpolation' or 'overlaying' data may prove to be useful. Parametric modelling, such as that provided by the AEZ methodology, whereby layers of information are combined and compared, appears to be especially suited to the application of GIS technology.

The GIS will be used in conjunction with a specially designed spreadsheet based upon the FAO AEZ crop yield model (FAO, 1978a). The spreadsheet was developed to provide a cheap, simple and reliable alternative to the computer model currently used to determine the constraint free yield of crops. These yield calculations will then be repeated for each of the crops in the study both before and after the climate change scenario and the results compared. The final land suitability classes derived for each land unit will be applied to the GIS and then be used to reduce the constraint free yield figures to provide the actual potential yields available for each crop. The final yields before and after the scenario, may then be compared within the GIS to provide an indication of the impacts of climate change upon crop productivity.

In response to the imprecision that currently surrounds sea level rise estimates, the impacts of sea level rise have been excluded completely from this work. The restrictions of time would not provide for inclusion of such a broad area and the number of variables altered had to remain manageable, so that possible causal relationships could be identified. In addition, predictions of the actual rise in sea levels are continually falling, reflecting the necessity for additional research into this and other neglected areas of relatively increasing importance.

Having determined the absolute effect of the climate change scenario in terms of the alteration in various crop yields, a simple optimisation routine will be applied to the major staple crops (all varieties of rice, wheat and potato) using the GIS, to provide an indication of the 'theoretical' maximum population supporting capacity of the land, before and after the climate change scenario, if the most calorifically significant crops were to be cultivated on each land unit.Thus providing an indication of potential population supporting capacities under present conditions and a benchmark for future development opportunities and strategies.

Technology, economics and national policy, in addition to climate act to influence crop yields, but the principal aim of this study is to assess the impact of climate change upon agriculture in the absence of significant technological change. This project does not attempt to anticipate any adaptation, technological innovation or other measures to diminish the adverse effects of climate change that may take place during the time frame of the research. It will be assumed therefore that the level of technology will remain relatively constant, although a differentiation between low and high levels of technology is incorporated into the land suitability assessment so that it will be partially considered. A section is included however, that suggests some of the major developments that may take place in the agricultural sector in the future, such as crop diversification techniques, which may act to ameliorate any negative effects (Chapter 10).

The research was initiated with an extensive literature review of the agricultural and economic regime in Bangladesh (Chapter 2), an examination of current research in relation to climate change, climate modelling (Chapter 3) and the alternative land evaluation techniques in use (Chapter 5). Having established which land suitability model to employ (Chapter 5), a three month period was spent in Bangladesh researching this model and the agricultural regime in more detail and collecting as much relevant data as possible, followed by a similar data collection visit to the Food & Agricultural Organisation Headquarters in Rome. Based upon the literature, the results from General Circulation Models (GCMs) were identified as the most appropriate to the study and several climatic variables from these GCM estimates were identified for application to the 1988 baseline climate of Bangladesh (Chapter 3). After carefully examining the FAO AEZ methodology, which is presented in the three sections of Chapter 8, a spreadsheet was designed to replicate the two processes of the land suitability assessment and the methodology used to predict the unconstrained yield of the crops, together with the application of the GIS to the methodology (Chapters 5 & 8). The climatic variables were then applied to the baseline conditions and the crop productivity was quantified both before and after the climate change scenario; all results have been collated in Appendix A6. A simple crop calorie optimisation procedure was undertaken to try and estimate whether the potential supporting capacity of Bangladesh could 'theoretically' be sufficient to sustain present and future populations (Chapter 9). The results of the land suitability assessment, the changes in crop suitability and the results from the optimisation routine are discussed in Chapter 9 together with the overall assessment of the success of the entire methodology. Finally, Chapter 10 provides a discussion of the possible changes that may occur in the agricultural system of Bangladesh in the future, in order to highlight other variables that may act to affect crop productivity in either a positive or negative manner.

It must be noted that this is not an official document, and therefore the results and opinions derived therein represent the personal interpretation of information gathered from many different sources. All original digital format data have been erased.

Chapter 2

The Geography, Economy & Agriculture of Bangladesh

2.1 Introduction

The following section outlines briefly the major geographical and physiographical features of Bangladesh and the prevailing climate regime, particularly in relation to agriculture. Details of the 14 crops chosen for the project are also included, and because of the significance of rice to the Bangladesh economy a section specifically detailing the alternative rice crops has been included. The alternative cropping patterns are also provided, together with a discussion of the major aspects of the agricultural economy. A detailed account of agriculture in Bangladesh is provided by Hossain (1991) in his book of the same name, if further information is required.

2.2 Physiography

Bangladesh is in effect the largest deltaic plain in the world. Physiographically, Bangladesh consists of 3 major units: hills, terraces and floodplains (see also Section 6.7.5). 80% of the land mass consists of fertile alluvial lowland, known as the Bangladesh plain. The country covers 820 km (north-south) and 600 km (west-east), occupying a surface area of approximately 140,000 km². 10,000 km² of this land area is covered with water. With the exception of the hill tracts to the northern and eastern parts of the country, the average elevation is less than 10 m above sea level. Hence, during the monsoon the deltaic plains are subject to frequent flooding. At its maximum extent the worst incidence of flooding in 1988 inundated over 60% of the land area. Based upon the 30 year mean, flooding inundates 20% of the land area each year (Mahtab, 1989).

2.3 Population

The population of Bangladesh is currently estimated at over 120 million (United Nations), approximately 84% of the total population live in rural areas (Hossain, 1991). The distribution of the population in 1981 and 1985 is shown in Table 2.1. The highest population density is in the Dhaka division, with the highest density of all districts in the capital Dhaka. Due to the increasing population, all districts have seen an increase in population densities, although the relative population distribution remains almost constant.

2.3.1 Population in The Future

Estimating how population will increase during the 50 year period of the climate change scenario, is difficult to achieve and somewhat artificial, since it is impossible to predict how any population will change over such a large time scale. On average, however, the populations of countries undergoing development, can be seen to exhibit a similar pattern of development. Usually, an initial increase in birth rate is experienced as medical facilities etc. improve and death rates decrease, this period is followed by a period of declining birth rates as further development occurs and the population appreciates the reduced necessity to reproduce.

Table 2.1 Distribution of Population Density by Division & District

Region	Land Area	Regional	Est. Population ('000)		Regional Share of		Density per Sq. km	
Rangpur	9,596	6.64	6,716	7,505	7.5	7.5	699.87	782.10

Source: BBS Statistical Yearbook (1989)

With this in mind, an attempt has been made to give some indication of how population figures could alter during the fifty year period from the 1988 climatic baseline. The range of projections from the Bangladesh National Physical Planning Project (1984) have been used to provide the exponential growth rates applied and the United Nations estimate that the population will reach 235 million by the year 2025. The 1988 baseline population of 106 million (Navin & Khalil, 1989) with an exponential growth rate of 2.08 until 1996, followed by a lower growth rate of 1.8, would produce a population in the year 2038 of approximately 267 million people. An exponential birth rate of 2.10 for the 1994 population of 120 million, would swell the population to 295 million by 2038. Whilst a more conservative exponential birth rate of just 1.86 for the 1994 population of 120 million would provide a population of 265 million by 2038.

Even within these broad boundaries it is obvious that the increases in agricultural productivity will have to be substantial if current trends are to be accommodated. Clearly action is required before the population increase is allowed to reach these or similar proportions. What the figures do reveal however, is that even adopting a relatively low growth rate (1.86), the population of Bangladesh is already so large that unless significant changes are made to both reproductive patterns and agricultural systems, Bangladesh will be unable to support its population. In addition, any reductions in productivity as a result of climate change will simply exacerbate the situation.

2.4 Agriculture in Bangladesh

The prevailing climate and the physiographic resources of Bangladesh provide agricultural conditions that, on one hand produce one of the most fertile areas of the world, whilst simultaneously falling victim to natural devastation including, floods, cyclones, hail storms and ironically, drought. In addition to natural phenomena, Bangladesh is also subject to the classical development problems: political instability, lack of mineral resources, rapid population growth, high population density and low agricultural yield.

The great majority of the population of Bangladesh rely upon agriculture for a living, 47% of the GDP in 1987, 58% of total employment and 40% of foreign exchange was generated by agriculture (BBS, 1988: FAO, 1993). During the same period, 65.5% of the economically active male population was engaged in agricultural activities, particularly in rural areas (BBS, 1988) with an average farm holding size during 1984 less than 2.5 acres. The agricultural labour force also suffers from high under employment due to the highly seasonal nature of agricultural activities.

2.5 Crops Chosen for the Project & Land Utilisation Types

14 crop species, including 8 varieties of rice were considered in the assessment, to correspond with the 14 crops identified in The Land Resource Appraisal of Bangladesh (FAO, 1988) as the most important to Bangladesh, in relation to production and areal extent. The crops are listed in Table 2.2.

2.5.1 Land Use Types

Each of the crops was considered at two levels of input, low and high. The attributes of these input levels are listed in Table 2.3 forming the basis for defining the Land Utilisation Types used in the assessment. A Land Utilisation Type (LUT) is a kind of land use, defined in more detail according to a set of technical specifications in a given physical, economic and social setting (FAO, 1983) see discussion by Beek (1974, 1975a, 1975b, 1978). The final 18 LUTs used in the project are listed in Table 2.4.

The land suitability assessment in Chapter 8II is applied to all the crops listed in Table 2.2 above, but the final stage of the evaluation, involving the optimum uses of the land will concentrate upon staple crops only, namely: the aus and aman varieties of rice, wheat and potato, which together constitute 85% of cultivated crops.

2.5.1.1 Rice Production

Due to the overriding importance of rice to the agricultural economy of Bangladesh, the following section discusses the varieties available and the alternative cropping patterns adopted. Rice production in Bangladesh may be sub-divided into 3 distinct rice seasons: the winter or rabi; the early monsoon, approximately equivalent to the northern hemisphere's spring; and the main monsoon, spanning the northern hemisphere's summer and autumn. The three rice crops are boro, aus and aman.

Table 2.2 The Crops Adopted for the Project

ID No	Common Name	Latin Name
1	Spring wheat	*Triticum aestivum*
2	White potato	*Solanum tubersum*
3	Rabi mustard	*Brassica juncea*
4	Lentil	*Lens esculenta*
5	Local boro	*Oryza sativa*
6	HYV boro (early maturing)	*Oryza sativa*
7	HYV boro (late maturing)	*Oryza sativa*
8	Local broadcast aus	*Oryza sativa*
9	Local transplanted aus	*Oryza sativa*
10	HYV transplanted aus	*Oryza sativa*
11	Jute	*Corchurus capsularis*
12	Jute	*Corchurus olitorius*
13	Local transplanted aman	*Oryza sativa*
14	HYV transplanted aman	*Oryza sativa*

Table 2.3 Attributes of Land Utilisation Types

Attribute	Low Inputs	High Inputs
Market Orientation	Subsistence production	Commercial production
Capital Intensity	Low	High
Labour Intensity	High, including uncosted family labour	Low, family labour costed if used
Power Source	Manual labour with hand tools	Mechanised
Technology	Traditional cultivars. No fertiliser or chemical pest, disease and weed control. Fallow periods. Minimum conservation measures.	High yielding cultivars including hybrids. Optimum fertiliser application. Chemical pest, disease and weed control. Increased conservation measures
Infrastructure	Market accessibility unnecessary. Inadequate advisory services	Market accessibility essential. High level of advisory services and application of research findings
Land Holding	Small, fragmented	Large, consolidated
Income Level	Low	High

Table 2.4 Land Utilisation Types Used in the Project

Crop	Rainfed	
	Low Input	High Input
Wheat	*	*
Potato	*	*
Mustard	*	*
Lentil	*	*
Local Boro Paddy	*	
HYV Boro (early)		*
HYV Boro (late)		*
Local B. Aus Paddy	*	
Local T. Aus Paddy	*	
HYV T. Aus Paddy		*
Jute	*	*
Local T. Aman Paddy	*	
HYV Aman paddy		*

Each * represents a Land Utilisation Type

During the Green Revolution, the International Rice Research Institute (IRRI) and the Bangladesh Rice Research Institute (BRRI) introduced high yielding strains which have been readily accepted by farmers.

i Boro or Winter Rice

The earliest success came with boro varieties, suited to the dry conditions of the rabi season (see Section 2.7). The high yielding varieties are generally transplanted around January/February for harvest in May/June. Cold resistant varieties that could be planted earlier to mature sooner have not yet been developed. Two varieties of HYV boro can be identified, early maturing and late maturing, both of which require irrigation. The most popular HYV remains IR-8 developed in 1966. The local varieties are more cold resistant, are transplanted two to three weeks earlier, tolerate deeper water because of their taller structure and mature from about early May onward.

During the dry season the boro rice crop is usually artificially sustained by use of irrigation. Only rainfed crops are considered for the project, thus the boro crop should be classified by the project as unsuitable for the vast majority of areas. It was considered necessary to include this variety however, to ascertain whether the climate scenario would have any positive effects upon boro rice production potential and to determine which growing conditions were not limiting, such as temperatures, soils etc.

ii The Aus or Spring Rice

Most HYV boro varieties can actually be planted as late as the second half of May if there is no risk of flooding, ripening between late May and late August and therefore corresponding to the aus period. The critical factor to success of these late planted crops, is that there must be flood protection for planting after late March. The HYV aus, despite being the same variety as the HYV boro generally yields less, due to the seasonally reduced amount of incoming solar radiation. The local aus varieties are usually broadcast in lowland areas in March/April, ripening in late July or early August to escape August flooding, but often suffering the effects of drought. This provides a short-term low yielding 'hungry gap' crop, to provide food before the main aman harvest. Although the risks from flooding at harvest time are great and it is often severely damaged or destroyed, making it the most risky of the crops.

A recent development in areas with access to irrigation is to use the local aus as a third crop. It is transplanted after the boro harvest in early June, matures in August and can be followed by HYV aman. Another system to grow three crops is to follow HYV boro with HYV transplanted aus. It matures in late August and can therefore be followed by the photosensitive local transplanted aman (see below) in September. It must be remembered that both systems require irrigation, flood free conditions and readily available means to prepare the land without delay between crops. This third crop provides an additional 42% to the net cropped area, which stood at 8.2 million ha in 1990/91 (EIU, 1993), of this net cropped area 40% was single cropped, 48% double cropped and 12% triple cropped (see Table 2.5). The three crop rotation is the most intensive cropping option available, although not generally adopted due to the limitations of soil exhaustion and costs, but this triple cropping may provide a possible way forward in the future. This option is discussed in Chapter 10.

iii The Aman or Main Season Rice

Two kinds of aman rice can be identified: fixed height and floating, which can grow with the rising water.Traditionally, the former is transplanted and the latter broadcast, although a recent development initiated by farmers, is to transplant the floating variety.

a Fixed Height Aman

The fixed height, or transplanted aman (t. aman) is the main rice crop of the country and is grown over the largest area. All the traditional local fixed height aman varieties are photosensitive, but the earlier HYVs are not. Non photosensitive species tend to suffer pollen sterility if planted late, with a severe reduction in yield as a consequence, if the cool weather starts early. As a result, earlier HYV t. aman must not be planted later than the second half of August. In contrast, local varieties can be planted as early as mid-July or as late as the end of September. Late planting does reduce yields however due to the decrease in the length of the growing season, but crop security is improved. However, some more recent releases of HYV from BRRI, which are slowly gaining popularity (FAP 2, 1992) have managed to overcome this problem.

Table 2.5 Land Utilisation in Bangladesh ('000' ha)

1 provisional
2 Simple addition of single, double & triple cropped area
3 Addition of single cropped area, twice double cropped area & three times triple cropped area

Source: BBS, Monthly Statistical Bulletin of Bangladesh

b Deepwater Rice

Deepwater rice is broadcast at the same time as aus, in April, and is the most adaptable of the three species. It is strongly photosensitive and does not mature until late November or early December. In certain instances aus and aman are sown together to ensure that at least one crop is successful, the aus is then selectively harvested in August, leaving the aman to face the rising waters. Deepwater aman can withstand water rising at 10 cms per day, if it is not excessively sudden. The photosensitive nature of the species means that it can be broadcast after boro. Although this is unusual because June plantings do not have sufficient time to develop to the stage where they can withstand the rise of water in August, this too is a risky practice.

Another innovation is to transplant deepwater rice after boro. This practice is more likely to be successful than late broadcasting, since the seedlings are usually about 1 metre tall, establish rapidly and therefore have a better chance to withstand August floods, than if broadcast in June.This practice is gaining popularity, but is constrained by labour shortage at the time of the boro harvest, which takes priority over preparing for a more risky crop.

The dates of planting and harvesting obviously fluctuate in relation to the prevailing weather conditions, (in particular the onset of the monsoon) flooding levels and rates of increase. Yields also fluctuate on a yearly basis, Mowla (1978) proposed that fluctuations in rice yield in Bangladesh are mostly related to fluctuations in annual rainfall, and by damage to rice caused by the frequent floods and cyclones.

2.6 Crop Production

Of the 140,000 km^2 land area of Bangladesh 67% is currently cropped (National Water Plan, 1986). Rice production is the main stay of the agricultural sector (see Section 2.5.1.1) it claims approximately 80% of total production, broadcast (b.), transplanted (t.) and deep water aman constitute the main rice crop and aus, the second largest. Aman constitutes just over 57% of this figure, boro 16% and Aus 27%. Wheat contributes 4%, Jute 6% and all other crops the remainder (BBS, 1988). According to Fabbri (1992) Bangladesh has 105,000 km^2 of land under cultivation, 89,000 km^2 of which are under rice (85%).

Table 2.6 provides the figures for the production of foodgrains between 1974 and 1989 and Table 2.7 the production of selected non-foodgrain crops between 1974 and 1987.

From the figures presented in the tables, the decline in food production per capita is obvious, in fact, the growth of food output has lagged behind population growth during the past 30 years. If this trend continues, the gap between food requirement and production will widen dramatically. For the foreseeable future therefore, increased agricultural production will be one of the most important requirements to help alleviate poverty and to create employment in the Bangladesh economy. The average per capita calorific intake is approximately 85% of the daily requirement and only 24% of the population receive the minimum calorific requirement or above (INFS, 1983), this too will decline if current population trends continue.

Table 2.6 Production of Foodgrains in Bangladesh Between 1974-1989 ('000' metric tonnes)

Source: BGD Food Directorate; World Bank; BBS Bulletin; USAID, Dhaka.

Table 2.7 Production of Selected Non-Foodgrain Crops in Bangladesh Between 1974-1987 (million metric tonnes)

Year	Jute	Tea	Tobacco	Sugarcane	Potato	Oilseed	Pulses

the same time series data on the least squares method.

[2] BGD USAID estimates as of June, 1989.

Source: BBS Agricultural Yearbook 1986; BBS Bulletin, 1988; IBRD.

Even during the 1970s scholars at Harvard University postulated that with the then technology Bangladesh was capable of producing 50 million tonnes of foodgrain, whilst in reality the actual output was only about 12 million tonnes (Hossain, 1991). Clearly Bangladesh has the capacity to increase agricultural output, but it is debatable whether an unstable agricultural system, stretched to its environmental limits will be able to support both the growing population and the impacts of climatic change.

2.6.1 Crop Productivity

The project provides an estimate of possible crop productivity. To facilitate comparision with other yield estimates, figures indicating suggested yields for some of the Bangladesh crops are provided in Table 2.8. Up to date yield figures for all the study crops specifically for Bangladesh, were extremely difficult to obtain, particularly in realtion to high and low yielding varieties, but the figures represent most crops for comparison purposes.

2.7 Climate and Growing Seasons

Bangladesh has a humid sub-tropical climate which is suitable for growth and cultivation of a wide variety of crop species. The climate may be broadly summarised by several features:

i. The highest temperatures prevail between the last week in March and early May.
ii. June is a transitional period, temperatures begin to decrease with the onset of the monsoon rains. Heavy rainfall is experienced from June to October.
iii. A period of equable temperatures prevails from July to September.
iv. There is a steady fall in maximum and minimum temperatures from October to the end of December.
v. The coolest period prevails from the last week in December to the last week of January.
vi. February is a transitional month, preceeding the three hottest months.

Table 2.8 Predicted Yields in t/ha for Crops in Bangladesh

Yield (t/ha)

- Computed Potential Yields for Example District of Bogra

The cropping pattern and potential productivity of the land are determined by four climatic factors: rainfall, evaporation, temperature and solar radiation, in combination with local physiography and depth and timing of inundation. Intensity of cropping is more specifically influenced by the time of onset of the monsoon rains, the amount and distribution of rainfall, the occurrence of natural calamities (such as storms and cyclones) and the length of flooding periods. Bangladesh farmers therefore have to make provision for natural disasters in their cropping programme, generally requiring a deviation from 'optimum' techniques available to other less calamity prone countries.

Crops are grown throughout the year in three distinct growing seasons, these are:

The kharif - The hot spring or pre-monsoon season. Lasting from the end of March to May. The temperature and evaporation rates reach their highest in this season. Rainfall occurs with occasional heavy thunder storms, damaging hail storms and cyclones.

The 2nd kharif - The hot monsoon season, from May to September. Characterised by high humidity and low solar radiation. More than 80% of the total annual rainfall occurs in this period. Kharif crops include: rice, jute, sugarcane, maize, soybean & sesame. The high soil moisture and flooding means that nearly 80% of the rice crops are grown during this season (Hossain, 1991), but the high risks from flooding induce farmers to adopt flood resistant rice varieties, which are generally low yielding.

The rabi season - The cool dry winter season, from mid-October to early March. There is negligible rainfall, low humidity and high solar radiation. Rainfed crops rely upon residual soil moisture. Winter foodgrain crops can not be grown without irrigation during this period. Rabi crops include: boro rice, wheat, mustard, groundnuts, potatoes, pulses, spices & vegetables.

2.7.1 The Growing Periods

Defining the length of the growing periods is fundamental for the land suitability assessment. The rainfed growing period from the moisture viewpoint has been defined by the FAO (1988) for the rabi and kharif seasons, by land type. For crop production, a soil moisture supply from rainfall and soil moisture storage of greater than half the potential evapotranspiration is considered potentially suitable for crop growth.

The Reference Kharif Length of Growing Period may be defined as:

> *the period during which moisture supply rate from rainfall (P) plus the contribution from available soil moisture storage (Sa) exceeds half the potential evapotranspiration (PET) rate.*

For rainfed dryland situations it approximates to 0.5 Potential Evapotranspiration (PET) during crop emergence in the field, as confirmed by empirical evidence from Kowal & Kassam (1978).

The Reference Rabi Length of Growing Period may be defined as:

> *the period after the end of the humid period when the moisture supply rate from rainfall and an assumed 250 mm of soil storage, exceeds 0.5 PET (see Figure 6.5)*

The length of the growing period from a climatic view point alone, and independent of crop, land type, soil and landform is defined in a reference manner by the FAO (1988). In the climatic resources inventory (described in Section 6.3) reference lengths of kharif and rabi growing periods are defined by combining information on reference length of growing period with information on land type specific inundation regime. These reference growing periods are then utilised for the agro-climatic suitability assessment (Section 8.2). Chapter 6 details the methodology used to delimit the reference moisture and thermal zones used to represent the growing periods.

2.7.2 Cropping Patterns

The cropping system in relation to rice alone is extremely complex, when considering other crops too the number of cropping pattern alternatives is immense. For the country as a whole there are nine basic cropping patterns with 60 variations of these, depending upon local agro-ecological conditions. Considering all the regions of Bangladesh together (Hossain, 1991), the most common cropping pattern is:

> *transplanted aman - fallow, aus/transplanted aman - fallow, mixed aus & broadcast aman - rabi and boro or broadcast aman - fallow.* Jute replaces aus in some parts and sugarcane is grown in all regions except Chittagong.

For the most popular alternatives, Figure 2.1 provides a schematic representation of the main cropping patterns used in Bangladesh. It must be remembered however, that the cropping patterns described are highly generalised and that in reality there are wide local differences.

2.8 Summary

This chapter has provided a brief insight into the pertinent areas of the agricultural system of Bangladesh, the crops chosen for the project and the types of cropping pattern alternatives available. In reality, the agricultural system of Bangladesh is extremely complex and the socio-economic factors affecting the system are numerous. The project makes no attempt to quantify these socio-economic factors, quantification of a subject of this magnitude falls outside the realms of the study. Chapter 10 does however attempt to make some provision for changes that may take place in the agricultural system, over the lifetime of the project. The results may then be discussed within some formal context and the significance of the proposed yield changes may be assessed.

Figure 2.1 **Cropping Patterns of Bangladesh**

Source Navin & Khalil (1989)

Chapter 3

Climate Prediction & Modelling

3.1 Introduction

To estimate the likely effects of climate change on agricultural productivity, it is necessary to obtain a quantitative representation of possible future climate change. The significant climatic variables may then be modified within the FAO-AEZ methodology described in Chapter 8, to provide an indication of potential climatic impacts upon the yields of the crops. Since climate change can not be accurately predicted, a plausible climate change 'scenario' is to be applied as a surrogate.

The following chapter details the rationale for the choice of the climate change modelling parameters. It is intended to provide a brief summary of the most quoted climate models available, avoiding excessive detail, the reader is directed therefore to the appropriate literature if further information is required. A discussion of the relative limitations of General Circulation Models (GCMs) is also included.

Having established the key climatic parameters to modify and having determined the possible magnitude of the change in theses values, for example mean daily temperatures may alter by 1°C, the variables will be applied to the 1988 baseline climate of Bangladesh (FAO, 1988 Report 3, Volume 1), to predict the possible impacts upon crop yield and ultimately upon population calorific availability.

3.2 Methods of Climate Prediction

Numerous methods of climate prediction are available, two main approaches to climate prediction are the 'analogue method' and 'numerical modelling'. The former estimates future climate change based upon reconstruction of past climates from palaeo-climatic data. The latter, uses first principles for climate simulations based upon equations believed to represent the physical, chemical and biological processes governing the atmospheric circulation. The former method essentially relies upon historic data sets and is therefore limited to predicting climates that have already been observed or are not caused by new processes. The latter is not restricted to historical data in this manner and allows the prediction of climatic scenarios formed as a result of climatic processes never experienced before. Thus the more suitable approach for climate prediction for this particular study, to predict conditions or forcings different from the present, is that of numerical general circulation modelling.

3.3 General Circulation Models (GCMs)

Numerous atmospheric models with various spatial resolutions are currently available to predict climatic parameters. Ranging from the most basic, zero-dimensional models, which measure the average global temperature independent of time, to extremely elaborate 3-dimensional General Circulation Models (GCMs). Most recent predictions of climatic change often utilise GCMs. Derived from weather forecast model representations GCMs are physically based, numerical, 3-dimensional models of the climate system. GCMs are the only available means to consider simultaneously the wide range of interactive physical processes that characterise the climate system and its geographical distribution, they provide the most accurate predictions for climatic change currently available. The climatic parameters used in this project have been based upon the results from GCMs.

3.3.1 GCM Methodology

In a GCM experiment, a control run is used to simulate the existing climate using prevailing CO_2 concentrations (approximately 350 ppm). This is then compared to a perturbed run when CO_2 concentrations are doubled or quadrupled. In this 'switch on' experiment, both model runs are allowed to reach equilibrium and the resulting climates are compared. The actual difference is recorded and is usually expressed in terms of global mean surface temperature (often referred to as the 'climate sensitivity') (Warrick & Jones, 1989).

GCMs are available for a network of grid points, with spacing varying between 4-8° latitude and 5-10° longitude, according to the particular GCM. The models generally show the simulated change in daily or monthly averaged climatic variables (temperature, precipitation and cloud cover) between 1 x CO_2 (present-day or baseline climate) and 2 x CO_2 (future) equilibrium conditions. They conventionally have 2-19 vertical layers, a horizontal resolution of 30 to 1000 km and a time step ranging from 10-40 minutes (Schlesinger, 1983).

3.3.2 GCM Limitations & Deficiencies

GCMs are currently the best models available to evaluate potential impacts of climate change, and although essentially similar in design, variations do exist in the projections that they make. For example, the way that processes are simplified for computational expediency provides different model results and different GCM structures (Warrick & Jones, 1989). The reasons for other anomalies, the major limitations and areas for error of the GCM are discussed in the following section.

3.3.2.1 Paramaterisation

The limited spatial resolution of the GCM prevents some of the important processes in the climate system from being resolved. Thus, a process known as 'paramaterisation' is applied to these variables. Based upon both observation and theoretical studies (Schlesinger 1983), the sub grid-scale physical processes are represented, on the scales resolved by the GCM using information available only on the resolved scales (wind, temperature, humidity and surface pressure).

The variables commonly paramaterised in GCMs are shown below:

(From: Schlesinger, 1983)

3.3.2.2 Feedback Mechanisms

To accurately model the magnitude and distribution of climate change it is fundamental to consider the role of 'feedback' mechanisms (Cess & Potter, 1988). Essentially, feedbacks introduce non-linearity into the climate system and can either amplify (positive feedback) or moderate (negative feedback) the climate response given by a particular climate forcing (Warrick & Jones, 1989). GCMs are able to replicate some of these 'feedbacks', although there are problems involved with the paramaterisation of these mechanisms. The most significant of these problems are discussed below.

i The Water Vapour Feedback

This is the best understood of the positive feedback mechanisms, recognised originally by Manabe & Weatherald (1967). Essentially, a warmer atmosphere can hold more water vapour. since water vapour is a greenhouse gas this causes a positive feedback to occur (Raval & Ramanathan, 1989) and a further temperature increase to result. This is further enhanced as the water vapour absorbs solar radiation, generating additional heat within the climate system.

The relationship between evaporation and precipitation remains unclear, an increase in surface temperature may lead to increased evaporation and thus precipitation, and globally precipitation may increase 10-20% (Stewart, 1989), although estimates vary.

ii The Cloud Feedback

Future changes in cloud properties may have positive or negative feedback implications. For example, if the global cloud amount decreases because of climate warming, this decrease reduces the effect attributed to clouds. Thus as the earth warms it is able to emit infrared radiation more efficiently, moderating the global warming and so acting as a negative climate feedback mechanism (Mitchell *et al*, 1989). Conversely, there is a related positive feedback, the solar radiation absorbed by the surface atmosphere system increases because the diminished cloud amount causes a reduction of solar radiation reflected by the atmosphere. The situation is further complicated by climate induced changes in both cloud vertical structure and cloud optical properties, which result in additional infrared and solar feedbacks (Cess & Potter, 1988).

Incorporating clouds into the models presents several serious difficulties. Firstly, cloud properties are largely sub-grid scale, thus the thickness of stratus clouds is generally much less than the vertical grid interval of the GCM. Secondly, there are a wide variety of cloud types, each with different radiative properties. The binary description of cloud cover used in the GCM is too over simplified to be of use, ideally necessitating different physical models for the different cloud types. Models therefore, must represent all the radiatively important cloud properties, in particular, fractional cover, height, liquid water content, drop size and spatial scale, if they are to be truly representative.

The third, and possibly most serious difficulty is that the process of cloud formation and cloud radiative properties remains incompletely understood.Diurnal variations of cloudiness for example, are poorly understood, but may be important for determining changes in the radiation balance.

GCMs have attempted to replicate cloudiness, but with little confidence in the results (Houghton *et al*, 1990, 1992). According to Spelman & Manabe (1984) and Cess *et al* (1989) the main reason for inter-model variation is a result of how these cloud-climate feedback processes are simulated. Clearly, a more complete understanding of cloud processes, both temporally and spatially, remains a high priority for future GCM development.

iii Ocean Coupling

Increases of ocean temperature significantly influences CO_2 induced climate change and oceans are also important for their uptake and storage of CO_2. Ocean GCMs are not yet available with enough spatial resolution to resolve the energy-containing eddies as seen in atmospheric GCMs. Rather, at present the most sophisticated ocean models for climate studies are of coarse resolution and heavily influenced by semi-empirical eddy diffusion paramaterisations. Even the coarse-resolution ocean models are not yet being employed in most GCM studies for future climate. GCM studies to date have largely assumed *swamp* or *simple mixed-layer* ocean models, although, both kinds of model neglect entirely horizontal energy transport by the oceans. To date, knowledge regarding the effects of the ocean upon CO_2 uptake remains scant. Hence it is likely to be some time before models can realistically replicate these processes, particularly until computer performance is considerably enhanced.

iv Sea Ice

Modelling of sea ice is particularly important because of its profound effects upon the surface heat flux and radiative feedbacks in high altitudes (see Hibler, 1979 and Hibler & Ackley, 1983). There have been at least 4 basic deficiencies in GCM treatments of sea ice: (a) lack of realistic heat transport (b) unrealistic treatment of the albedo of sea ice (c) unsatisfactory models for cloud properties at the sea ice margins and, (d) oversimplified models of the thermodynamics and dynamics of the sea ice itself.

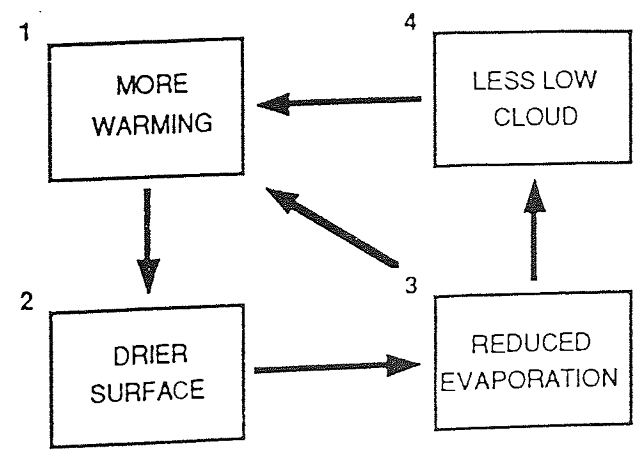
v Surface Albedo

Ocean albedo varies according to a multitude of factors, ranging from solar zenith angle to the scattering of the solar beam by cloud particles. Land surface albedos are even more complex, being dependent upon atmospheric conditions and surface micro-climates. Soil albedo depends upon soil moisture and on soil chemical and physical structure. Both the numerical and conceptual basis for specifying surface albedos in GCMs remain deficient. Numbers have been used for model albedos inconsistent with the available observational studies, and possible changes in surface albedo with climatic change have not been included beyond a crude treatment of albedo change from change in snow and sea-ice cover. General consensus (Cohen & Rind, 1991: Covey *et al*, 1991 & Ingram *et al*, 1989) maintains that current paramaterisation of surface albedo in GCMs remains inadequate.

vi Soil Moisture

Soil moisture has a significant impact upon ecosystems and agriculture. Some models propose a large decrease in soil moisture over land in summer, if temperatures increase. This could create a positive feedback (see Figure 3.1), with higher surface temperatures and decreased cloud cover, resulting from reduced evaporation (Meehl & Washington, 1988). Soil moisture data remains scarce and conventional GCM treatment of soil moisture is still rather crude. The models assume that soil acts as a bucket, which after being filled adds its surplus to runoff. The full bucket evaporates, as would a moist surface until it has lost some fraction of its capacity. At lower levels of water in the bucket, evaporation is assumed to be linearly proportional to its remaining water content. Variations in surface roughness because of differing vegetation cover are usually neglected, thus current model representation remains limited.

Figure 3.1 Schematic Representation of Soil Moisture Temperature Feedback Through Changes in Evaporation and Low Cloud



Clearly, feedbacks account for many of the difficulties in modelling climate change. For more detailed information regarding feedback processes, reference can be made to Washington & Parkinson (1986) or Cess & Potter (1988).

Despite GCMs containing incomplete and somewhat crude descriptions of climate processes, it must be noted that certain deficiencies may in fact make little difference to the projections of future climate. Physically more complex descriptions are usually more complicated and more difficult to understand than are simpler paramaterisations, hence it may be argued that they are often also more susceptible to serious logical or programming errors in their formulation.

3.3.3 Model Validation

Recent efforts have been made to achieve a systematic intercomparison of models to provide greater confidence in their predictions. The WGNE/PCMDI Atmospheric Model Intercomparison Project (AMIP), incorporated virtually all GCMs, to simulate the decade 1979-1988 with common climatic variables. The detailed results are published in Gates (1992) and summarised in Houghton *et al*, (1992), these are presented later in the chapter.

3.4 Transient Response & Coupling or Equilibrium?

The majority of predictions of climate change are based upon equilibrium studies, i.e., when the heating of incoming short wave solar radiation is in balance with the cooling outgoing longwave radiation, the climate system is said to be in equilibrium. Whilst greenhouse gases continue to accumulate in the atmosphere, equilibrium will not be attained. This may call the validity of equilibrium studies into question.

The last few years has seen attention moving away from the equilibrium response to climate change towards transient simulations with coupled atmosphere-ocean models. Since the timing of the atmospheric response to climate change is fundamentally tied to ocean heat uptake, the significance of the influence of the ocean may delay a CO_2 induced warming by several decades.Thus for a realistic climatic model, the atmospheric processes have to be coupled with oceanic heat transport. These models are significantly disadvantaged because of the huge inertia provided by the deep oceans. Consequently the time taken to run the model is lengthy and therefore expensive and a 100-1000 fold increase in current computing, communications and data management capabilities will be required before the models can be realistically utilised (Sharp, 1995).

Coupled models of the ocean-atmosphere system are still in an early stage of development, although Gates *et al* (1992) present the results of the most recent model simulations. In summary, the models are in overall agreement with the IPCC business-as-usual scenario[1] approximating a warming of 0.3°C/decade (Houghton *et al*, 1992), except over the high-latitude Southern ocean and the northern north Atlantic ocean. Thus it was considered that equilibrium response modelling remains a valuable tool for climate change prediction.

3.5 Intergovernmental Panel on Climate Change (IPCC)

The most recent climate change and climate modelling knowledge has been reviewed and synthesised by the Intergovernmental Panel on Climate Change (IPCC) (Houghton *et al*, 1990, 1992; IPCC, 1990, 1992). The IPCC was established in 1988 and includes contributions from several hundred scientists from 25 countries. Divided into three working groups to address: the reasons and mechanisms behind climate change, the potential impacts of climate change and finally, the formulation of strategies to respond to climate change. The IPCC Assessment was recently updated by a Supplementary Report (Houghton *et al*, 1992) which indicates some of the advances made into previously unresolved areas, particularly the results of modelling *transient* climate response, and also a summary document (IPCC, 1992). The relevant findings from these supplementary reports have been combined into this summary.

3.6 Agreements Between Model Predictions

The points of general agreement between models for the main equilibrium changes in global climate due to CO_2 doubling are that:

[1] 'Business-as-usual' represents one of the scenarios of possible future greenhouse gas emission, for use by the IPCC working groups. Also known as the '2030' high emissions scenario, it assumes that few or no steps area taken to limit greenhouse gas emissions. Rate of energy use and clearing of Tropical forests continue and fossil fuels remain the world's primary energy source. Under this scenario, the equivalent of doubling pre-industrial CO_2 levels occurs according to Working Group I (Houghton *et al*, 1990) around 2025.

3.6.1 Temperature

- the lower atmosphere and earth's surface will warm
- the stratosphere will cool
- near the earth's surface, the global average warming lies between +1.5 °C and +4.5°C, with a 'best guess' of 2.5°C,
- the surface warming at high latitudes is greater than the global average in winter, but smaller than in summer
- the surface warming and its seasonal variation are least in the tropics

3.6.2 Precipitation

- the global average increases (as does the evaporation), the larger the warming the larger the increase.
- increases at high latitudes throughout the year
- increases globally by 3 to 15% (as does evaporation)
- the zonal mean value increases in the Tropics although there are areas of decrease. Shifts in the main tropical rain bands differ from model to model.
- changes little in sub tropical areas

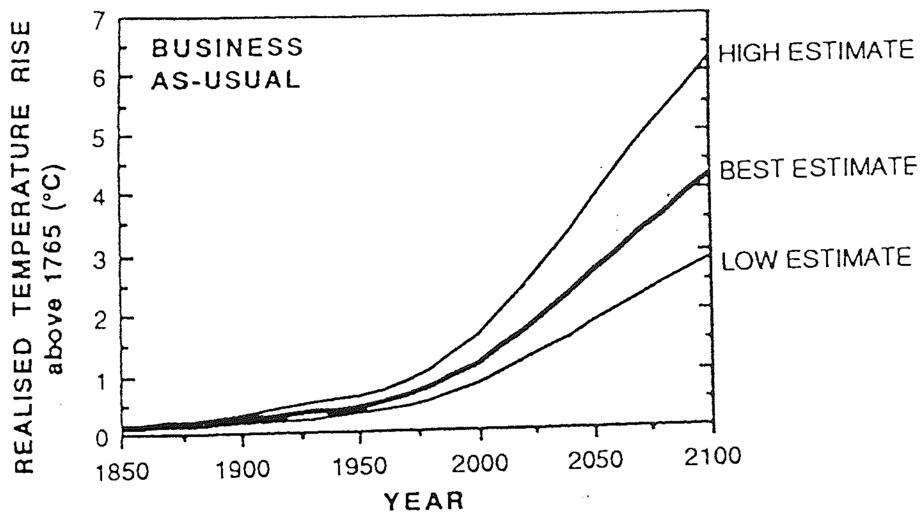
3.6.3 Soil Moisture

- increases in high latitudes in winter
- decreases in northern mid-latitude continents in summer

3.7 IPCC Conclusions

Having considered all available evidence, the IPCC (Houghton *et al.* 1990, 1992; IPCC, 1990, 1992) concludes that the global atmospheric equilibrium sensitivity to **doubled** CO_2 is within the range 1.5-4.5°C, equivalent to 0.2-0.5°C per decade over the next century (Business-as-Usual, 'Best Estimate' Scenario). This will result in a likely increase in global mean temperature of about 1°C above the present value by 2025 and 3°C before the end of the next century. Figure 3.2 below, illustrates the simulations of the increase in global mean temperature from 1850-1990 and predictions of the rise between 1990 and 2100 resulting from the Business-as-Usual emissions (see Warrick & Oerlemans, 1990).

Figure 3.2 Simulation of the Increases in Global Mean Temperature from 1850-1990 & Predictions of the Rise Between 1990-2100 resulting from the Business-as-Usual Scenario



Source IPCC (1990)

Note that the temperature rises shown above are **realised** temperatures; at any time the globe would be committed to further temperature rise towards the equilibrium temperature. For the Business-as-Usual *best estimate* case, for example, a further 0.9 °C rise would be expected, about 0.2 °C of which would be realised by 2050.

The IPCC (Houghton *et al*, 1990) considers that warming may be greater in high latitudes (perhaps 10°C), as sea ice melts back; warming will be less in lower latitudes (perhaps less than 1°C), where evaporative cooling could restrain the change; warming will be greater during the winter compared to the summer and global precipitation will increase on average, especially in mid to high latitudes. Projected temperature changes will vary considerably both spatially and between seasons and specific details regarding regional differences remain scant due to the low model resolution.

The following assumptions were made by the IPCC (1990) in deriving the above estimates:

- The concentrations of the greenhouse gases increase in the IPCC 'Business as Usual' scenario.
- The 'best guess' of the magnitude of the global mean equilibrium increase in surface temperature due to doubling CO_2 (the climate sensitivity) is 2.5 °C.
- The most reliable estimate of the regional patterns of change is given by the high resolution models.
- The patterns of equilibrium and transient climate change are similar.
- The regional changes in temperature, precipitation and soil moisture are proportional to the global mean changes in surface temperatures.
- The changes in global mean temperature can be derived from a simple diffusion-upwelling box model.

A comprehensive list of all the models employed in the IPCC assessment, the research groups involved and the relative features is illustrated in Figure 3.3.

3.8 Regional Modelling

Ideally, for accurate yield predictions the study requires detailed information on a regional scale. In particular, consideration of how regional temperature and precipitation regimes change seasonally during the growing periods, since these changes will vary regionally and in a non-uniform manner.

Unfortunately, at present there is little or no confidence in the projections of regional climate change, firstly because careful validation of GCM simulations of present regional scale features is lacking, and secondly, shifts in continental-scale features are dependent on dynamic and physical details poorly treated in GCMs. Any changes in regional

Figure 3.3 Summary of the Results from Global Mixed Layer Ocean-Atmosphere Models used in Equilibrium 2 x CO_2 Experiments (IPCC, 1990)

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patterns of climate remain speculative therefore (Grotch & MacCraken, 1991 & Hansen *et al*, 1988). As indicated above, the general deficiency of GCMs that their horizontal resolution (typically 250-700 km) is inadequate to replicate most of the regional features of climate, remains one of the most significant hurdles to accurate regional modelling.

3.9 Selection of Climate Model Parameters for the Project

In the light of current knowledge, Working group I (Houghton *et al*, 1990) has attempted to provide an estimate of possible regional climate change for 5 selected areas of the world, incorporating south east Asia. Reference to Figure 3.4 below illustrates the regions studied and their locations. This research represents the only comprehensive regional studies for south east Asia, it is intended therefore to incorporate these results into this project.

Figure 3.4 **Map Showing the Location & Extents of the Five Different Climatological Regimes Selected for the IPCC.**
Bangladesh is in Area 2 (5-30°N, 70-105°E)

Source IPCC (1990)

The estimates of regional temperature, precipitation and soil moisture suggested for south east Asia are shown in Table 3.1. The results are based upon three high resolution models (CCC, GFDL & UKMO - see Figure 3.3), although results from five low resolution models were also included in deriving the estimates. The high resolution models were considered to be of fundamental importance for regional climate prediction, since they provide the most accurate predictions currently available. Two of the models (CCC and UKMO) include the diurnal cycle which, according to the IPCC (1990) provides a more realistic representation of some of the feedback mechanisms, which may influence the quality of their climate simulation. The coupled models, although more highly developed, are still in their infancy and do not provide significantly different results from the non-coupled models (see above); experience difficulties with systematic errors (Trenberth, 1992) and most importantly they are coarse grid and unsuitable for application to regional modelling.

Table 3.1 **Best estimates of changes in areal means of temperature, precipitation and soil moisture over south east Asia, from pre-industrial times to 2030, based upon the Business-as-Usual Scenario. The figures have been scaled to correspond to a global warming of 1.8°C, the 2030 warming associated with the IPCC 'Best Guess' sensitivity of 2.5°C and allowing for the thermal inertia of the oceans (confidence is low)**

Source IPCC (1990)

In essence, the actual climate scenario to be applied to the baseline climate of Bangladesh remains subjective, and the validity of any regional prediction remains low. The intention however, is to demonstrate the methodology involved in calculating the actual impact that a particular climate scenario may have upon the agricultural productivity of Bangladesh, and to demonstrate how the GIS can be used to facilitate the evaluation process. The aim is not to debate the existence of climatic change, but instead to provide a representation of the future climate that would be useful for exploring the application of GIS, preparing for the time when more accurate model predictions become available.

3.10 Figures to be Applied to the Baseline Climate of Bangladesh

Having isolated three regional estimates for the major climatic variables, it becomes necessary to restrict the actual number of variables applied in the project. Modification of all the climatic parameters at this early stage would yield results of limited use, since it would be impossible to isolate any causal relationships between an individual climate variable and any change in crop suitability and/or yield.

The key parameters to crop growth are temperature, water, solar radiation and CO_2, based upon the data provided by the IPCC (Houghton *et al*, 1990), the following parameter changes were applied to the baseline climate figures for Bangladesh:

3.10.1 Temperature

The results presented by two of the models, namely the Canadian Climate Centre Model (Boer *et al*, 1989) or CCC and the United Kingdom Meteorological Office Model (Mitchell *et al*, 1989) or UKMO were in reasonably close agreement regarding temperature change. Both models assume that there is no seasonal variation in this figure. In line with the suggestion by Mitchell & Ericksen (1992) that the temperature increase in the Tropics is expected to be only 50-75% of the global average warming. It was decided therefore to apply the average of both temperature change estimates. Thus, during both the rabi and kharif seasons, the mean daily temperature is to be increased by 1.5°C. This change in temperature will be applied to the model for calculating the unconstrained yield figures and also applied to the agro-climatic suitability assessment, reflected in the movement of the thermal (T- zone) boundaries (see Section 6.8.1)

3.10.2 Precipitation

Precipitation is estimated to increase during the kharif by all models, varying between 5-15%. Estimates during the rabi season present less agreement. Actual precipitation values are not directly incorporated into the land suitability model, soil moisture is considered more directly (see Section 3.10.3 below). Precipitation during the rainy kharif is not limiting to crop growth, thus slight changes in overall amount, will have little effect upon crop growth during this period. Timing and intensity are considered more vital (see Section 3.10.4 below). During the rabi season, rainfall is in such short supply, that again crop growth is more dependent upon soil moisture contribution.

The impact of precipitation although not incorporated directly, has been reflected according to its impact upon solar radiation, since this effects photosynthesis. For the unconstrained yield calculations, the incidence of solar radiation has been increased by 5% during the rabi season, representing a slight decrease in the incidence of rain cloud. During the kharif season the amount of incoming solar radiation has been decreased by 5%, corresponding to increased incidence of rain clouds. The modifications are somewhat arbitrary, but allow for the proposed regional effects of decreased rainfall during the dry season and increased rainfall during the wet.

3.10.3 Soil Moisture

The CCC and UKMO models both estimate that soil moisture may remain unchanged during the rabi season and all three models propose an increase between 5-10% during the kharif. Despite the proposed increase during the rainy season, it was decided that the soil moisture values would remain unaltered. As suggested for precipitation, soil moisture is not limiting during this period, thus a slight increase will have minimal impact. Additionally, it was decided not to modify this figure in order to limit the number of variables being altered simultaneously. Also, because the impacts of sea level rise have been excluded, its contributions to soil moisture would have some effect and would need to be considered to provide a representative estimate.

3.10.4 Flood Hazard & Extreme Events

The soil suitability assessment (Chapter 8II) incorporates a land factor referred to as 'flood hazard', which represents the frequency of flooding events. According to estimates in Section 4.3.2.3 the incidence of extreme precipitation events may increase. To reflect this, the flood hazard ratings were altered to represent an arbitrary increase in flood frequency corresponding to one rating unit, for example, an area with a storm hazard frequency of <2% is reclassed to a storm hazard between 2-6%. These types of event have more impact upon the agriculture of Bangladesh than the average precipitation.

In a similar manner, research estimates an increase in extreme events related to temperature. The agro-climatic suitability assessment considers the frequency of days with temperatures in excess of 40°C, which has a bearing upon crop growth and development. Reference to Section 6.8.2 explains how the extreme temperature - e zones - are modified to represent this for the agro-climatic assessment.

3.10.5 Carbon Dioxide

The data provided by the GCM are based upon doubling of CO_2 levels as described earlier, the direct effects of the increased levels of CO_2 on photosynthesis and water-use efficiency were not considered. Although, Chapter 10 describes some of the possible consequences of increased CO_2 that may need to be taken into consideration in the future.

3.11 Summary

This chapter has provided a brief insight into current climate modelling capabilities, limitations, the models chosen to provide the projections for future climatic change and the climatic variables to be applied to the suitability assessment. The figures indicated in Section 3.10 will be applied to the crop model in Chapter 8III or the suitability assessment in Chapters 8I-II, to indicate the possible effects upon yield as a consequence of this climate change scenario.

Chapter 4

Climate Change & Agriculture

4.1 Introduction

Chapter 3 provided a brief indication of current research regarding the possible magnitude and consequences of climate change. This chapter illustrates specifically the impacts of the major climatic variables upon the agricultural system and some of the possible effects should these variables alter. Increased atmospheric CO_2, atmospheric warming and changes in precipitation patterns, potentially affect the agricultural system. The importance of sufficient soil moisture and the possible effects of increased drought as a result of higher temperatures for example, are well recognised, but effects upon the incidence of pests, disease and weeds under an altered climatic regime, or how increased temperatures may alter evaportanspiartion are less obvious. The major issues for consideration during the latter stages of the project are therefore addressed. The chapter begins by identifying some of the major contributors to the subject, then considers the main areas separately.

4.2 General Impacts

Studies assessing the impacts of climate change upon agricultural potential have limited application to the Developing world, the Tropics in particular are significantly under-represented in the literature. No comprehensive study has been undertaken to assess the impact that climate change could have upon agricultural potential in the Tropics, almost all the data are restricted to mid-latitudes and Developed countries. Parry (1990) surveys the scant literature, restricted in the main to the effects of altered precipitation and movement of the Inter Tropical Convergence Zone. He too concludes that more study is required in the semi-arid and humid Tropics. Much of the current work on climate change and world agriculture has in fact been collated by Parry (1990) in his book of the same name.

The general impacts of climate change on agriculture are provided by Parry, Carter & Konijn (1988a & 1988b) who provide a detailed assessment of the potential agricultural impacts for cool temperate, cold and semi arid regions, but no comparable study exists for the humid tropics. Bolin *et al* (1986) provide the results from a scientific review of the greenhouse effect and its environmental consequences, including the response of food crops to increased CO_2 and climate change. Several national studies have been undertaken to assess impacts upon agricultural productivity, five by IIASA and UNEP (Parry & Carter, 1989 & 1990) in Iceland, Finland, the former USSR, Japan, regions of Canada (Smit, 1989) and a United States study by the US EPA (Smith & Tirpak, 1989). Other countries including Australia (Pearman, 1988), New Zealand (Salinger *et al*, 1990), the UK (UKCCIRG, 1991) and West Germany (Study Commission of Eleventh German Bundestag, 1989) have undertaken similar surveys utilising existing climate data and knowledge.

In a similar manner, studies involving modelling the impacts upon agriculture of CO_2 induced climate change utilising GCMs (see Section 3.3) are numerous, but are also generally limited to the Developing world, in particular Europe and North America. For example, Parry *et al*. (1990) consider an equivalent doubling of CO_2 i.e., taking into account the combined effects of all greenhouse gases, utilising 5 GCMs in climatic change experiments and the implications for agriculture in Europe. Mooney & Arthur (1990) undertook a similar study to this research, using a GCM scenario and the FAO crop-yield model (FAO, 1978a) to determine the impacts of climate change in Manitoba. The first specific effort to combine individual studies of climate change and agriculture by Rosenzweig & Parry (1994) to provide a global assessment of the potential impacts of climate change is particularly informative, concluding that despite only a small overall decrease in global food production, the developing countries will suffer most (the findings of which are discussed by Reilly, 1994). Some studies do exist for Asia, for example Bachelet *et al* (1992) examine specifically the impacts of climate change on rice yield in Thailand using GIS climate scenarios, but they are rather fragmented and have not been applied to Bangladesh.

4.3 The Major Agro-Climatic Variables

General texts on the impacts of climate change propose various consequences for agriculture should key agro-climatic variables alter. Some of the major areas for concern include for example: carbon dioxide induced changes in air temperature, rainfall and solar radiation and the consequences for soil moisture, evapotranspiration, the carbon budget and climatic extremes. The following section provides some of the opinions regarding these and other key areas. The impacts on agriculture are broadly divided into two: The direct effects of CO_2 on plants and the effects of changes in climate.

4.3.1 Plant & Ecosystem Response to Elevated CO_2 Levels

Irrespective of climate model predictions, if man-made emissions of CO_2 could be kept at present rates, it is generally considered that atmospheric CO_2 concentrations would still increase from approximately 350 ppm (current levels) to about 450 ppm by the year 2050 (IPCC, 1992). Regardless of actual levels therefore, the earth's biota will be living in a CO_2 rich environment (although doubled CO_2 levels are actually adopted for the project, see Chapter 3). The consequences of this are examined below. The impacts of elevated concentrations of CO_2 on crop growth and yield have in fact been studied for nearly 100 years (Strain & Cure, 1985; Wittwer, 1985) although the effects of other (equally significant) greenhouse gases have yet to receive similar attention.

4.3.1.1 Plant Responses

In this section two crop groups are considered with different photosynthetic pathways, namely - C3 and C4 species - these terms reflect the number of carbon atoms characteristically involved in photosynthesis. Most of the earth's biomass (approx. 95%) is accounted for by C3 species, but a number of plants important to humans, such as maize, are C4 species. Global food security depends upon about 20 plant species, of these, 16 have a C3 photosynthetic pathway (Parry & Swaminathan, 1992). The response of crops to climate change is determined according to which of these two crop groups they belong.

In general, the effects of elevated CO_2 on plants are based upon experimental evidence derived from leaf chambers, plant growth chambers, greenhouses and environmentally controlled phytotrons. Evidence from actual field experiments is more limited, due to difficulties in control. Reviews of the vast literature (e.g., Bowes, 1993; Warrick & Gifford, 1986; Rawson, 1992; Nicolas *et al*, 1993; Strain & Cure, 1985) conclude that the effects of higher CO_2 on plant growth and yields are on balance, beneficial. This is specifically in response to two leaf-level processes: photosynthesis and reduced evapotranspiration.

i Photosynthesis

Parry (1990) considers that the greenhouse effect may be important for agriculture since increased atmospheric CO_2 concentrations and elevated temperatures can have a direct effect on the growth-rate of plants (see also Calder, 1993; Mooney *et al*, 1990). Increased CO_2 in the atmosphere can enhance plant growth, it can increase the rate of photosynthesis, leading to greater leaf expansion and a larger canopy, and it can reduce water losses from plants (Acock & Allen, 1985; Cure, 1985). It has been indicated that a doubling of atmospheric CO_2 will cause a short term (minutes to hours) increase in photosynthesis (Kimball, 1983; Gifford, 1988). Although in some plants the increase is reduced after longer term (weeks or months) exposure (Sage *et al*, 1989).

The actual yield response to this 'CO_2 fertilisation' is reported to vary. According to Parry, Porter & Carter (1990) for many species, a doubling of CO_2 will lead to a 10-15%

increases in dry matter production, providing that all other factors remain constant. Cure (1985) reported a yield increase of nearly 40% with doubled CO_2 enrichment in wheat and barley in the US, whilst Okamoto *et al* (1991) consider that the greenhouse effect may have detrimental effects to crop yields in the central US. Warrick (1988) suggested yields of C3 crops could increase by 10-50% and C4, 0-10%, for a doubling of CO_2. Whilst, Hunt *et al* (1991) performed CO_2 enrichment experiments on different plant species with varying levels of success. Acock & Allen (1985) suggest that a doubling of CO_2 may increase the photosynthetic rate by 30-100%, depending upon other environmental conditions, such as temperature and available moisture. Rosenberg (1992) also concludes that C3 crops respond to increased atmospheric CO_2 concentrations with increased rates of photosynthesis. Research in the humid tropics remains scant, although it is clear that for both C3 and C4 plants, the response is still very species dependent and closely linked to environmental conditions.

Determining the actual increase in usable yield rather than of total plant matter that might occur as a result of increased photosynthetic rate, is also problematic. In controlled environmental studies where temperature and moisture are optimal, the yield increase can be substantial, averaging 36% for C3 cereals such as wheat, rice, barley and sunflower under a doubling of CO_2 concentration. Few studies have yet been made however, of the effects of increasing CO_2 in combination with changes of temperature and rainfall (Parry 1990) or indeed air pollution, for example. Much of course will depend upon these parallel effects for the yield potential of different crops (Edwards & Walker, 1983).

ii Transpiration

Elevated CO_2 can influence plant responses to limitations of water. Short term measurements show that increased CO_2 reduces water loss (transpiration) rates per unit leaf area and increases water use efficiency (which is the ratio of photosynthesis to transpiration), contributing to greater plant growth and yield (Farquhar & Sharkey, 1982; MacCracken *et al*, 1990). Morison (1987) suggests that a doubling of ambient CO_2 concentration causes a 40% decrease in stomatal aperture in both C3 and C4 plants, which may reduce transpiration by 23-46%, which could lead to increased biomass accumulation for plants growing in arid environments. Uncertainties do remain however, such as how much the greater leaf area of plants due to increased CO_2 will balance the reduced transpiration per unit leaf area (Gifford 1988). The net effect of high CO_2 on total water use per unit land area under field conditions is less certain. This is because the increase in leaf area and root extension observed in high CO_2 plants, tends to increase total water use, and may counteract the effect of low transpiration per unit leaf area. Rosenberg (1992) also suggests that transpiration rates may be reduced because of stomatal closure caused by high ambient CO_2 concentrations, particularly in C4 crops, although this response is uncertain also.

Elevated CO_2 can also influence plant responses to limitations of light, nutrient availability and other environmental factors. CO_2 enrichment can increase plant growth at low light intensity, although for some plants the relative enhancement of growth by high CO_2 appears to be equal at low and high light. (Sionit *et al*, 1982). Likewise, high CO_2 can increase plant growth in some situations of nutrient stress (Rosenberg *et al*, 1990). A number of C3 plants growing under nitrogen-deficient conditions exhibited increased growth when the CO_2 concentration was doubled (Wong, 1979; Sionit *et al*, 1981; Goudriaan & de Ruiter, 1983), but if the water deficit was severe and long lasting, water stress-induced inhibition of photosynthesis may dominate the photosynthetic enhancement of high CO_2.

iii Biomass Allocation

Increases in CO_2 can affect how plants allocate carbon among various organs. Research suggests that with increasing CO_2, plants allocate more carbon below ground than above, so that the root to shoot ratio increases. High CO_2 can also increase the number of branches, tillers, flowers or fruits on a plant (Curtis *et al*, 1990)

iv Phenology & Senescence

Elevated CO_2 has been shown to influence the phenology and senescence of plants. Annual plants may develop more quickly under elevated CO_2, reaching full leaf area, biomass and flower and fruit production sooner than plants at ambient CO_2 (Paez *et al*, 1984). There is also some evidence of delayed senescence of some species under elevated CO_2 (Mooney *et al*, 1990), this could extend the growing season and lead to increased biomass accumulation.

4.3.1.2 Limits to Knowledge

The direct effects of high CO_2 have been studied under controlled experimental conditions, but their magnitude and significance in the open field remains uncertain, due to the complex nature of the linkages involved between the biological effects of photosynthetic efficiency and temperature, sunlight and moisture availability. Although beneficial effects seem fairly unequivocal, there is still uncertainty as to their importance relative to large-scale climatic effects. One reason for this uncertainty is that greenhouse and field chamber environments are not identical to field conditions, being much smaller and less variable and having different, less windy evaporative regimes. In addition, as mentioned above, laboratory results artificially presume that rainfall conditions and soil moisture availability remain unchanged in a CO_2 enriched world.

As mentioned previously, the impacts of increased CO_2 on productivity have generally been considered in isolation from the combined effects of UVB radiation increases, atmospheric pollution and global warming - this represents a significant knowledge gap. Krupa & Krickert (1989) recognised this and considered the combined effect of CO_2 enrichment and UVB radiation. Their research suggested that the CO_2 and the effects of UVB are additive and the possible positive effects of CO_2 enrichment on plant growth can be reduced by the negative effects of increased UVB radiation.

Another reason for uncertainty, is that physiological feedback mechanisms may limit the extent to which direct CO_2 effects are realised. Crop plants have sometimes been observed to acclimatise eventually to higher CO_2 levels; their photosynthetic rates decline to levels similar to or only slightly higher than those observed at present atmospheric concentrations. Also, most experiments have tested a step change of CO_2 over only one annual crop-life cycle. This approach cannot be used to determine the long-term evolutionary response to higher CO_2 levels, which may tend towards less efficient photosynthesis. Studies of the interactive effects of elevated CO_2 concentrations and higher temperatures, under different water and nutritional regimes are also few in number, and results have been inconsistent.

4.3.2 Effects of Altered Climate Conditions

4.3.2.1 Increased Atmospheric Temperature

Temperature and CO_2 interact to affect photosynthesis and growth. Although warming at low latitudes is predicted to be less pronounced, it may impact on agriculture by affecting soil moisture availability, growth habit, extreme climate events and/or by raising temperatures above the threshold of tolerance for particular cultivars.

i Effects on Growth Rates

In mid and high latitudes and at high altitudes, temperature is often the limiting factor for plant and animal growth, modification to the temperature regime, as proposed in the project, could have several consequences. From the research undertaken in the Tropics, an apparently small increase in mean annual temperatures could sufficiently increase stress on temperate crops such as wheat, so that they become unsuitable (Mitchell & Ericksen, 1992). Temperature also determines the potential length of the growing and grazing seasons, it generally has a significant effect on the timing of developmental processes and on the rates of expansion of plant leaves. The latter in turn, affects the time in which the crop canopy can begin to intercept solar radiation and thus the efficiency with which solar radiation is used to make plant biomass (Monteith, 1981). Plant development does not begin until temperatures exceed a particular threshold, then the rate of development increases broadly linearly with temperature to an optimum, above which it decreases broadly linearly (Squire & Unsworth 1988).

However, the effects of plant development on biomass production depends upon whether the growth habit of the plant is 'determinate' (a discreet life cycle which ends when the grain is mature, such as in cereals), or whether it is 'indeterminate' (continues to grow and yield throughout the season, such as in grasses and root crops). Temperature increase shortens the reproductive phases of determinate crops, decreasing the time during which the canopy exists and thus the period during which it intercepts light and produces biomass. The canopy of indeterminate crops however, continues to intercept light until it is reduced by other events such as frost or pests, and the duration of the canopy increases when increased temperatures extend the season over which crops can grow. An increase in temperature should therefore generally lead to lower yields in cereals and higher yields of root crops and grassland. Although higher temperatures may also lead to higher rates of evaporation and therefore reduced moisture availability, which could also be expected to affect yields (see Section 4.3.2.2 below).

ii Effect on Growing Seasons

Overall increases in temperature can be expected to lengthen the growing season of indeterminate crops, by encouraging more rapid maturation of plants (Parry & Duinker, 1990). Parry (1990) also suggests that in mid and high latitudes increased temperatures, particularly in temperature limiting regions, extend the growing season and reduce the growing period required by crops for maturation. Increases in temperature are also likely to affect the crop calendar in low latitude regions, particularly where more than one crop is harvested each year. For example, in Sri Lanka and Thailand, a 1°C warming would probably require a substantial rearrangement of the current cropping calendar, which like Bangladesh, is finely tuned to present conditions (Kaida & Surarerks, 1984; Yoshino, 1984)

The IPCC (1992) concludes that a prolonged growing season may increase potential productivity at high and mid latitudes, but it is unlikely to open up large new areas for production and will probably be confined to the northern hemisphere.

iii Yields

In addition to crops being determinate or indeterminate, whether crops respond to higher temperatures with an increase or a decrease in yield depends upon whether their yield is strongly limited by insufficient warmth. Again literature regarding this area is excessively mid/high-latitude biased. In areas where temperature is not constraining, increased temperatures would probably lead to decreased cereal yield due to a shortened period of crop development (Smith & Tirpak, 1989). Yields of root crops such as sugar beet and potatoes, with an indeterminate growth habit, can be expected to see an increase in yield with increasing temperatures, provided these do not exceed temperatures optimal for crop development (Squire & Unsworth, 1988). In general, very few detailed regional studies on the effects of changes in climate on crop yields have been undertaken.

Initially, only one study has used a common set of experiments for a number of case study areas around the world, that of Brouwer (1988). Today, the various publications by IPCC (1990, 1992) provide invaluable information on all aspects of climate change.

Rice yields are significantly affected by temperature and solar radiation. Baker *et al* (1992) determined the effects and possible interactions of CO_2 and temperature on the growth and yield of rice, they concluded that grain yield increases due to CO_2 enrichment were small and non-significant, being more strongly affected by temperature. According to Parry & Swaminathan (1992) when the minimum temperature increases from 18 to 19°C, there is decrease yield of about 0.7 t/ha. Readjustment of the harvest period prior to the onset of higher temperatures would help, but this would be difficult where the crop season has to be tailored to the monsoon rainfall period. In one Asian study, Sinha & Swaminathan (1991) predict that in north India, every 0.5°C increase in temperature, resulted in a drop in the duration of wheat crop by 7 days, which in turn reduced yield by 0.45 tonnes/ha. Considerable generic variability is also exhibited among genotypes of rice, wheat and other plants in relation to tolerance to several biotic and abiotic stresses. More studies are required at the micro-level, in order to understand the interrelationships between CO_2 concentration, temperature and precipitation.

4.3.2.2 Effects of Evapotranspiration

i Changes in Soil Moisture & Water Use by Plants

Soil moisture is critical for agriculture and ecosystems, higher actual evapotranspiration, as a result of higher temperatures of the air and land surface, may have important consequences for agriculture (Parry, 1990). Even in the Tropics where the expected temperature increase is predicted to be smaller than elsewhere, the increased rate of moisture loss from the plants and soil would be considerable (Parry, 1990; Rind *et al*, 1989). It may be somewhat reduced by greater humidity and increased cloudiness during rainy seasons, but could be more pronounced in dry seasons. It is difficult therefore, to identify shifts in the moisture limits to agriculture. Very little is actually known about the regional impacts in the humid tropics, due to the general lack of regional precipitation change estimates. Relatively small changes in the seasonal distribution of rainfall can have disproportionately large effects on soil moisture, and thus on the viability of agriculture in Tropical areas from high potential evapotranspiration, primarily as a consequence of higher air and land surface temperatures (Parry & Swaminathan, 1992).

In most Tropical and equatorial areas of the world the yield of agricultural crops is limited more by the amount of water received by and stored in the soil than by air temperature. Reliability of rainfall particularly at critical phases of crop development, can explain much of the current variation in agricultural potential in Tropical regions. Transpiration is effected by rainfall, but in a non straightforward manner; it also depends upon how much of the rainfall is retained in the soil, how much is lost from evaporation through the soil surface and how much remains in the soil that the crop cannot extract. Transpiration rate is determined by air humidity, with generally less dry matter being produced in a drier atmosphere (Monteith, 1981). Thus, changes in rainfall and humidity would be likely to have significant effects upon crop yields. In Bangladesh however, during the main summer kharif period humidity is so high that it is not in fact a limiting factor.

Parry, Porter & Carter (1990) utilising GCMs in their study, generally agree that there will be reduced soil moisture availability due to higher rates of transpiration from plants and increased evaporation from soil surfaces exposed to higher temperatures, but for crops grown in lower latitudes, where the growing period is limited by rainfall, they are much less clear of the consequences. They consider that there are no certainties about the regional pattern of soil water changes that may occur, in fact MacCracken *et al* (1990) concludes that increased precipitation, over and above the increase in evapotranspiration may actually create a soil moisture increase.

Recent surveys by the IPCC (1990) have made a preliminary (tentative) identification of those regions where there is some agreement among the GCM experiments, concerning the regional implications for soil water availability, if atmospheric CO_2 levels were to double (Parry, 1990: Parry & Duinker, 1990). The IPCC (1992) considers it prudent to assume that crop water availability will generally decrease in some regions, with subsequent ramifications for food production. South east Asia is considered to be one of these vulnerable regions, as a consequence of this reduced crop water availability and a limited resource capacity in relation to population it is consequently faced with reduction of the agricultural resources base.

4.3.2.3 Extreme Weather Events

Important effects from changes in climate need not only stem from changes in average temperature and rainfall, but also from changes in the frequency of extreme climatic events (Rind *et al*, 1989; Mitchell & Ericksen, 1992). Among subsistence farmers in particular, the probability of a yield in a given year being more than a minimum necessary to feed the household is probably more important than the average over several years (Parry, 1985). Levels of risk such as these may well be altered quite markedly by apparently small changes in mean climate, particularly the risk of successive extremes, which can quickly lead to famine in food deficit regions. Risk analysis seeks to determine changes in the probabilities of either extreme climatic events, such as drought or high temperatures, or the ensuing changes in the probabilities of low or high yields. Mearns *et al* (1984) found that the relationship between changes in mean temperature and corresponding changes in the probabilities of extreme temperature events are non-linear and that relatively small changes in mean temperature could result in relatively large changes in event probabilities.

Wigley (1988) proposes that a shift in the mean annual surface temperature of the planet may cause the probability of extreme temperature, precipitation and other weather events to increase. Kerr (1991) also suggests that if global temperatures continue to rise in accordance with current predictions, increases in the number and severity of storms, floods, droughts and other short-term weather extremes may be one of the earliest observed and most dramatic effects. In addition, the frequency of hot and cold days can be markedly altered by changes in mean monthly temperature.

Much research has been undertaken by Pittock and colleagues at Austrailia's Commonwealth Scientific and Industrial Research Organisation (CSIRO), in relation to monsoons, cyclones and other extreme events in a warmer world (see Whetton & Pittock, 1991a & 1991b; Pittock *et al*, 1991; Whetton *et al*, 1992). Pittock concludes that *inter alia*, flood frequency will increase in response to increased rainfall intensity and dry spells will increase as rain falls on fewer days (Whetton & Pittock,1991a & 1991b).

Working Group I of the IPCC (Houghton *et al*, 1990) offers a guarded assessment of the risks of climate change. They conclude that the combination of elevated temperatures, drought and flood, probably constitutes the greatest risk to agriculture at both regional and global level. There is also a distinct possibility that, as a result of high rates of evapotranspiration, some regions in the Tropics and sub Tropics could be characterised by a higher frequency of more intense drought, than at present, although specific regional predictions are impossible (IPCC, 1992). Mitchell & Ericksen (1992) consider all sides of the debate, in conclusion they suggest that:

> *"there is a cautious general agreement that worsening weather extremes are possible and portentous; but few are willing to predict the magnitude and timing of future extremes, much less the regional pattern of events".* (p 144)

4.3.2.4 Precipitation & the Monsoon

Monsoon rainfall has a large social and economical impact on the people in Asia. The dates of onset and withdrawal are determined by the sharp increase and decrease respectively, of the five-day means of rainfall and the changes of the circulation over India. Currently, increased flood and drought losses are often associated with the occurrence of abnormal region-wide monsoons (Swaminathan, 1987). Potential changes to the patterns of the monsoon are therefore of fundamental importance to agriculture in Bangladesh. According to the National Defence University (1980), of the major weather/climate variables, precipitation emerges as the most important to Bangladesh and that absolute values of rainfall are less important during the rainy season than the timing of the monsoon. Although excessive rainfall, usually as the result of cyclonic activity, will destroy much of the crop for that particular growing period.

It is tentatively suggested in the literature (Schneider & Rosenberg, 1989; Parry, 1990; Parry *et al*, 1990) that in a warmer world monsoons are more likely to penetrate poleward in both Africa and Asia, as a result of an enhanced ocean-continent pressure gradient (itself the result of more rapid warming of the land than the ocean in the pre-monsoon season). Total rainfall could increase in currently drought prone areas e.g., the Sahel and NW India, it is also possible that the increase in rainfall would come from more intensive rainstorms occurring over a shorter rainy period. If current levels of pre-monsoon rains important for the germination of crops at the beginning of the growing season were to diminish, then the growing seasons could be shortened and the potential for agriculture reduced. In addition, more intense rainfall in Bangladesh could exacerbate the problems of flooding and increase soil erosion (Kitoh & Tokioka, 1987), the greater surface runoff could decrease soil permeability and produce less available soil moisture. In contrast, on increasing the concentration of greenhouse gases in the Max Plank Institute global coupled model, Lal *et al* (1992) found no evidence for a significant change in the mean onset of the date of the Indian Monsoon or for changes in precipitation in the monsoon region.

With specific reference to the southeast Asian monsoon, Parry (1990) suggests that increased summer rainfall may occur, whilst winter rainfall may decrease. Preliminary results from a UNEP funded project (Panturat & Eddy, 1989) indicate that in northern Thailand, this new rainfall regime may cause a decrease in rice yields. If CO_2 enrichment is included, this may be somewhat ameliorated, although increased temperatures could promote more rapid growth, increase losses to pests and thus reduce yields overall. In summary, Parry (1990) highlights the uncertainty regarding the implications of climate change for rice yields in humid tropical and equatorial regions, due to the sensitivity of the rice crop to water availability at certain times during the growing season, the lack of regional estimates of precipitation changes and uncertainty regarding the response of rice to elevated CO_2 under field conditions.

In a warmer world the Inter Tropical Convergence Zone and polar frontal zones may advance further poleward, as a result of an enhanced ocean-continent pressure gradient. The differential warming described above, could increase total rainfall in some areas of Asia, although there is currently little agreement as to which regions might be most affected (IPCC, 1990). Haarsma *et al* (1992) concluded that the number of simulated tropical disturbances increased, with little change in their average structure and intensity. A report by the National Research Council (1991) on the policy implications of global warming comes to similar conclusions about mid-latitude storms as well as tropical cyclones. However, Broccoli & Manabe (1990) found an increase in the number of tropical storms if cloud cover was prescribed, but a decrease if cloud was generated within the model.

4.3.2.5 Weeds, Pests & Diseases

The effects of climate change can not be isolated to cultivated crops, weeds too will experience the same effects. At present the effects of weeds can not be underestimated, for example in Bangladesh weeds can reduce the local aus crop by up to 90% (Rashid, 1977). Therefore even a slight increase in the occurrence of weeds could have significant consequences for farmers.

According to Morison (1989) C3 crops in temperate and subtropical regions could benefit from reduced weed infestation, 14 of the world's most troublesome terrestrial weed species are C4 plants in C3 crops, the difference in response to increased CO_2 may make such weeds less competitive. In contrast, C3 weeds in C4 crops, particularly in Tropical regions could become more of a problem, although the final outcome will depend upon the relative response of crops and weeds to climatic changes too.

Pest and disease problems are more severe in tropical regions due to multiple cropping and the availability of alternative hosts throughout the year. The IPCC (1992) suggests that some of the serious weeds, insect pests and pathogens of today may become less important under altered climate conditions, and some of the less important ones may become more serious. Experience with some of the high yielding varieties of rice in Asia demonstrates that when the micro-environment is altered through irrigation and fertiliser application, pests which were not previously important before, such as the brown plant hopper, become a serious problem (Mitchell & Ericksen, 1992). Allam (1975) provides further information on the entomological problems of the main crops grown in Bangladesh if required. Indian Agriculturist Suresh Sinha suggested at the Second World Climate Conference, in Working group II (IPCC, 1992) that the Executive Summary took insufficient account of the fact that Developing countries have roughly 10 times more pests per crop than Developed countries and that the behaviour of these pests depends largely on climatic conditions such as humidity, temperature and light.

Insects, in particular, will respond directly to shifts in temperature (Walker, 1991). A number of important effects of global warming on insect pests have already been identified, these include: increases in the rate of development and in the number of generations produced per year, earlier establishment of pest populations in the growing season and an increase in the risk of invasion by migrant and exotic species. Shifts in agricultural potential which could enable the production of new crops in regions may also encourage the introduction of pest species (Parry, Porter & Carter, 1990). Studies also suggest that temperature increases may extend the geographical range of some insect pests currently limited by temperature, although to a lesser degree at low latitudes (EPA, 1989; Hill & Dymock, 1989; Porter *et al*, 1992). An important unknown, however, is the effect that changes in precipitation amount and air humidity may have on the insect pests themselves - and indeed on their predators, parasites and diseases. Climate change may significantly influence interspecies interactions between pests, their predators and parasites (Schneider, 1991).

4.4 Other Areas for Consideration

Clearly, the impacts of climate change upon agriculture are not isolated to crop yields. Agriculture within any country exists as part of a social and economic framework functioning on a global scale and all facets of the ecosystem will experience the new climatic regime. This overall picture has not been addressed here, although the following section highlights a small sample of other areas for concern.

Parry (1990) suggests that a rise in atmospheric temperature could have a significant impact on the performance of farm animals, in addition to the effects that might result from altered yields of grassland and forage crops. Vegetation cover (or lack of it) strongly controls the amount of solar radiation heating absorbed by the land surface by varying the albedo (reflectivity). Heat absorbed by the surface, in addition to heating the soil, provides energy for evaporation and for heating the atmosphere directly (sensible heat). Thus, changes in albedo can strongly affect evaporation and atmospheric heating and so influence the hydrological cycle and atmospheric circulation (Houghton *et al*, 1990).

4.4.1 Global Food Trade & Vulnerable Regions

This and previous studies of the impacts on agriculture of climate change have for the most part, dealt with isolated regions or nations and have ignored the interconnected nature of the world food system. Ideally, an understanding of the potential impacts in other parts of the world is necessary to characterise regional or national outcomes within a global series of interrelated systems. Both long and short term changes in climatic conditions in different countries and regions, interactively affect global food production, demand, prices and trade (see for example, Kane *et al*, 1992 or Sonka & Lamb, 1987). These factors in turn depend on changes in agricultural production potential, crop and livestock systems and the actual adjustment mechanisms adopted by different countries. This too fell outside the boundaries of the project, but needs to be noted.

4.4.2 Environmental Quality Associated With Changes in Agricultural Practices

Pure quantification of the impacts of climate change can not be isolated from other non-economically based considerations, for example, the natural environments may also suffer because of agricultural responses to climate change (Easterling *et al*, 1989; Walker, 1991). Increased water demand for irrigation, greater use of pesticides, the potential for increased soil erosion etc. may all adversely affect natural habitats. Shifts in regional production patterns imply changes in ground and surface-water pollution, and chemical pesticide usage may change to control crop and livestock pests. Loss of biological diversity may diminish the germ-plasm base on which the adaptive capacity of agricultural crop breeding programs depend (see Jackson *et al*, 1990). Soil resources may be exposed to increased wind and water erosion, if agricultural regions expand into areas previously protected by natural land cover. Similarly, social adjustment to climate change in the agricultural system remains largely unaddressed, Parry (1990) makes some reference to this, although not in relation to the Developing world. These considerations tend to be marginalised when higher population priorities prevail, but these too are areas for consideration in the future.

4.5 Summary

Prediction of the potential impacts of climate change on agriculture is not only complex, but subject to the same limitations as regional climate modelling. The distinct lack of information for Tropical regions provides a clear priority for future investigation and necessitates somewhat broad conclusions for assessing future impacts. Predictions of impacts upon soil moisture in particular, are unreliable at present, although the general consensus proposes that soil moisture may decline in Tropical regions. In addition, regions dependant upon unregulated river systems (such as Bangladesh) are even more vulnerable to hydro-meteorological change. Circumstantial evidence suggests that climate extremes may increase in frequency, although quantification is difficult. This is of fundamental importance to a country like Bangladesh where climatic extremes can determine the success or failure of crops. The literature suggests that agricultural pests and diseases may experience increased rates of development, extensions of geographical range, earlier establishment of pests during the growing season and increased risk of invasion by exotic species. The implications of this for Bangladesh in the future will depend upon future pest management practices and the degree of reliance upon mono-culture. On a more positive note some scientists emphasise improved yields due to enhanced photosynthesis under increased CO_2 concentrations and more efficient water use seen in controlled settings. Others are more sceptical as to whether the benefits will be seen in farmer's fields, particularly those in the southern hemisphere. Overall, the research suggests that even if the negative impacts are only slight, areas of present day vulnerability are least able to adjust (IPCC, 1992) and food security at a regional level in less developed countries like Bangladesh could be seriously threatened (Sinha *et al*, 1988; Parry, 1990; Parry & Duinker, 1990).

Chapter 8 illustrates how some of these variables are incorporated into the AEZ model. The direct effects of increased temperatures and the modification of photosynthesis rates on productivity, can actually be determined by the crop productivity model. The incidence of climatic extremes is accommodated in the Soil Suitability Assessment (Chapter 8II) because of its significance to Bangladesh. Whilst the indirect effects such as CO_2 enrichment and the altered incidence of pests and disease, can only be estimated at present (see Chapter 10).

Chapter 5

Land Evaluation

5.1 Introduction

The following chapter provides a brief description of the history of land resource assessment and land evaluation, some of the alternative methods available and the land evaluation method finally adopted for application to the project, together with the rationale for this decision. Also included is how the use of a Geographic Information System (GIS) may facilitate the land evaluation process compared to traditional methods.

5.2 Land Resource Assessment - A Brief History

Population pressure and competing land uses were the precursors that initiated the necessity for land use planning. Land evaluation forms a critical part of this planning process and may be defined as 'the technique for assessing the potential of land for specified land use alternatives'. The foundations of the subject lie in relatively simple land resource inventories, which essentially listed and classified land attributes, with limited planning potential. As the necessity for a more formalised approach to land use planning grew, land capability schemes were developed.

5.2.1 Land Capability

First seen in the 1930's in the US, land capability classification is achieved primarily by interpreting the degree of limitation which land conditions pose to one or more land uses. Providing planners with regionalised areas of land with similar kinds and degrees of limitation. The whole approach is dependent upon the prior availability of data in the form of climatic, soil and topographic maps. Spatial units are then determined by the superimposition of these maps, which are then graded according to capability. Today the application of land capability schemes remains of significant value in land use planning and management.

Land capability schemes saw widespread adoption during the post 1960's period and led to the development of the USDA Land Capability Method by the Soil Conservation Service of the US Department of Agriculture (Klingbiel & Montgomery, 1961). The USDA method was specifically developed to identify sustainable forms of land use when pressure from competing land uses was intense. The method was criticised for lacking precise quantitative criteria, but its flexibility provided its major strength (Young, 1973). Land capability methods in Canada closely followed those in the US, incorporating several modifications including, land capability schemes for forestry, recreation and wildlife.

British methods of land capability relate back to the Land Utilisation Surveys of the 1940's (Stamp, 1962), primarily grading land according to land use characteristics. The 1960's saw the Agricultural Land Classification, a more recent version of which is provided by the Ministry of Agriculture Fisheries & Food (MAFF, 1988). The late 1960's saw the development of a land use Capability Classification (Bibby & Mackney, 1969) again modelled on the USDA scheme.

5.2.2 LESA - Land Evaluation & Site Assessment

The United States Department of Agricultural Soil Conservation Service (SCS) Land Evaluation and Site Assessment (LESA) model was developed in direct response to the National Farmland Protection Policy Act, as a consequence of ever increasing demands on land for non agricultural uses. LESA (SCS, 1983; Steiner, 1987) has two subsystems, as its name suggests: (a) Land Evaluation (LE) and (b) Site Assessment (SA). The LE subsystem is used to rate (maximum value 100 points) the physical quality of soils for alternative land uses and to rank these according to suitability. The SA subsystem rates (maximum 200 points) the socio-economic factors which contribute to the viability of a site for crop production. The final combined score thus providing the guidelines as to whether to retain or convert existing cropland (Wright, 1981; Wright *et al*, 1983). Parts of the LESA system have already been implemented in automated Geographic Information System (DeMers, 1992)

5.3 Qualitative Land Evaluation Methods

The physical land evaluation methodologies described so far, generally constitute qualitative land evaluation. They indicate the degree of suitability of land for a particular land use in a descriptive way only (marginally suited, well suited etc.), no attempt is made to quantify this suitability or to predict yields. This following section briefly describes the main qualitative land evaluation methods currently available.

5.3.1 The Framework for Land Evaluation

During the late 1960's it became apparent that a standardised, internationally applicable methodological approach to land evaluation was necessary. The United Nations Food and Agricultural Organisation (FAO) responded by developing the 'Framework for Land Evaluation' (FAO, 1976), after a background document (FAO, 1973) and the proceedings of two meetings of international consultants (Brinkman & Smyth, 1973; FAO, 1975). The 'Framework' exists as a set of guidelines for a parametric land suitability, rather than as a classification system *per se*.

More recently the FAO concentrated upon more closely defined land uses and published a series of manuals based upon the Framework methodology (FAO, 1976), such as Rainfed Agriculture (FAO, 1983), Irrigated Agriculture (FAO, 1985) and Forestry (FAO, 1984). Davidson (1992) expounds the FAO Framework very well, Dent & Young (1981) discuss implementation of the Framework and FAO (1984 & 1985) published detailed guidelines for field workers.

Since the publication of the Framework (FAO, 1976) several different methodologies have been developed utilising its basic principles for their evaluation process. Some of these are outlined below and an extensive review is provided by Chidley *et al* (1993).

5.3.2 ALES - Automated Land Evaluation System

The manual procedures associated with land evaluation, including calculation of suitability and construction of matching tables are extremely time-consuming and potentially erroneous. Attempts were made therefore to automate these processes. Rossiter (1989, 1990) advocated the use of a micro-computer expert system to function as a framework or 'shell', whilst allowing users to customise their own land evaluation projects. As a result, the Automated Land Evaluation System (ALES) was developed at Cornell University (Rossiter *et al*, 1988, Rossiter & Van Wambeke, 1989). ALES is able to perform both physical & economic suitability analyses in accordance with the FAO Framework for Land Evaluation (FAO, 1976) for land map units. The general criticism of economic evaluation, that results are quickly outdated, does not apply to ALES. Altered economic parameters can be input and a new evaluation repeated almost immediately, and ALES also has the advantage of easily changeable decision rules. Johnson & Cramb (1991) provide a summary of the components of ALES.

5.4 Quantitative Land Evaluation Methods - Yield Prediction

Quantitative land evaluation methods yield quantitative expressions for crop production, such as crop yield in kilograms of dry matter per unit area, and associated inputs (e.g., cubic meters of water, kilograms of nutrients). The following section describes several crop models which have been developed to incorporate selection schemes to allow quantification.

5.4.1 LECS - Land Evaluation Computer System

A similar study of Agricultural Productivity based upon the Framework (FAO, 1976) was developed by Wood & Dent (1983a & 1983b) for the outer islands of Indonesia. The Land Evaluation Computer System (LECS) has been described as perhaps the most complete quantified land evaluation System to date (Purnell, 1987). Its particular strength is its inherent flexibility, allowing for future expansion and refinement when necessary. Despite this potential it was considered inappropriate for Bangladesh, due to the specialist inundation data required in the Evaluation System for the Country and its rather specific tailoring towards Indonesian agriculture. The manual by Wood & Dent (1983a) provides a well documented description of the system, whilst Purnell (1987) provides a less detailed overview.

5.4.2 WOFOST - World Food Study

The WOFOST model described by Van Keulen & Wolf (1986) and Van Diepen *et al* (1989) provides a quantitative simulation model for crop production. Essentially, WOFOST simulates the growth and production of a crop and the soil-water balance in daily time steps under prevailing weather and site conditions. Producing as output an estimated production of roots, stem, leaves and storage organs, for three different sets of growth constraints.

The model is based upon crop physiological behaviour and thus provides a scientific approach to crop growth and yield estimates, although data input requirements are greater than similar models and a socio-economic analysis is not available. Van Diepen *et al* (1989) indicate the limitations and assumptions of the simulation procedure and Davidson (1992) discusses WOFOST in comparison to similar simulation models. Van Dijk & Galassetti-Morrey (1993) discuss the success of WOFOST when incorporated with a GIS to try and maximise yields and economic benefits of agriculture in Thailand, in a similar manner to this project. In practical terms, WOFOST requires an extremely complex dataset for successful modelling. In relation to this project, WOFOST provides a greater level of accuracy than necessary, but most importantly would require additional data to that available currently, it was therefore considered impractical for the project.

The methodologies described above are not intended to provide an exhaustive list of all models, instead they serve to illustrate the range of models available. Modelling based upon crop-cut studies and recorded yields are other alternatives, for example. Reference to the FAO publication (AGLS, 1990) and FAO (1991b) is suggested to provide full details of the main alternatives, their relative strengths and weaknesses and their relative computing requirements. The remainder of this chapter is dedicated to Agro-ecological Zones, the model utilised during the project.

5.5 Agro-ecological Zones

Following the Framework (FAO, 1976) the most far reaching and comprehensive agricultural productivity potential methodology became the FAO's Agro-ecological Zones (AEZ) study. The AEZ project began in September 1976 (FAO 1978a, 1978b, 1978c & 1980) to study the production potential of land resources of the Developing world, as a contribution to the investigation of agricultural futures to the year 2000 (Higgins *et al*, 1986), attempting to quantify how much rainfed agricultural land remained in the Developing world. To accomplish this, a special climatic inventory was produced; the FAO/UNESCO Soil Map of the World (FAO, 1969-80) provided the database for soils and topography and the requirements of the selected crops were determined. Superimposition of the climatic inventory on the Soil Map of the World created a database of 45,000 unique agro-ecological cells, within which soil and climatic conditions were known and quantified (Higgins & Kassam, 1980). For each, crop requirements and crop growth models were applied to estimate potential rainfed yields and output for a range of levels of agricultural inputs.

5.5.1 Land Resource Appraisal of Bangladesh for Agricultural Development

The overall aim of the Agro-ecological Zones (AEZ) project was to provide a comprehensive overview of the physical environment in relation to actual and potential land use. During the 1980's this methodology was expanded and developed to create (*inter alia*) the Land Resource Appraisal of Bangladesh for Agricultural Development (FAO, 1988). Initiated in 1979, this provided a national-level geographical framework for understanding the agricultural productivity potential across Bangladesh, in relation to climate and hydrology.

The Land Resource Appraisal of Bangladesh (FAO, 1988), is complemented with information on land use and capability for individual soil association units (see Chapter 6), using the Reconnaissance (1:125,000 scale) Soil Survey Reports of the 1960-70's. The survey did however exclude soils within the Sundarban forest area controlled by the Forest Department, information for this area was extrapolated therefore for the purpose of the appraisal (Rashid *et al*, 1991).

The concept of the agro-ecological region is based on the superimposition of four levels of information: physiography, soils, land levels in relation to inundation and agro-climatology. The country is thus divided into 30 agro-ecological regions, essentially following the major physiographic units (see Section 6.7.5) and 88 agro-ecological sub-regions reflecting variations in soils or flooding.

5.6 Why use the AEZ Methodology?

Of the various qualitative and quantitative methods reviewed, it was decided to use the AEZ method because:

- The methodology provides an appropriate scale - it is not too large scale to render it useless with the available data.
- The methodology has been specially developed for application to Bangladesh.
- Special attention was given to the agricultural constraints pertinent to the Bangladesh agricultural system, for example, inclusion of inundation levels and seasonal flooding parameters.
- AEZ is currently recognised and utilised by investigators involved with land appraisal issues in Bangladesh.
- The AEZ methodology was developed to be readily transferable to other projects and access to the accumulated data was to be relatively simple. The success of this aim will therefore become apparent.

5.7 Crop Yield Prediction with AEZ

As outlined in Section 5.4 several quantitative evaluation models are available to provide yield estimates. AEZ contains its own model for this purpose and has been adopted for the study to maintain methodological continuity.

5.7.1 The AEZ Model Base

Briefly, the model involved calculating a radiation limited optimum yield figure. Correction factors are then applied to reduce this optimum yield according to the soil characteristics, agro-climatic factors (pests, workability constraints, for example) length of the growing period and the technology (input) level. The output is a Land Suitability Class (from Very Suitable (VS) to Unsuitable (NS), see Section 8.2.4), which can be quantified according to the estimated yield figures.

5.7.2 Yield Calculation Using the Spreadsheet

Instead of using the AEZ yield prediction model on a mini-computer (the approach of the FAO), the yield model was developed instead to function from a spreadsheet. The spreadsheet format was adopted for several reasons. Firstly, spreadsheets are relatively user-friendly, readily available and they are increasingly becoming more powerful. It is easier to develop new models more quickly by using a spreadsheet than by using high level languages. The powerful editors within spreadsheets can be successfully used to modify any changes made to modelling assumptions and more specifically, many programmers would already use a spreadsheet to edit their data, thus using the spreadsheet for the entire process would provide continuity. The spreadsheet chosen was initially developed by Chidley (1992 pers. comm.) incorporating the methodology from the Agro-ecological Zones Project for Africa (FAO, 1978a). This spreadsheet has subsequently been altered and modified to increase its applicability to the project. The spreadsheet-based yield prediction methodology was also adopted in an attempt to simplify the overall process. Originally, the yield prediction for the AEZ methodology (if not undertaken by minicomputer) was undertaken by hand which was both time consuming and subject to error. The spreadsheet was intended to provide a transparent, cheap, simple and reliable alternative to the AEZ computer package. The Spreadsheet is detailed further in Section 8.9.1.

5.8 The Role of GIS in Land Evaluation

5.8.1 Manual Cartographic Methods, The Limitations

Land evaluation traditionally involved manual techniques, whereby a cartographic technician visually interpreted and classified the various map sheets necessary for a land evaluation according to a set of pre-defined criteria (including, soils data, vegetation etc.). These were then physically overlaid and summarised manually to produce the final land evaluation. This approach has a number of limitations, it can be:

- Extremely time-consuming
- Highly labour intensive
- Subjective
- Subject to human error, and
- Map scales can vary

Potentially the capacity for error is extensive. It is intended therefore, to utilise the capabilities of the GIS to reduce the errors involved with land evaluation techniques.

5.8.2 The Geographic Information System

The GIS adopted for the project was that of IDRISI (Eastman, 1990). IDRISI provides relatively cheap, powerful microcomputer raster based GIS software and allows relatively unskilled operators to undertake map overlaying quickly and easily in comparison to the laborious planimetry described above. IDRISI represents one of the main GIS systems used by Developed nations and is slowly being adopted by Developing countries. The resolution for the maps in the GIS was 200 m grid squares, based upon the Bangladesh projection system described in Section 7.4.2. For the final stage of the research, the suitability of the land for the staple crops of Bangladesh is to be compared and maximised using a GIS. In this instance the public domain Geographic Resources Analysis Support System (GRASS) GIS was used instead of IDRISI, since it provided a flexible map comparison and manipulation function ideally suited to requirements of the project. The GRASS GIS only became available towards the end of the project, so that it's application was limited to the latter stages of the methodology.

In addition to overcoming the limitations described in the section above, GIS offers other advantages. For example, the parametric approach to land evaluation provided by the AEZ methodology is particularly appropriate to this type of GIS application. Parametric classification utilises separate layers of information, which are built up on component attributes, such as climate, soils and vegetation. Data on these component variables can thus be stored and processed according to the user's needs, and are present in a form conducive to the overlay process fundamental to the AEZ methodology. The overlay process is just one of the many capabilities of a GIS. These capabilities are numerous (and expanding) ranging from simple methods for retrieving subsets of information from a database, univariate and multivariate methods of statistical analysis and spatial analyses using neighbourhood functions and interpolation methods. The facility for spatial modelling is particularly useful, it allows an almost unlimited range of capabilities for data analysis and is adopted throughout the project. GIS also have the potential to identify and quantify data errors and the problems of error propagation caused by, for example, digitising or map overlaying (see Burrough, 1993).

Climatological data generally exists for discrete sites across a country. A GIS can be employed to interpolate these data across the entire surface of interest quickly and easily, thus increasing the utility of the data for land use planning. An additional reason for using a GIS is in an attempt to simplify the complex land evaluation process, so that relatively unskilled workers can undertake the evaluation, releasing funds and/or manpower to be deployed elsewhere. Much of the work regarding the impacts of possible climatic change may then be undertaken by local people. The project was undertaken with a minimal knowledge of GIS, to test the 'user-friendliness' of such a system first hand.

GIS also have the potential advantage of being able to incorporate the fuzziness theory[1] (Kaufman, 1975; Zadeh, 1965) in relation to the applied modelling rules, challenging the established classical set theory adopted in the project. It is suggested that classical set theory can not tolerate imprecision, causing information loss and inaccuracy in analysis. Recent research reveals that adoption of fuzzy relational data models may be more representative of geographic information, of the type used in land resource assessment (see for example, Wang *et al*, 1990). This clearly provides a basis for further research.

[1] In fuzzy set theory a membership function is defined to express the degree to which a cell or area is a member of a particular set.

The essence of this project is to assess the success involved with the application of the GIS IDRISI to facilitate the land evaluation process and to evaluate potential crop productivity changes for Bangladesh. As described, the scope for GIS is continually improving, although the application of GIS to the issues of Developing countries is in its early stages, it appears to represent a significant contribution for improving the Land Evaluation Process in the future.

Chapter 6

The Land Resources of Bangladesh

6.1 Introduction

Details of four resources are fundamental to the FAO-AEZ methodology:

- Climate
- Inundation
- Soil, and
- Landform

the following section provides a description of each of these resources, their data source and a brief discussion of the compilation of the data inventory, with specific application to the climate change scenario and the suitability assessment. The final section describes how the climate change scenario was applied to the appropriate climate variables for use later in the project.

6.2 The Hydro-Climatic Resources of Bangladesh

This first section describes the first two of the sources of data for these resources, namely the Climatic Resources Inventory and the Inundation Resources Inventory, which when combined provide the Hydro-Climatic Resources Inventory. These inventories provide reference descriptions of thermal, soil moisture (from the viewpoint for assumed available soil moisture contribution from soil moisture storage) and surface hydrological characteristics of soils for 11 inundation-level related land types (see inundation below). The structure of the hydro-climatic resources inventory is provided schematically in Figure 6.1.

Figure 6.1 Structure of the Hydro-Climatic Resources Inventory

Source FAO (1988: Report 4)

Entire volumes in the FAO-AEZ methodology (FAO, 1988) have been dedicated to the rationale behind the compilation of these Inventories. It is necessary however to provide a brief description of these inventories in order to explain how the climate change scenario was applied to these data. The reader is referred to the appropriate sections in the AEZ methodology (FAO, 1988) referenced in the text, if further detail is required.

6.3 The Climatic Resources Inventory

6.3.1 The Thermal Regime of Bangladesh

The thermal regime of any area can be defined according to the time course of temperature changes throughout the year. Bangladesh is located between 20° 30' N and 26° 45' N, distant enough from the equator to experience a seasonal variation in temperature, further influenced by the effects of the sea and inland water bodies, rainfall regime and altitude. A schematic representation of the seasonal thermal regime of Bangladesh is presented in Figure 6.2. The seasonal regime comprises three periods, introduced in Section 2.7, namely:

i. The **hot period**, occurring approximately during the pre-kharif transition or 'summer' period.

ii. The **warm period**, occurring approximately during the kharif growing period

iii. The **cool period**, occurring approximately during the rabi or 'winter' period

Each of these three periods possess different temperature characteristics and the suitability of each in terms of crop temperature requirements can be markedly different. Temperatures during the warm (kharif) period remain similar across the country, whilst temperatures during the cool (rabi) and hot (pre-kharif transition) period can vary.

Figure 6.2 Schematic Representation of the Seasonal Thermal Regime for Bangladesh

From FAO (1988: Report 4)

6.3.2 Temperature Requirements of Crops

6.3.2.1 The Thermal - T Zones

To take into account crop temperature requirements the FAO-AEZ methodology (FAO, 1988) relies upon the subdivision of the country into zones related to prevailing temperature regime, which form part of the Climatic Resources Inventory of Bangladesh (FAO, 1988: Report 4). These zones were based upon the crop temperature requirements for photosynthesis and growth, and for phenology and development (see Section 8.2.1)

The temperatures considered to be critical were:

- Mean daily temperature values of 20°C and 22.5°C and minimum temperature values of 15°C and 17.5°C. The time periods during which temperatures fall above or below these critical thresholds form the basis of the thermal zone delimitation, and take into account the spatial and temporal variations in the prevailing temperature regime.

- The occurrence of extremely high temperatures during the hot period (maximum temperatures >40°C) and low temperatures during the cool period (minimum temperatures <10°C).

An inventory of the frequency of occurrence of the number of days falling into the above categories during the rabi season was created, based upon historical daily temperature data (Reference to FAO, 1988: Report 4 p97-131 provides full details). Temperatures are relatively uniform over the whole country during the kharif season, consequently a separate mapped inventory for this season is not presented. During this season mean maximum temperatures are in the range 30-34°C, mean daily temperatures 26-30°C and mean minimum temperatures 22-26°C.

Having established the inventory of the thermal resources a mapped inventory was constructed to schematically represent the temperature zone boundaries. The thermal zones are represented as - T zones, and the extreme temperature zones as - e zones. The mapped inventory was compiled by the FAO as follows:

i. Plotting on the 1:500,000 scale base map the individual station data for the period of time (in days) when the minimum temperature was less than 15°C and the frequency of occurrence of maximum temperatures greater than 40° C.

ii. Constructing isolines to differentiate five thermal zones based upon the difference in minimum temperature conditions during the cool period (winter/rabi) corresponding to minimum temperatures <15°C for 30-40, 40-50, 50-70, 70-90, and 90-110 days and designating them T1, T2, T3, T4 and T5 respectively.

iii. Constructing isolines to differentiate four extreme temperature sub-zones based upon the occurrence of maximum temperature >40°C during the hot (summer/pre-kharif transition period) at frequencies in the range 0-0.5, 0.5-5, 5-10 and 10-15 days and designating them e1, e2, e3 and e4 respectively.

The actual thermal zones (T & e) are shown on the Climatic Resources Inventory for Bangladesh from the FAO-AEZ Appraisal (FAO, 1988), presented in Figure 6.3, Tables 6.1 and 6.2 accompany the map and indicate the number of days belonging into each thermal zone category.

In order to undertake the agro-climatic suitability assessment, this map was digitised into the GIS using the TOSCA digitising package, this digitised map is show in Figure 6.4. Clearly, when the IPCC regional temperature change estimates (Houghton *et al*, 1990) are applied to the climate data, the thermal resources inventory zone boundaries will alter, this zone delineation is detailed later in the chapter.

6.4 Moisture Resources Inventory

6.4.1 Rainfall

Bangladesh has a monsoon rainfall climate with a distinct dry season. Mean annual rainfall varies from 1250 mm in the extreme west of the country to 6000 mm in the north-east corner, although mean annual rainfall is in the range 1500-3000 mm across the entire country. Coefficients of variation of mean annual rainfall are in the range 15-25% (FAO, 1988). The growing period has been used as the basis for assessment of hydro-climatic resources. It is defined as the period in which moisture supply permits crop growth (see also Section 2.7.1).

Figure 6.3 Generalised Climatic Resources Inventory of Bangladesh

Aston University

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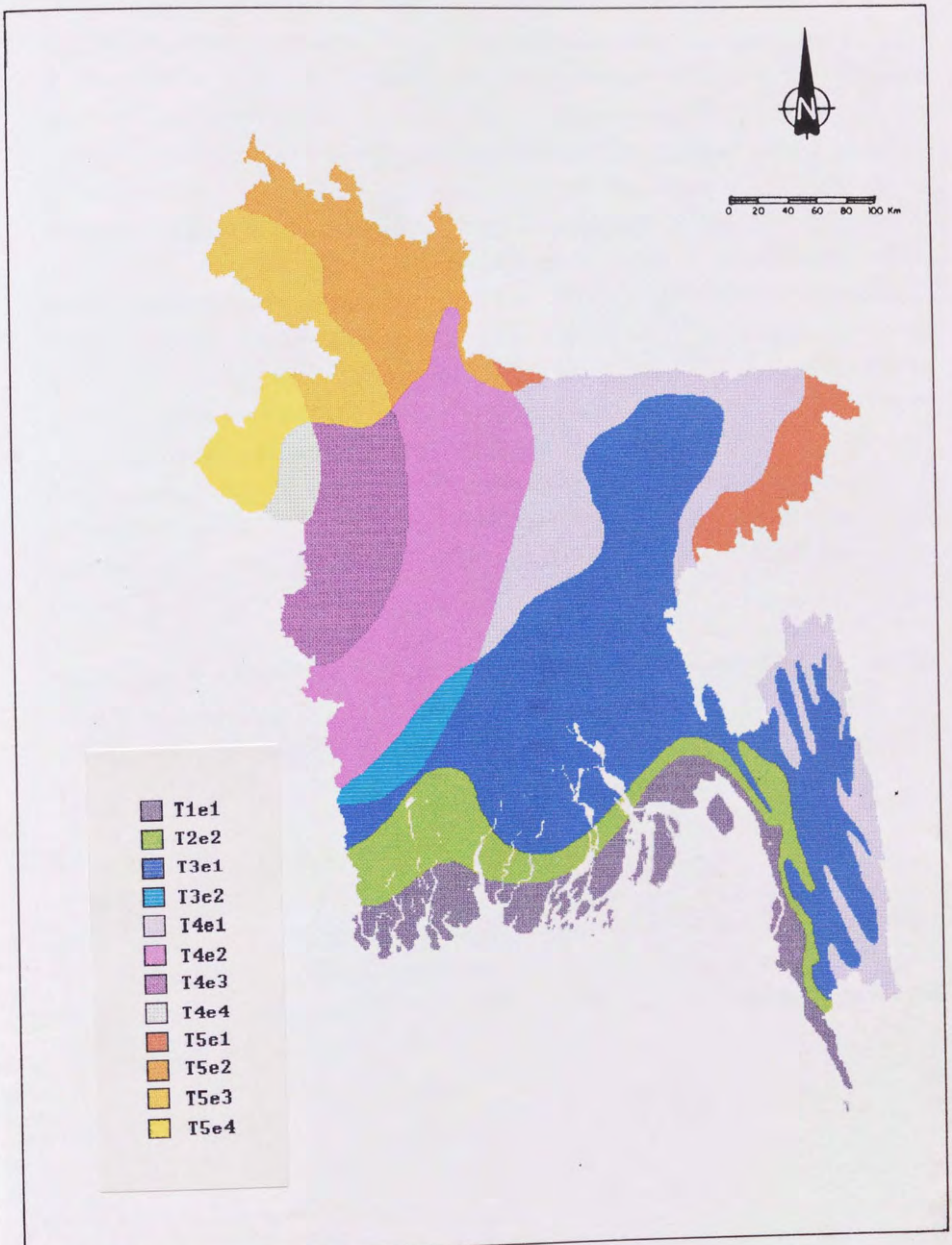
Table 6.1 Categories to Accompany Thermal T Zones in Figure 6.3 Representing the Cool Period - Winter Rabi Growing Period (Nov/Dec - Feb/Mar)

Zone Symbol	Minimum Temperatures <15°C Days	Period	<17.5°C Days	Period	Mean Temperatures <20°C Days	Period	<22.5°C Days	Period	No of Days with min temps <10°C
T1	30-40	16 Dec-20 Jan	65-80	2 Dec-12 Feb	15-25	23 Dec-12 Jan	70-80	1 Dec-14 Feb	0
T2	40-50	6 Dec-20 Jan	70-85	26 Nov-12 Feb	25-30	17 Dec-!4 Jan	70-80	25 Nov-9 Feb	0-15
T3	50-70	6 Dec-4 Feb	80-105	24 Nov-14 Feb	30-50	14 Dec-23 Jan	80-90	24 Nov-18 Feb	5-15
T4	70-90	29 Nov-17 Feb	105-120	15 Nov-9 Mar	40-70	9 Dec-3 Feb	90-110	19 Nov-27 Feb	15-25
T5	90-110	20 Nov-28 Feb	120-135	11 Nov-19 Mar	60-80	3 Dec-11 Feb	110-120	9 Nov-5 Mar	25-35

Table 6.2 Categories to Accompany Extreme e zones in Figure 6.3 Representing the Hot Period - Summer/Pre-kharif Transition Period (Feb/Mar - Apr/May)

Zone Symbol	No. of Days of Maximum Temperature > 40°C
e1	0 - 0.5
e2	0.5 - 5
e3	5 - 10
e4	10 - 15

Figure 6.4 Digitised Thermal Zone Boundaries For Bangladesh



6.4.2 Seasonal Moisture Regime

The seasonal moisture regime in Bangladesh is divided into a dry and wet season. Based upon the heuristic interpolations of experienced agro-climatologists, the dry (rabi) season is described as the period when precipitation is less than half the potential evapotranspiration (PET) rate, this represents the majority of the time. Following the dry season there is a pre-kharif transition period characterised by unstable showers which are erratic in distribution, frequency and intensity. There is insufficient soil moisture supply during this transition period for reliable crop establishment or optimum crop growth (FAO, 1988). As rainfall intensity increases during this period, a point is reached when precipitation continually exceeds firstly, half the PET rate and finally, the full PET rate. The period when precipitation continuously exceeds half the PET rate is referred to as the rainy or kharif season, this period is considered suitable for crop growth. The wet season continues until a point is reached when precipitation again falls below the full PET rate. This project is primarily concerned with rainfed crops, it must be remembered however that the introduction of irrigation during periods of insufficient precipitation and soil moisture storage would clearly allow the cultivation of previously unsuitable crops, which is increasingly occurring in Bangladesh. The significance of this is further discussed in Chapter 10.

A schematic characterisation of the moisture regime and growing periods for rainfed crops is presented in Figure 6.5. The figure includes the further subdivisions of the growing periods, not detailed here. The reader is directed to pages 1 to 96 of the FAO (1988) Report 4, for further details.

6.5 Moisture Zones

In a similar manner to that detailed above the AEZ methodology (FAO, 1988) produced a mapped inventory of the moisture resources, comprising the reference length of the pre-kharif transition period - p zones, and the reference kharif length of growing period zones - K zones. The inventory was compiled by:

Figure 6.5 Schematic Characterisation of the Moisture Regime

Source FAO (1988: Report 4)

i. Plotting the individual station data for mean reference length of pre-kharif transition period and mean reference kharif length of growing period on the 1:500,000 base map.

ii. Constructing isolines at 10 day intervals of mean reference length of pre-kharif transition period with values of 20, 30, 40, 50 and 60 days, thus delineating six zones of 10-20, 20-30, 30-40, 40-50 and 50-60 days, designated as K1 to K12.

The moisture zones (p & K) from the FAO-AEZ appraisal (FAO, 1988) are also shown on the Climatic Resources Inventory Figure 6.3 Tables 6.3 and 6.4 accompany the map and indicate the number of days belonging into each moisture zone category.

The growing period zone suitability map was also digitised into the GIS (Figure 6.4) for application in the suitability assessment. Reference to Section 6.8.3 provides an explanation of the location of the moisture zone boundaries after applying the IPCC regional soil moisture change estimates (Houghton *et al*, 1990).

6.6 The Inundation Resources Inventory

The inundation resources inventory defines the hydrological characteristics of soils in six basic hydrological land types, each land type is related to a specific range of inundation depths during the peak rainfall kharif period. The six land types are:

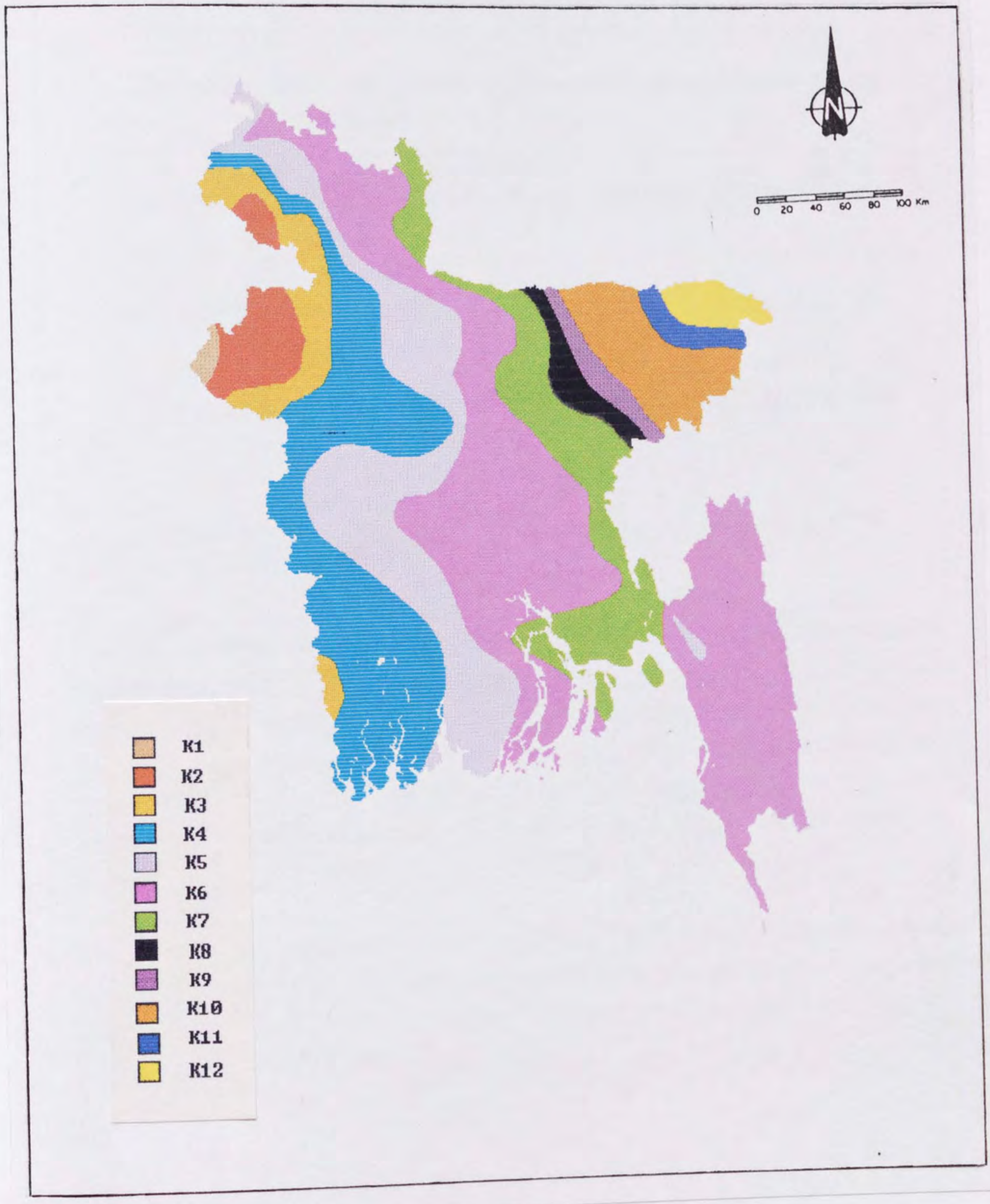
Table 6.3 Categories to Accompany Moisture p Zone Map Representing the Transition Periods

	Pre-Kharif Transition Period (p)		
Zone Symbol	Days	Period	Dry Days
p1	10 - 20	17 Mar-2 Apr	1 - 9
p2	20 - 30	20 Mar-14 Apr	9 - 17
p3	30 - 40	22 Mar-26 Apr	17 - 24
p4	40 - 50	24 Mar-8 May	24 - 32
p5	50 - 60	24 Mar-18 May	32 - 39
p6	60 - 70	17 Mar-21 May	39 - 48

Table 6.4 Categories to Accompany Moisture K Zone Map Representing the Growing Periods

	Kharif Growing Period (K 100)		Rabi Growing Period (R 250)	
Zone Symbol	Days	Period	Days	Period
K1	170-180	27 May- 18 Nov	105-115	12 Oct-30 Jan
K2	180-190	24 May-25 Nov	115-125	15 Oct-12 Feb
K3	190-200	21 May- 2 Dec	115-135	15 Oct-17 Feb
K4	200-210	18 May-9 Dec	115-135	15 Oct-17 Feb
K5	210-220	9 May-10 Dec	120-145	15 Oct-22 Feb
K6	220-230	3 May-14 Dec	120-145	21 Oct-2 Mar
K7	230-240	27 Apr-18 Dec	120-145	24 Oct-5 Mar
K8	240-250	24 Apr-25 Dec	135-150	24 Oct-5 Mar
K9	250-260	18 Apr-29 Dec	135-150	27 Oct-18 Mar
K10	260-270	12 Apr-2 Jan	135-150	27 Oct-18 Mar
K11	270-280	3 Apr-3 Jan	135-150	1 Nov-22 Mar
K12	280-290	27 Mar-6 Jan	135-150	3 Nov-25 Mar

Figure 6.6 Digitised Map of Growing Period Zone Boundaries For Bangladesh



i. **Highland (H)** - land which is above normal inundation level and would normally not develop wetland conditions unless rainwater was retained on the surface by bunding (building small levees) on suitable soils.

ii. **Medium Highland 1 (MH1)** - land which is generally inundated less than 30 cm.

iii. **Medium Highland 2 (MH2)** - land which is generally inundated in the range 30-90 cm.

iv. **Medium Lowland (ML)** - land which is generally inundated in the range 90-180 cm.

v. **Lowland (L)** - land which is generally inundated in the range 180-300 cm.

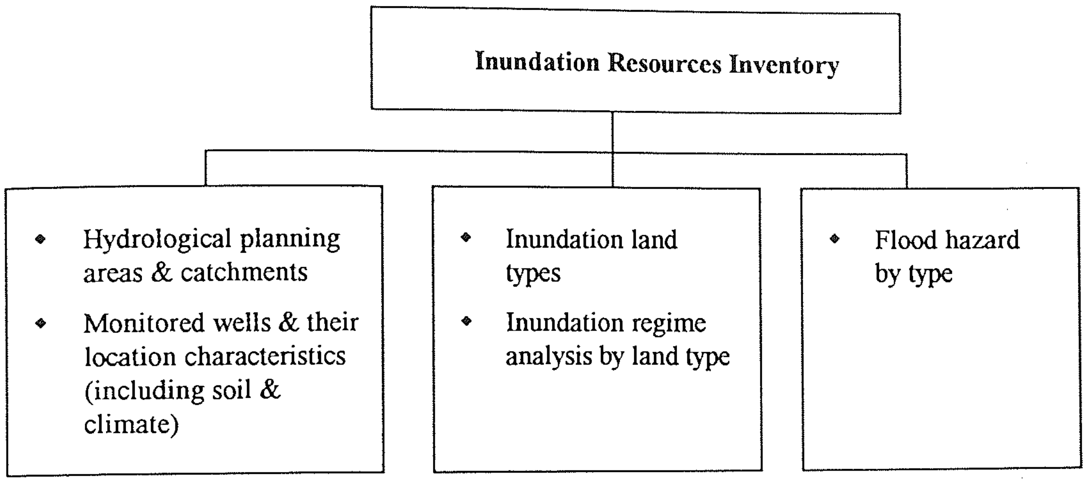
vi. **Very Lowland (VL)** - land which is generally inundated more than 300 cm.

These six inundation types are further divided according to whether or not they remain in a wetland condition throughout the kharif and rabi seasons. Land which is inundated during the kharif season and remains in a wetland state during the rest of the year, including the rabi season, is referred to as bottom land. Thus, 11 surface hydrology land types can be differentiated. The inundation land types are presented in Figure 6.7 adopting 8 categories to provide a 'generalised' representation of the inundation categories.

The inundation resource inventory thus provides a quantified characterisation of the inundation regimes for the soil association unit, in terms of depth, duration, begin and end dates and hazard to crop cultivation. The structure of the inundation resources inventory is presented in Figure 6.8.

Figure 6.7 Generalised Inundation Land Types of Bangladesh

Figure 6.8 Structure of the Inundation Resources Inventory



Having established the sources and structure of the hydro-climatic resources data. The two remaining data sources need to be examined.

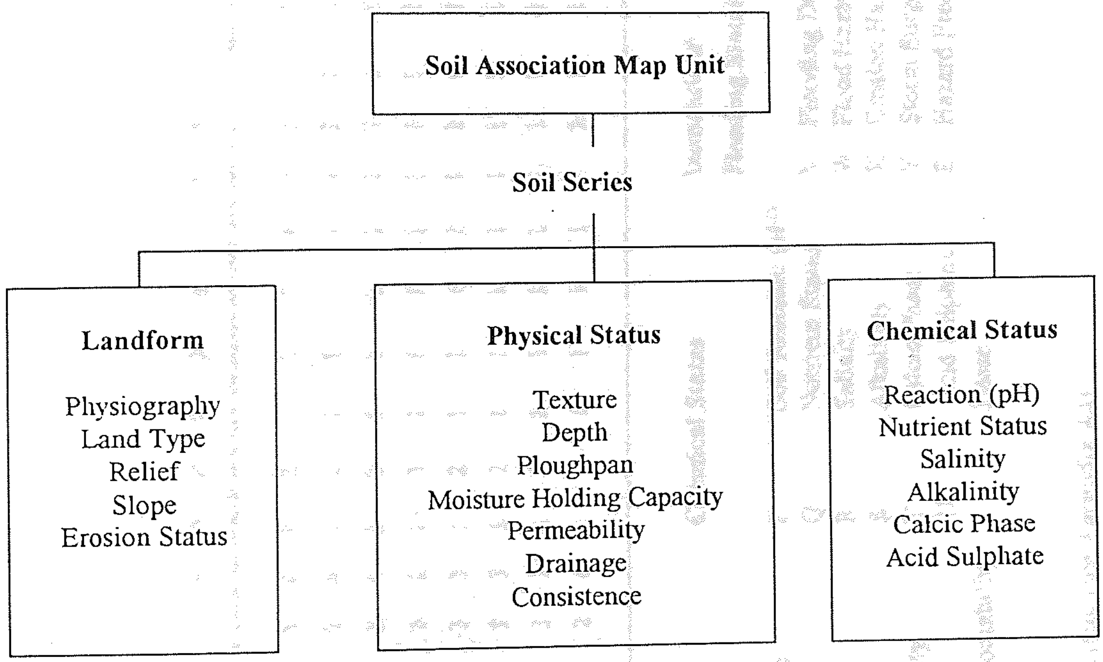
6.7 The Soil & Landform Resources of Bangladesh

6.7.1 Land Resource Inventory, the SODAPS Database

The main source of information on soils and landforms for Bangladesh was a computerised database from the Bangladesh Soil Survey Data Processing System (BANGLA SODAPS, Antoine, 1982), updated in 1984 and 1986 (Chidley, pers. comm.). The structure of the soil & landform database is shown in Figure 6.9 below. For each soil association unit the data were available as a spreadsheet and manipulated using the package 'Excel'. An example section of the database, indicating the format of the data is shown in Figure 6.10, together with a brief description of the column identifiers used for the land factors.

The database provides the foundation for a comprehensive national and sub-national planning database and contains the information necessary to assist agricultural planners faced with *inter alia,* identifying areas of food production potential or physical resource constraints to crop production. In agreement with Antoine (1990) who suggests that the SODAPS requires modification to include socio-economic factors of agricultural production, it would be beneficial to incorporate further map or image data and appropriate models to allow for greater ability and accuracy to deal with the intricacies of agricultural development resource planning. It remains to be seen however, whether the database will be updated regularly to maintain its utility.

Figure 6.9 Data Held Within the Soil & Landform Database



Chapter 8II provides the methodology for the soil suitability assessment and illustrates the sub-division of the classes shown in the Figure above and their applicability to the soil suitability process.

The database provides information for 1034 individual soil association map units, which are used throughout the project to represent the soil characteristics for each mapped unit, hence a brief description of the soil association is provided below. Further details can be found in Report 5, Volume 2 (FAO, 1988).

6.7.2 Soil Association Map Units

In Bangladesh, individual soils can not be mapped as pure units at the 1:125,000 scale used in the Reconnaissance Soil Surveys. Instead, the different soils that occur within a physiographic unit/sub-unit are mapped together as a soil association. An example soil association is illustrated and explained in Figure 6.11.

Figure 6.10 Example of Data from SODAPS Database & Brief Description of Column Identifiers

A	B	C	D	E	F	G	H	I	J*	K	L*	M*	N	O	P*	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC
BN179	380	6	0	4	1	1	1	13	4	1	2	3	4	1	2	1	1	1	1	1	3	1	1	1	1	359	19	0
BN179	380	6	0	2	1	1	1	13	4	1	2	3	4	1	2	1	1	1	1	1	2	1	1	1	1	120	6	0
BN179	258	6	0	4	1	1	1	20	5	1	2	2	4	1	2	1	1	1	1	1	3	1	1	1	2	51	3	0
BN179	55	8	0	1	1	1	1	15	4	1	2	3	2	1	3	1	1	1	1	1	1	1	1	1	1	34	2	0
BN179	380	8	0	1	1	1	1	13	4	1	2	3	3	1	2	1	1	1	1	1	1	1	1	1	1	34	2	0
BN179	380	8	10	1	2	1	1	13	4	1	2	3	3	1	2	1	1	1	1	1	1	1	1	1	1	34	2	0
BN179	576	6	0	1	1	1	1	2	5	1	5	3	1	1	3	2	1	1	1	1	1	1	1	1	1	34	2	0
BN179	258	6	0	2	1	1	1	20	5	1	2	2	4	1	2	1	1	1	1	1	2	1	1	1	2	17	1	0

Landform

A Soil Association Map Code
B Soil Series Code
C Soil Variant Code
D Soil Phase Code
E Inundation Land Type
F Relief
G Slope
H Erosion Status

Physical Status

I Topsoil Texture
J Soil depth
K Ploughpan
L Soil Moisture
M Soil Permeability
N Drainage
O Consistence/Workability

Chemical Status

P Soil Reaction (pH)
Q Nutrient Status
R Salinity
S Alkalinity
T Calcic Phase
U Acid Sulphate Phase

Inundation/ Flooding Status

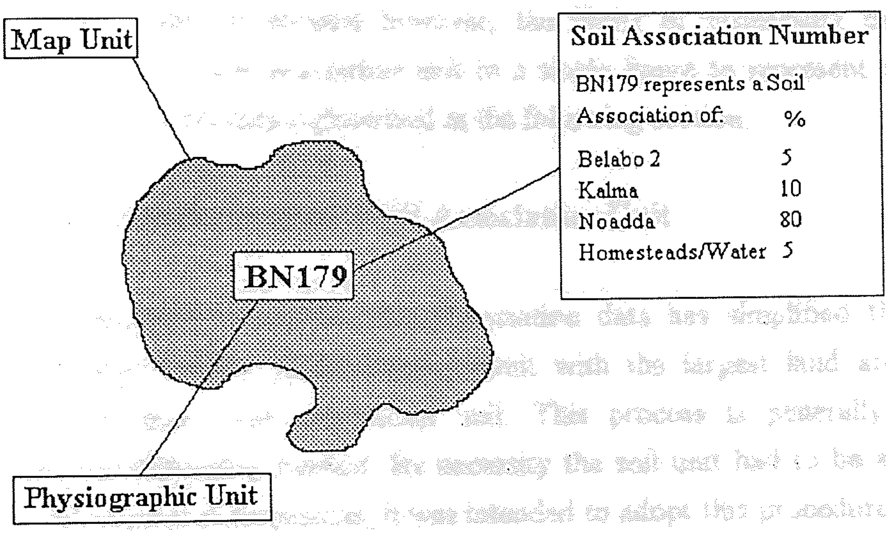
V Flooding Depth
W Flood Hazard
X Erosion Hazard
Y Storm Surge Hazard
Z Hazard Frequency

Land phase

AA Area (km^2)
AB Homestead & water Area
AC Miscelleneous Land Area

* Denotes columns with a slightly different classification system (see Appendix A4)

Figure 6.11 The Soil Association Unit



6.7.3 The Soil Association Number

The soil association Number (BN179) represents a unique combination and percentage proportion of soil series. Where a soil series is defined as:

> *A group of soils formed in the same (or similar) parent material, with a similar arrangement of horizons and with closely similar distinguishing characteristics (e.g. colour, sub-soil texture, structure, reaction).*

The soil series is one of the 574 individual soil units identified by the Reconnaissance Soil Surveys. Reference to Figure 6.10 illustrates the data for the soil association unit BN179 as it appears in the soil database.

The map unit is the smallest geographically delineated area on the map of soil and land resources, representing the mixture of soil and land properties in the given proportions described above. Strictly speaking this map unit should not be broken down. Reference again to soil association unit BN179 indicates that it consists of 8 unmapped sub-units. For the soil suitability process however, the limits of processing capacity required simplification of the soil association unit to a single figure to represent the 8 soil series. This simplification process is described in the following section.

6.7.4 Simplification of the Soil Association Unit

Previous research involving the soil association data has simplified the soil unit, for example at ISPAN the soil association unit with the largest land area was used to represent the entire soil association unit. This process is generally accepted as a reasonable simplification method. By necessity the soil unit had to be simplified. In the absence of an alternative process, it was intended to adopt this procedure for this project, thus it was necessary to establish whether it would be appropriate to do so.

Initially, the soil suitability procedure detailed in Chapter 8II was undertaken for all of the sub-units within the soil associations of wheat. Thus, for example, the soil association BN179 had 8 sub-units, which generated 8 soil suitability ratings:

Soil Association Sub-units	Soil Suitability Rating	Area Covered by Sub-unit (%)
BN179 -1	S3	53
BN179 -2	S3	18
BN179 -3	S2	7
BN179 -4	S3	5
BN179 -5	S2	5
BN179 -6	S2	5
BN179 -7	S1	5
BN179 -8	S3	2

The methodology requires a single figure to represent the soil suitability rating for each soil association, since each soil association unit represents a single area within the GIS.

Therefore, from these 8 results a single representative figure had to be derived. Adopting the procedure above, the sub-unit with the largest surface area within the soil association was taken to be representative of the whole soil association, i.e., BN179-1, with the corresponding soil rating S3. Examination of the area figures in the last column of the table above, reveals that 78% of the total area occupied by soil association BN179 may be classified as S3. In this instance therefore, it would appear acceptable to adopt the largest areal soil sub-unit to represent the entire soil association. This process was then repeated for each of the 1034 soil associations and their sub-units, for the wheat crop, to see whether it was practical to adopt this process for all of the soil association units.

To examine the reliability of this method of simplification, each soil association's sub-units were individually examined to see whether they gave the same soil suitability rating as the unit with the largest area. In just less than 900 of the 1034 soil association units (87%) the sub-unit with the largest surface area represented the most frequently occurring soil suitability class according to areal extent. Simplification of the complex nature of the soil association unit is fundamental to the methodology and the additional detail provided (if it could be handled) would be of no real benefit. It was considered appropriate therefore to adopt this approach in the absence of an alternative, until data handling capabilities improve or an alternative simplification process is developed. This methodology was therefore applied for the remainder of the project the soil association sub-unit with the largest surface area was adopted to represent the soil association unit as a whole.

6.7.5 The Physiographic Unit

Physiography includes the combination of the geological material in which particular kinds of soil have formed and the landscape upon which they occur. Twenty physiographic units have been recognised in Bangladesh, some of which have been divided further into sub-units. A list of the units and their symbols is provided in Figure 6.12.

Having established the structure, source and content of the land resource inventories of Bangladesh, it is necessary to examine the effect that the IPCC regional climate estimate (Houghton *et al*, 1990) may have upon these resources in the future.

Figure 6.12 Physiographic Units of Bangladesh

Symbol		Description
1	(Ph)[1]	Old Himalayan Piedmont Plain
2	(Ta, Tm)	Tista Floodplain
3	(Kb)	Karatoya-Bangali Floodplain
4	(Al)	Lower Atrai Basin
5	(Pl)	Lower Purnabhaba Floodplain
6		Brahmaputra Floodplain
6a	(Ba)	Active Floodplain
6b	(By)	Young Brahamaputra & Jamuna Floodplains
6c	(Bo)	Old Brahmaputra Floodplain
7		Ganges River Floodplain
7a	(Ga)	Active Floodplain
7b	(Gh)	High Ganges River Floodplain
7c	(Gl)	Low Ganges River Floodplain
8	(Gn, Gs, Gm)	Ganges Tidal Floodplain
9	(Gb)	Gopalganj-Khulna Bils
10	(Ab)	Arial Bil
11	(Mm, Ml)	Meghna River Floodplain
12		Meghna Estuarine Floodplain
12a	(Mn)	Young Floodplain (non-saline)
12b	(Ms)	Young Floodplain (saline)
12c	(Mo)	Old Floodplain
13		Surma-Kusiyara Floodplain
13a	(Se)	Eastern Floodplain
13b	(Sb)	Sylhet Basin
14	(Pn)	Northern & Eastern Piedmont Plains
15	(Cc)	Chittagong Coastal Plain
16	(Ci)	St. Martin's Coral Island
17	(Bl, Bn, Bd)	Barind Tract
18	(Mt)	Madhupur Tract
19	(Hh, Hl)	Northern & Eastern Hills
20	(Ha)	Akhaura Terrace

1 - Prefix symbol used for the physiographic unit/sub unit on the Land Resource Inventory map sheets and the AEZ Code in the SODAPS database. For example AEZ Code *BN179*, represents the *Barind Tract* Physiographic Unit (Bn, No. 17).

6.8 Delimitation of the New Climate Zones

6.8.1 New Thermal - T Zones

Based upon the IPCC regional temperatures estimate (Houghton *et al*, 1990), a temperature increase of 1.5°C across both rabi and kharif seasons was applied to the thermal climate data (Appendix A2). It was necessary therefore to determine the effect that this would have upon delineation of the thermal zone boundaries. To date, no attempt has been made to quantify this boundary movement.

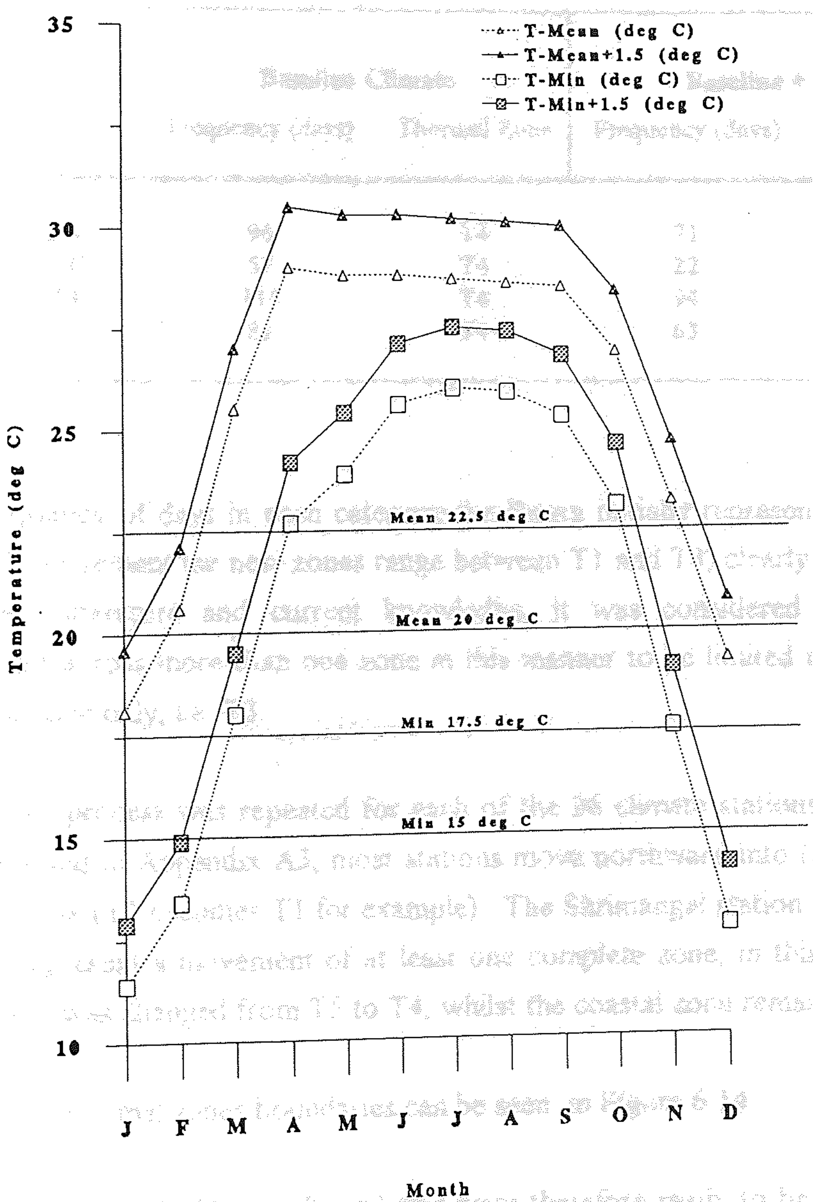
As described in Section 6.3.2.1 the thermal zones essentially represent the number of days falling into five critical temperatures categories:

- Minimum temperatures less than 15°C
- Minimum temperatures less than 17.5°C
- Mean temperatures less than 20°C
- Mean temperatures less than 22.5°C
- Minimum temperatures less than 10°C

For modelling purposes it was assumed that the standard deviation of mean temperature remained unchanged under the climate change scenario, the monthly, minimum and mean temperatures for each of the 26 climatic stations were increased by an increment of 1.5°C and plotted on a graph (Figure 6.13 illustrates the graph for Bogra). According to the literature (see Section 4.3.2) there may actually be some alteration in the standard deviation of mean temperatures, thus some allowance is made for this in relation to the frequency of extreme temperature events. The possible effects upon the associated extreme temperature (e) zone boundaries are described in Section 6.8.2. The likelihood of an increase in extreme events in relation to flood hazard is also incorporated and is described in Section 4.3.2.3.

The number of days falling into each of the first 4 categories was determined, both before and after the temperature increase. These frequency figures correspond to the thermal zone categories. The 10°C category was not included, since none of the temperature data for the chosen year fell below this figure, thus no differentiation could be made based upon this figure.

Figure 6.13 **Temperatures Before & After the Climate Change Scenario For Bogra**



Considering initially the baseline climate for each of the 26 climate stations (FAO, 1988), the number of days falling into each category should represent the current thermal zones, for example, **Bogra** provided the following figures:

Table 6.5 Frequency Data for the Thermal Zone Allocation - Bogra

	Baseline Climate		Baseline + 1.5°C	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	96	T4	71	T2
T-mean < 20°C	57	T4	22	T1
T-min < 17.5°C	115	T4	94	T3
T-min < 15°C	82	T4	63	T3

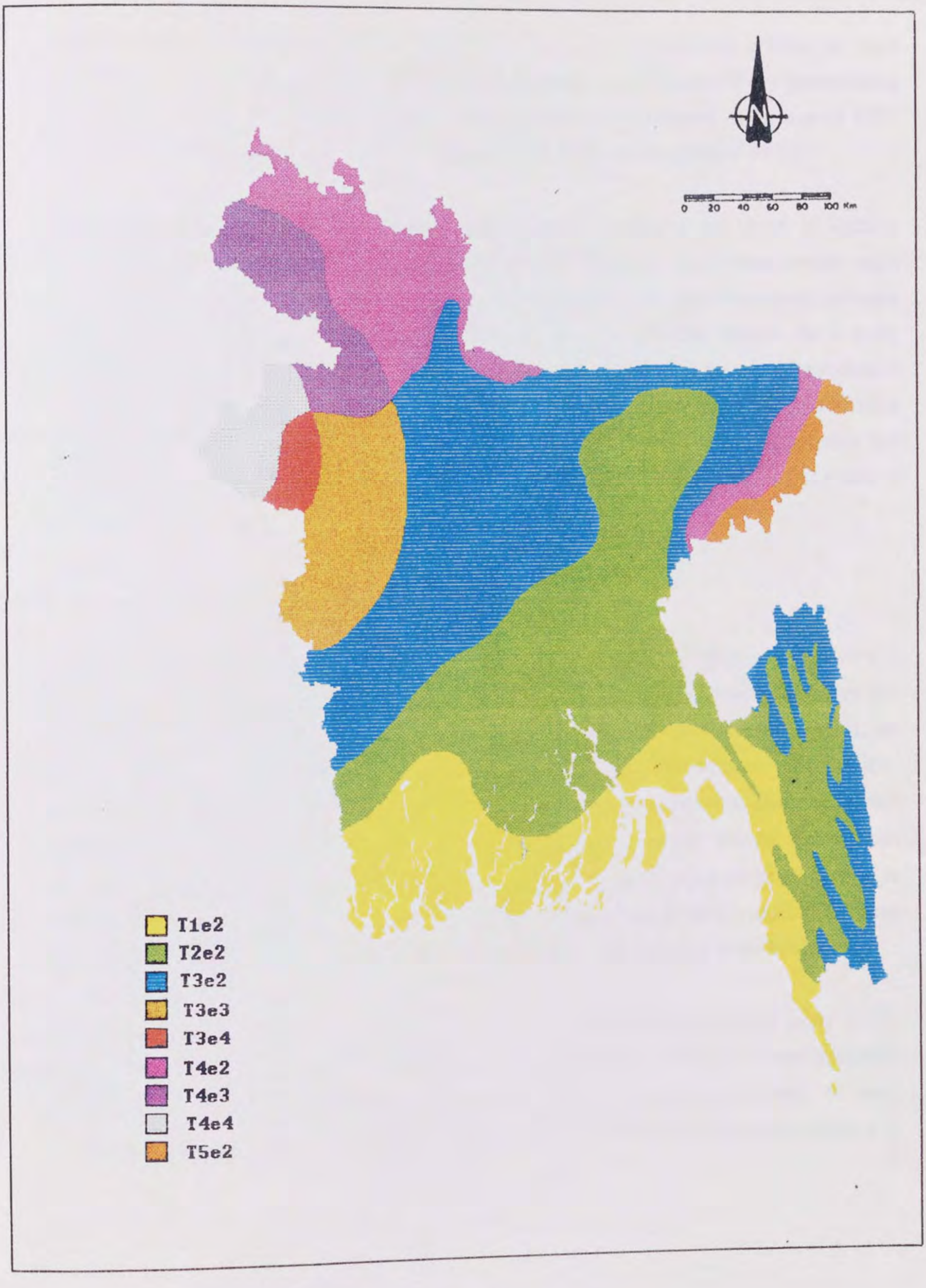
The frequency of days in each category for Bogra initially represents the T4 zone, with the 1.5°C increment the new zones range between T1 and T3, clearly no longer T4. Based upon the literature and current knowledge, it was considered appropriate with a movement across more than one zone in this manner to be limited to delimitation to the adjacent zone only, i.e. T3.

The above process was repeated for each of the 26 climate stations. The summary data are presented in Appendix A3, most stations move northward into (at least) the adjacent thermal zone (T2 becomes T1 for example). The Shrimangal station was the only site that did not represent a movement of at least one complete zone, in this instance half of the zone T5e1 was changed from T5 to T4, whilst the coastal zone remained as T5.

These final thermal zones boundaries can be seen in Figure 6.14.

These new thermal (T) zone boundaries were therefore ready to be applied to the agro-climatic suitability (Section 8.2) to represent the possible future thermal regime.

Figure 6.14 Thermal Zone Boundaries After the Climate Change Scenario



6.8.2 The Extreme Temperature - e Zones

Temperatures in excess of 40°C and below 10°C are also considered critical to crop development. The extreme temperature zone boundaries are delineated by determining the frequency of occurrence of days with extremely high temperatures in excess of 40°C during the hot period and the occurrence of minimum temperatures below 10 °C.

Delineation of the new e zones was difficult. Reference to the literature review in Section 4.3.2.3 indicates that current research considers that the incidence of extreme events such as excessive temperatures may increase, but quantification of this frequency remains subjective. In an attempt to provide for some variation in extreme events the e zone boundaries were moved eastwards, corresponding to half a day increase of maximum temperatures exceeding 40°C, which remains within the limits of possibility. To undertake the agro-climatic suitability it was necessary to combine the T and e zones to provide the pre-requisite thermal suitability classes. Figure 6.14 indicates the positions of the new e zone boundaries.

6.8.3 The Moisture - K Zones

As outlined in Section 6.4.1 the moisture zones represent the period when soil moisture is sufficient to support crop establishment and growth. The existing K zone boundaries are show in Figure 6.3. Based upon the IPCC regional scenario (Houghton *et al*, 1990), no change in the soil moisture content is proposed during the dry rabi season. In addition, with the imprecision in relation to the effects of increased precipitation and the varied responses in soil moisture levels (Section 4.3.2.2), the changes would have been impossible to quantify. During the kharif (rainy) season, the soil moisture contribution is not a limiting factor to crop growth, so despite the scenario proposing a possible increase of 5% during this period, this is likely to have little impact and has also been excluded.

When considering the impact of a 10% increase in precipitation, during the rainy kharif season, again water is not a limiting factor for crop growth and has not been included. Consequently, the K zone boundaries remain unchanged. The main constraint to crop growth is considered to be temperature change. The 10% increase in precipitation is however indirectly applied to the crop yield model, according to the effects upon rain cloud formation and the consequences for incoming solar radiation.

In a similar manner the estimated 5% increase in precipitation during the (dry) rabi season is applied only to the unconstrained yield model. During this period most moisture utilisation by crops is provided by the soil moisture reservoir, any precipitation increase is unlikely to have any significant effect upon this reservoir since the amount of rainfall during this season is so low.

6.8.4 The Transition Period - P Zones

As mentioned in Section 6.4.2 the pre-kharif transition period is a period of switching from dry to moist conditions. The length of this period is independent of land type or soil moisture, but is dictated instead by the frequency of individual rainstorms and the amount of rain falling in them. As detailed in Table 6.3 the average length of the pre-kharif transition period varies from 10 to 20 days in zone p1 in the north-east, to 60 to 70 days in zone p6, in the south-west. The length of the pre-kharif transition period zones exhibits considerable year to year variation. Therefore, the standard deviation for all zones is high, ranging from 15 to 20 days in the north-east to 20 to 25 days in the broad belt crossing the centre of the country, to 20 to 25 to 30 days in the west and south, thus making forecasting the start of the period imprecise and making it impossible to determine whether a real change in the mean would actually occur under the climate change scenario. The impact of climate change upon this variable has not been considered therefore, since insufficient data exists to allow any valuable quantification and any values may well fall within the standard deviation of the existing figures.

As above, the K and p zones were also combined to provide the 49 zones necessary to represent the growing period suitability for the second agro-climatic assessment.

Having established the boundaries of the various zones, the maps were digitised into the GIS in preparation for the agro-climatic suitability assessment. The suitability of both the Te zones and PK zones for crop cultivation was determined by the AEZ (FAO, 1978a, 1988) methodology and is presented in tabulated format in the results Appendix A6.

Chapter 7

Data Collection & Processing

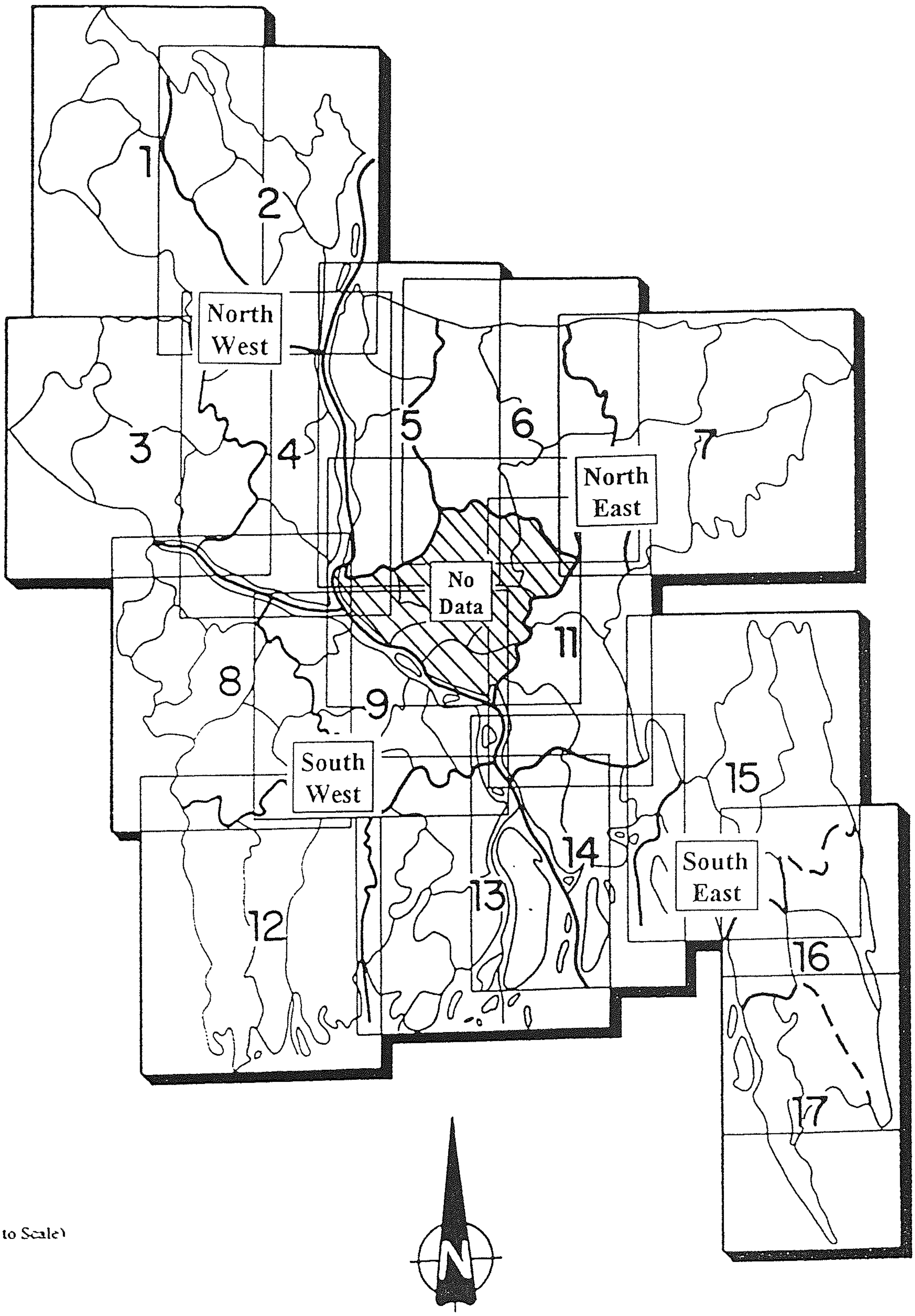
7.1 Introduction

This chapter provides sources for all data used in the project and describes the methods of data collection. The problems associated with data acquisition, accuracy and format incompatibility are also discussed, most of which may be applied to any data source, although certain problems relate specifically to dealing with a developing country.

7.2 The Regions of Bangladesh

For land evaluation, the country had to be subdivided into manageable areas. The Land Resources Appraisal of Bangladesh for Agricultural Development (FAO, 1988) divided the country according to the 17 numbered areas, illustrated in Figure 7.1. Much of the mapped data for the project adopted these subdivisions. Limitations of computer processing capacity generally necessitated use of individual map sheets at certain times (for example, overlaying and reclassification requires considerable disk space), although for final presentation the sheets were concatenated into 4 study regions. These regions

Figure 7.1 Map Sheets Covering The Four Study Regions of Bangladesh



(Not to Scale)

are used at all other times and are therefore described below as:

Region	Map Sheets			
North West	1	2	3	4
North East	5	6	7	11
South East	14	15	16	17
South West	8	9	12	13

As detailed in Section 7.4.1 below, the area covered by map sheet 10 has been omitted from the study, this was due to an inability to acquire all the data necessary to complete the full land evaluation. The area contains the principal urban area, covers approximately 12,000 km² (8.5 % of the country area) and corresponds to the missing area on the countrywide maps, presented in the Appendix A6.

7.3 Collection of Literature & Other General Information

Acquisition of reference material printed in Bangladesh is difficult. A three month period was spent in the country collecting data from various sources, particularly the library of ISPAN (see below), the libraries of the Bangladesh FAO office and personal contact with people involved with similar work. Without these personal visits, it would have been virtually impossible to gain much of the currently held information. In addition, a 2 week period was spent using the reference facilities at the FAO Headquarters in Rome and talking to staff involved with land evaluation.

7.3.1 ISPAN

The severe flood in Bangladesh in 1988 initiated a concerted international effort to seek a solution to the flooding problem. In response, in 1990 the Flood Action Plan (FAP) was established by the Bangladesh Government in collaboration with the United Nations Development Programme (UNDP) and the World Bank. The FAP was divided down into various numbered projects, each concerned with a particular task. FAP 19 was established for Geographic Information Systems, co-ordinated from the USAID (United States Agency for International Development) funded offices of ISPAN in Dhaka. One of the responsibilities of FAP 19 was to construct a National Database for Bangladesh to facilitate the accurate recording of geographical information for exchange with other FAP projects and Bangladesh agencies. This database contained digital maps of Bangladesh, detailing the position and boundaries of individual soil association units (see Section 6.7.2), these maps were used for this project. The soil association boundaries are based upon the Reconnaissance Soil Survey Maps of the Bangladesh Soil Association Institute (1960's-1970's) and are the most up to date available.

It must be remembered that the dynamic nature of the river banks, floodplains and suspended sediment in the Bangladesh river system, will generate a degree of inaccuracy in the location of certain soil association boundaries, this is fundamental to the system and without re-mapping after every flooding event will remain a source of error. In an attempt to reconcile differences between adjoining soil association map sheets in the position of river channels in Districts surveyed in different years, the river channels and soil association boundaries along the Ganges (Padma) river were amended in the database using 1963 and 1969-70 airphotos; the Brahmaputra river using the 1963 airphotos and the Jumuna river using the 1969-1970 airphotos. Quantification of the reliability of this data source is therefore impossible, but it does provide the only comprehensive database currently available. The mapped river courses will be held constant for the 50 year period for the climate change scenario therefore, although in reality they are expected to alter considerably (see Chapter 10).

7.4 The Digital Soil Association Maps for the GIS

The digital soil association information was originally copied in ERDAS format onto five 3.5" floppy disks, from the ArcInfo GIS held at ISPAN. The data occupied 6 megabytes in total and was converted to *IDRISI* format on return to the UK, using the *Erdidris* command. The legends for the maps detailing the soil association classes were provided in DBase format, but originally no hard copies of the maps were available and correct allocation of the 3746 legend categories was initially impossible. Eventually, copies of the original maps for the project were acquired from Bangladesh (sheets 3, 11 & 14 were never received), and the legend categories that were tentatively allocated previously were verified with the hard copies. This in itself was a tedious and time consuming process, requiring visual comparison of the digital maps and the hard copies, the entire process from data acquisition to creation of final digital maps took several months.

7.4.1 Acquisition of Missing Data

All the soil association maps for the country were finally reconstructed, with the exception of map sheet 10 for central Bangladesh (see Figure 7.1). The digital map for this area was initially unavailable and subsequent acquisition in the same format has been impossible, although attempts were made.

7.4.2 Bangladesh Transverse Mercator Projection

The digital soil association maps provided by FAP 19 adopted a new mapping projection specifically developed for Bangladesh by FAP 18 (the Topographic Mapping project). Tentatively termed the Bangladesh Transverse Mercator the projection is based upon the 90° central meridian and the Everest ellipsoid, in summary the projection has the following features:

Tentative Name	Bangladesh Transverse Mercator
Projection	Transverse Mercator
Ellipsoid	Everest 1830
Scale Factor	0.9996
Central Meridian	90° East
Latitude of Origin	0° (Equator)
False Easting	500,000
False Northing	-2,000,000

To aid in field location, FAP 19 adopted a metric grid that covers all of Bangladesh. The X-Y co-ordinates of this grid are established by designating a 'false easting' of 500,000 metres and a 'false northing' of -2,000,000 metres from its origin at 0° N (Equator) and 90° East. With this grid, all locations in Bangladesh may be identified by positive X and Y values ranging between 0 and 999,999 metres.

This projection was adopted throughout the project for all digital maps held within the GIS, an accurate grid system was fundamental to the accuracy of the work since overlaying like cells was critical to the suitability process, any inaccuracy in cell location would have resulted in the wrong cells being compared. It can not be overemphasised that two separate map projections could result in errors of 10s of cells (the accuracy of overlaying was first discussed by McAlpine & Cook, 1971; see also Burrough, 1993).

7.5 Climatic Data

The climatic data was obtained from FAO (1988) Report 3 - Land Resources Database, Vol.1 - The Climatic Database, collected by the Bangladesh Meteorological Office and representing the most recently available complete climate data set. This data is also available in the FAO CLIMWAT Database (FAO, 1993b) and in other global climate datasets such as for example, the Global Maximum-Minimum Temperature Dataset available from the Internet.

The climate data for 26 climate stations was used, the locations and altitude of which are illustrated in Table 7.1 and the positions of which are shown in Figure 7.2.

Using 1988 as the baseline climate, data was available for the following climate variables:

- Mean monthly precipitation (mm)
- Mean monthly 24 hour temperature (°C)
- Mean monthly maximum temperature (°C)
- Mean monthly minimum temperature (°C)
- Mean daily temperature (°C)
- Mean night-time temperature (°C)
- Mean incoming solar radiation (cal/cm^2)
- Relative humidity (mbar)

The actual data for the stations are provided in Appendix A2. The FAO (1988) produced a Hydro-Climatic Resources inventory used later in the study which details the thermal, moisture and inundation regimes for Bangladesh. This inventory is detailed separately in Chapter 6.

Figure 7.2 **The Climate Stations of Bangladesh**

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Table 7.1 The Location of the Climate Stations

Station Number		Latitude °N	Longitude °E	Altitude M
1	Barisal	22.45	90.22	4
2	Bhola	22.41	90.39	5
3	Bogra	24.51	89.22	20
4	Brahmanbaria	23.57	91.08	6
5	Chandpur	23.16	90.42	7
6	Chittagong	22.16	91.49	6
7	Comilla	23.26	91.11	10
8	Cox's Bazar	21.26	91.58	4
9	Dhaka	23.46	90.23	9
10	Dinajpur	25.39	88.41	37
11	Faridpur	23.36	89.51	9
12	Feni	23.02	91.25	4
13	Hatiya	22.16	91.06	4
14	Jamalpur	24.56	89.57	20
15	Jessore	23.11	89.10	7
16	Khulna	22.47	89.32	4
17	Mymengsingh	24.43	90.26	19
18	Narayanganj	23.37	90.85	9
19	Pabna	24.00	89.16	14
20	Patuakhali	22.22	90.21	3
21	Rangamati	22.38	92.12	63
22	Rangpur	25.44	89.14	34
23	Rajshahi	24.22	88.34	20
24	Satkhira	22.43	89.05	6
25	Sirajganj	24.27	89.42	15
26	Sylhet	24.54	91.53	35

7.6 Physiographic Data

The physiographic data (including soils, landform and topography) were also obtained from ISPAN, FAP 19 in Bangladesh. The data were acquired for the 17 mapped regions of the country on three 3.5" floppy disks, occupying approximately 4 MB in Lotus spreadsheet format. The relevant data for each soil association unit was provided as a series of figures corresponding to the various parameters, Figure 6.9 illustrates the format of the spreadsheet. In a similar manner to the Hydro-Climatic Resource Inventory above, Inundation, Soils and Landform Inventories are also produced by the FAO (1988), these too are detailed in Chapter 6.

7.7 Population & Agricultural Statistics

In addition to the FAO data, the majority of statistical data were provided by Navin & Khalil (1989) in their statistical database. The Bangladesh Bureau of Statistics (BBS) provided the main sources of data, their publications include: The (1983-84) Bangladesh Census of Agriculture and Livestock Report published in 1986, Volume I & II, The Yearbook of Agricultural Statistics in Bangladesh, Monthly Bulletins & Statistical Pocket Books of Bangladesh. The Bangladesh Ministry of Food's Food Planning and Monitoring Unit provided data on the current and forecasted food supply situation and macroeconomic data may be acquired from the International Bank for Reconstruction and Development.

7.7.1 Data Reliability

Most of the data are based upon sampling techniques and aggregations up to national level, therefore there are many ways that errors may occur. For example, time series analysis can be problematic, since there have been three agricultural censuses in Bangladesh each adopting a slightly different sampling technique (for each, a different percentage of villages were sampled). The most recent census in 1983-84, also changed the basic unit of analysis from the 'agricultural holding' to the 'agricultural household', which is more likely to have an effect upon the continuity of subsequent figures.

An additional problem is that there are major inconsistencies even within BBS's recently published data. For example, the area under production of pulses reported in the 1983-84 census is 2.14 million acres, whereas subsequent 'Monthly Statistical Bulletins' and 'Yearbooks of Agricultural Statistics' indicate that the area is only about 636,000 acres. Similarly, according to Boyce (cited in Navin & Khalil ,1989) official statistics for annual rice output may be underestimated by 400,000 metric tonnes. Nevertheless, the data is the only source available and Navin & Khalil (1989) altered any spurious figures and discarded those when field experience suggested something different.

7.8 Land Suitability Ratings

The suitability ratings used in Section 8.6 to undertake the land suitability assessment are published by the FAO in the various volumes of the Land Resources Appraisal of Bangladesh (FAO, 1988). The Bangladesh Agricultural Research Council (BARC) is continually updating the FAO resources database, therefore BARC furnished computer printouts of the most up to date suitability ratings, recently modified to reflect current research into this area. Much of the land suitability rating data came with little or no explanatory text or legends. This did not compromise the accuracy of the project, but often produced significant delays for interpretation. For example, additional FAO reports had to be referenced in order to interpret the lists of figures provided by BARC.

7.9 Agro-climatic Data

All data relating to the requirements of crops, such as climate, soil and agro-climatic, were contained within the FAO ECOCROP Database - Version 1.0 (FAO, 1994), although much of these data were also provided in FAO Report 6 (FAO, 1988).

7.10 Data Processing

For most of the computer processing an Elonex 486 DX-33 personal computer with 4 MB of RAM and 2 hard disks totalling 300 MB was used, a colour S VGA monitor was also necessary to display images in the GIS. Much of the 300 MB hard disk was used to store the data, so that approximately 100-150 MB were available as working disk space. The speed of the data processing could have been significantly increased if the 16 map sheets of Bangladesh had been concatenated into a single image, however disk space and processor limitations necessitated repeating the methodology upon each separate map sheet singly.

7.11 Summary

Clearly, work of this nature presents problems particularly with data acquisition, although incompatibility (see Fabbri, 1992 for further discussion) and accuracy also contributed to the difficulties experienced. Many man hours were spent simply acquiring data and upon receipt, much time was spent interpreting and verifying, a time-consuming but fundamental aspect of the project (or indeed any project of this nature). Despite the limitations of data, an attempt has been made to acquire the best data set currently available. This is the best data set available.

Chapter 8

Methodology

This chapter details the methodology used for the entire land suitability assessment. Due to the complexity of the processes the chapter has been divided into 3 sub-sections:

I. The Agro-Climatic Suitability Assessment
II. The Soil Suitability Assessment and,
III. Calculation of the Crop Yield

I. Agro-climatic Suitability Assessment

8.1 Introduction

The first section outlines the methodology utilised to undertake the agro-climatic suitability assessment. The methodology is based upon the agro-ecological zones methodology developed for the African Agro-Ecological Zones Project (FAO, 1978-81). Full details of the suitability assessment and the modifications necessary for Bangladesh can be found in FAO (1988, Report 6), emphasis is given to the developments made to the automation of the process with the aid of a spreadsheet and the GIS. A worked example adopting wheat under low input traditional conditions, illustrating the entire procedure, is provided.

Having undertaken the methodology once, the regional climatic variables described in Chapter 3 were applied and the methodology repeated. The difference in yield obtainable for each crop was then calculated to determine the impact of the climate change scenario. These results are presented in Appendix A6.

8.2 Agro-Climatic Suitability Assessment

8.2.1 Crop Climatic Adaptability

Crops have climatic requirements for photosynthesis (growth and yield formation) and phenology (development pattern), both of which have a relationship to yield. The rate of crop photosynthesis and thus growth, is related to the carbon assimilation pathway and its response to temperature and radiation. However, the phenological climatic requirements which must also be met, are not specific to a photosynthetic pathway. In the FAO-AEZ methodology (FAO, 1978: Report 1), based extensively upon the work of Kassam *et al* (1977), crops are classified into four climatic adaptability groups according to their photosynthetic characteristics. The inventory of photosynthetic characteristics for Bangladesh (FAO, 1988: Report 6) was sub-divided according to these 4 adaptability groups and the following information provided:

Table 8.1 Average Photosynthetic Response of Individual Leaves of 4 Groups of Crops to Radiation and Temperature

Source FAO (1988, Report 6)

The full list of crop attributes helpful in assessing the climatic adaptability of the crops is given below:

- Species
- Photosynthesis Pathway
- Crop Adaptability Group
- Length of Growth Cycle
- Harvested Part
- Main Production/Use
- Growth Habit (determinate/indeterminate)
- Life span (natural & cultivated)
- Yield Location
- Yield Formation Period
- Photoperiodic Sensitivity
- Special Temperature Requirements

The required data for each of the crops in the study was provided in the report (FAO, 1988: Report 6). This data for the example crop of wheat is presented in Table 8.2.

8.2.2 Agro-climatic Suitability Classification Methodology

The next step required consideration of the suitability of the climatic zones (defined in Section 6.3) for crop production. This agro-climatic suitability classification aimed to: (a) evaluate the prevailing climatic conditions with regards production potential and (b) to assess the likely effects of abiotic stresses (moisture & temperature), biotic stresses (pests, diseases, weeds) and workability, that operate through yearly weather variations. The agro-climatic suitability classification was achieved via the following steps:

Table 8.2 Climatic Adaptability Attributes of Spring Wheat

Spring Wheat

Source FAO (1988: Report 6)

i. matching crops to **temperature conditions** in each of the thermal zones, including assessing any loss in yield potential due to temperature stress;

ii. matching crops to **moisture conditions** in each of the growing period zones, including assessing loss in potential yield due to moisture stress;

iii. assessing loss in yield potential due to **biotic stresses** caused by pests, diseases and weeds;

iv. assessing **workability constraints** resulting from climatic and weather conditions;

v. combining the above assessments into an agro-climatic suitability classification.

In the Bangladesh AEZ system the assessment of agro-climatic constraints is achieved by semi-quantifying the constraints in terms of reduction ratings. These ratings were determined according to the different constraints and their severity, for each crop/LUT in each length of growing period and in each thermal zone. The ratings considered inter-year variations in weather and related environmental conditions over a period of years. The thermal suitability assessment used five suitability classes to rate the requirements /constraints, namely:

S1 where requirements are fully met, no or only slight constraints resulting in no significant yield loss

S2 sub-optimal, moderate constraints, resulting in yield losses of the order of 20%

S3 sub-optimal, severe constraints, resulting in yield losses of the order of 40%

S4 sub-optimal, very severe constraints, resulting in yield losses of the order of 60%, and

NS unsuitable, extremely severe constraints, yield suppression would be 80% or more.

8.2.2.1 Matching Crop Temperature Requirements to Temperature Conditions in the Thermal Zones

This matching procedure provided a thermal suitability classification of each thermal zone for each crop/LUT. The actual matching required three steps:

i. assessing the temperature suitability for phenology (i.e., crop development) providing the **thermo-phenology rating**.

ii. assessing the temperature suitability for photosynthesis (i.e., crop growth and yield formation), by comparing the rate of photosynthesis at the prevailing day-time temperature with the maximum photosynthesis rate at optimum temperatures. This is the **thermo-photosynthesis rating,** and

iii. combining the thermo-phenology assessment with the thermo-photosynthesis assessment to derive the overall loss in yield and the **thermal suitability classification**.

The final thermal suitability classes for each crop provided by the FAO (1988) are presented in Table 8.3. For example, a crop of wheat belonging to thermal zone T1e1, would have a thermal suitability rating of S3,' sub-optimal.

The thermal suitability assessment for each crop can be undertaken, using the figures above and the digitised version of the thermal (T & e) zone maps (see Figure 6.4). The final suitability classes were allocated to the map in the GIS using the *Reclass* command with a user-defined classification defining the new integer value for the class and the range of old values to be assigned this class. This process was repeated for each of the crops in the study both before and after the climate change scenario. A thermal suitability map is then produced for each crop depicting the thermal suitability class areas and positions. The thermal suitability maps for wheat are presented in Appendix A6 Figures A6.1 and A6.2, together with the areal extents of the thermal classes for the remaining crops in Table A6.5.

Table 8.3 Thermal Zone Suitability Ratings

Based upon FAO (1988)

8.2.2.2 Matching Crop Moisture Requirements to Moisture Conditions in the Growing Period Zones

Utilising the growing period zones defined in Section 2.7.1, the second matching procedure provided the moisture suitability classification of each moisture zone for each crop/LUT, the matching procedure required three steps:

i. Assessing how well the crop growth cycle fits into the length of growing period available (rabi or kharif), including the effect of the inter-year variability in its length and assuming no temperature (or other) constraints. Providing the **moisture period rating**

ii. Assessing moisture quality in each Length of Growing Period Zone by Thermal Zone, taking into account any temperature-moisture period interactions, this considered the constraints that arise from shortage or excess of water during the growing period. Such constraints can affect crop yield formation and produce quality. The effect of water shortage depends upon its severity and on the crop growth stage when it occurs. Such effects can be taken into account using the approach described in Doorenbos & Kassam (1977). Problems of excess moisture relate to delays in planting which can, in turn lead to end of season water shortages, or to water logging. Excess moisture can also reduce produce quality. This provides the **moisture quality rating** and,

iii. Combining the moisture period assessment with the moisture quality assessment to derive the **moisture suitability classification**.

The effects of biotic constraints (described below) are combined with this classification to provide the growing period suitability Classification .

8.2.2.3 Assessing Yield and Quality Reducing Factors of Pests, Diseases and Weeds (the Biotic Constraints)

In order to assess the constraints imposed by weeds, pests and diseases, the effects on yield that operate on crop growth potential (e.g., pests and diseases affecting the vegetative parts in grain crops) were separated from those effects on yield that operate directly on yield components, yield formation and produce quality.

The complex and dynamic nature of pest, disease and weed constraints and their inter-relationships made it extremely difficult to quantitatively assess their overall effect upon yield. There is also a general lack of information and knowledge regarding these constraints, thus a somewhat tentative overall rating and suitability classification for these constraints was produced by FAO (1988, Report 6). From this evaluation, the biotic constraint rating and the biotic suitability classification could be determined.

8.2.2.4 Climatic & Weather Factors Which Affect the Efficiency of Farming Operations and Cost of Production (the Workability Constraints)

Workability constraints are those that make crop management and husbandry operations difficult and increase the marginal cost of production. Operations include those related to land preparation, sowing, cultivation and crop protection during crop growth, and harvesting (including operations related to handling the produce during harvest and ability to dry the produce).

Workability constraints have their origin in prevailing weather and soil conditions. They vary from crop to crop between growing periods and also within growing periods, due to soil characteristics (e.g., operational problems of timely land preparation, sowing and harvesting under wet conditions or stoniness; problems of handling wet produce; problems of applying fertilisers and biocides effectively to crops under wet conditions; problem of achieving effective water control in the case of wetland crops). These workability constraints can cause direct losses in yield and produce quality, and/or impart a degree of relative unsuitability to an area for a particular crop from the view point of how effectively farm operations can be conducted at a given level of inputs and costs.

8.2.3 The Growing Period Suitability

The moisture suitability, biotic suitability and the workability suitability classifications are combined into a single suitability classification known as the 'growing period suitability classification'. According to the growing period zone, a single figure has been derived by FAO (1988) to represent this. Table 8.4 provides the necessary information to undertake this second classification. The growing period suitability classes utilise the same figures S1 to S4 and NS as the thermal suitability classification (Section 8.2.2).

Based upon this data, wheat for example, in the moisture zone - K1p5, would have a growing period suitability rating of S3 (moderate limitations). In a similar manner to the thermal suitability classification, these growing period classes were allocated to the digitised map of the K and P zones in the GIS using the *Reclass* command and a user-defined classification system.

Table 8.4 Growing Period Zone Suitability Ratings (Non-Irrigated)

Cont ...

Table 8.4 Growing Period Zone Suitability Ratings (Non-Irrigated)

Source FAO (1988)

The final growing period suitability classification map for all the regions for wheat is presented in Appendix A6 Figure A6.3, together with the areal extents of the growing period zones for the other crops in Table A6.6.

8.2.4 The Agro-climatic Suitability Classification

The final stage was the agro-climatic suitability classification. This was derived by combining the two constraint ratings (thermal and growing period) to assess overall yield losses. The classes were evaluated according to the following combinations from FAO, determined by experimentation with actual figures:

Table 8.5 Agro-climatic Suitability Classes, Derived From The Thermal & Growing Period Suitability Ratings

Thermal Suitability Rating	Growing Period Suitability Rating	Agro-climatic Suitability Class	Thermal Suitability Rating	Growing Period Suitability Rating	Agro-climatic Suitability Class
S1	S1	VS	S4	S1	ms
	S2	S		S2	ms
	S3	MS		S3	NS
	S4	ms		S4	NS
	NS	NS		NS	NS
S2	S1	S	NS	S1	NS
	S2	MS		S2	NS
	S3	ms		S3	NS
	S4	ms		S4	NS
	NS	NS		NS	NS
S3	S1	MS			
	S2	ms			
	S3	ms			
	S4	NS			
	NS	NS			

As indicated in Table 8.5 the agro-climatic suitability employs five different classes, which have the same meaning as the previous 'S' classification but a different nomenclature, these classes are defined as follows:

VS - *very suitable*, crop yield is 80% or more of the maximum attainable
S - *suitable*, yield is 60 to 80% of the maximum attainable
MS - *moderately suitable*, yields of 40 to less than 60%
ms - *marginally suitable*, yield of 20 to less than 40%
NS - *not suitable*, yields of less than 20%

Mapping the combination of the thermal suitability and the growing period suitability was achieved by cross-classification of the digital coverage maps for these two parameters, utilising the *Crosstab* command in the GIS. The cross-classification operation allows maps to be overlaid producing a new image and legend showing the combination of all categories from the original maps using the logical AND operation. This map was then reclassified using the *Reclass* command according to the combinations presented in Table 8.5 above. For example, an area with a thermal suitability rating 'S1' (represented as 1 in the GIS) and a growing period suitability rating 'S2' (2 in the GIS) would be reclassified as - Suitable 'S' (2 in the GIS). This process was repeated for each of the crops in the assessment before and after the climate change scenario. The final agro-climatic suitability maps for wheat are presented in Figures A6.4 and A6.5 in Appendix A6, together with the areal extents of the classes for the other crops in Table A6.7. These agro-climatic suitability maps were then ready for use with the soil suitability assessment, which is described in the following section.

II. Soil Suitability Assessment

8.3 Introduction

The following section outlines the methodology used to evaluate the suitability of the soil for supporting various land use types (LUTs). A brief description of the methodology is provided here, although detailed descriptions of the soil suitability assessment process, the calculation of the limitation ratings and the conversion problems involved for an example soil association unit, are provided in Appendix A4.

8.4 Basic Soil Requirements of Crops

The soil suitability aims to assess the suitability of the soils for crop production. To achieve this the fundamental crop soil requirements were determined by the FAO. In addition, these requirements have to be understood within the context of limitations imposed by landform, inundation and other features, which do not form a part of the soil composition, but may have a significant influence on the use that can be made of the soil.

The basic soil requirements of crop plants relate to the following *internal* soil properties:

i. The **soil temperature regime,** as a function of the heat balance of soils which, in turn is related to annual and seasonal and/or daily temperature fluctuations;

ii. The **soil moisture regime**, as a function of the water balance of soils as related to the soil's capacity to store, retain, transport and release moisture for plant growth and/or the soil's permeability and drainage characteristics;

iii. The **soil aeration regime**, as a function of the soil air balance as related to its capacity to supply and transport oxygen to the root zone and to remove carbon dioxide;

iv. The **natural soil fertility regime**, as related to the soil's capacity to store, retain and release plant nutrients in such kinds and proportions as required by crops during growth;

v. The **effective soil depth** available for root development and physical support of the crop;

vi. Soil **texture and stoniness**, both at the surface and throughout the whole depth of soil, required for normal crop development;

vii. The absence of soil **salinity** and of specific toxic substances or ions deleterious to crop growth;

viii. Soil **accessibility and trafficability** under certain management systems

ix. Other specific properties e.g., soil tilth as required for germination and early growth.

8.4.1 The Soil Requirements & Characteristics

Using the above information it was possible to provide a simple correlation between the basic soil requirements listed above and the soil characteristics that can be used as soil factors to rate crop performance (Brammer, 1985), this relationship is given below in Table 8.6.

Table 8.6 Relationship Between Basic Soil Requirements & Soil Characteristics

Basic Soil Requirements	Soil Characteristics (Land Factors)
Moisture availability [1]	Effective soil depth Available soil moisture holding capacity Drainage
Nutrient availability	Nutrient availability Soil reaction
Oxygen availability[2]	Soil permeability Drainage
Foothold for roots	Effective soil depth
Lack of Salinity	Soil salinity
Lack of Toxicity	Soil reaction[3]
Accessibility & trafficability (workability)	Topsoil consistency & bearing capacity
Soil tilth for crop establishment	Topsoil consistency & bearing capacity

1 Moisture availability is influenced by climatic factors
2 Oxygen availability is influenced by inundation and flooding characteristics
3 Chemical properties of soil parent material may also be involved in some cases

These soil factors provide 8 internal land factors for use in the soil suitability assessment. The optimum and critical ranges of the soil characteristic listed above were determined for each of the crops by the FAO (1988), for example, the optimum soil depth for rainfed wheat is >120 cms becoming critical between 25-120 cms. Having identified these 'internal' soil requirements the 'external' requirements of inundation and landform had to be included.

Inundation and landform are 'external' requirements which contribute to crop success in addition to the 'internal' soil requirements described above. The inundation requirements for a selection of crops are presented in FAO (1988, Report 6). The external factors include: erosion status, inundation and flood hazard. These provide 3 more land factors for inclusion into the soil assessment.

Having identified the 11 critical land factors recognised by the FAO (1978a) as being limiting to crop production, the actual soil data had to be gathered.

8.5 The Soil Attributes

The main data describing the soil attributes for the whole of Bangladesh were held the SODAPS database described in Section 6.7.1. Appendix A1 details the column descriptions and the scheme for describing the land factor ratings within the database.

From the 29 land factors held within the database, the critical 11 include:

1. Depth of inundation (i)
2. Flood hazard (f)
3. Soil Depth (d)
4. Available soil moisture holding capacity (m)
5. Permeability (p)
6. Drainage (w)
7. Top soil consistence & bearing capacity (t)
8. Soil reaction (a)
9. Nutrient availability (n)
10. Soil salinity (s)
11. Slope/Erosion (e)

(The letters after the factors correspond to the land factor identifiers used in the FAO methodology)

A soil suitability spreadsheet was created that used these relevant land factors from the SODAPS database (Section 6.7.1) for each soil association unit, in preparation for the soil suitability assessment. To date, this approach for the allocation of the soil ratings to the land factors has never adopted the facility of a spreadsheet. The first section headed 'Land Factors' of Figure 8.1 provides an example of the 11 land factors and their values for some example soil association figures.

8.6 Rating the Limitations to Crop Growth

Having established the values for the 11 land factors, the AEZ methodology allocates a figure representing the limitation that the prevailing land factor may impose upon crop growth, based upon the critical values detailed above. These *limitation ratings* were provided for the individual crops by the Bangladesh Agricultural Research Council (BARC). The ratings consist of a number between 0 and 4, depending upon how limiting an attribute for a particular soil unit is. For example, a soil unit with a slope of class 1 (less than 3 degrees) is classed as providing no limitation to crop growth and is therefore allocated the limitation rating 0. The crop suitability limitation ratings for the individual crops are presented in Table 8.7.

The soil suitability spreadsheet was then updated to include tables of these limitation ratings for each of the land factors. These figures were then used as 'look-up' tables within the spreadsheet to allocate the appropriate limitation ratings to the land factors. An example of the format of one of these tables is presented in Table 8.8.

The spreadsheet was modified to use the *vlookup* facility to allocate the corresponding limitation ratings to the land factor ratings. Placing the land factor identifier letters in alphabetical order in the first column allowed a search to be made down the list until the correct factor was found and then using the land factor rating figure across the top (1 to 6), the limitation rating could be identified.

The spreadsheet function with the table range called 'limitation':

= @VLOOKUP(e, Limitation, 1)

Figure 8.1 Excerpt from the Soil Suitability Spreadsheet for Wheat

Land Factors

	erosion	depth	moisture	permeability	drainage	consistence	soil reaction	nutrients	salinity	inundation	flood hazard
Soil Assocn	e	d	m	p	w	t	a	n	s	i	f
BN179	1	2	4	1	4	1	3	1	1	3	1
BN180	1	2	4	1	2	1	1	1	1	1	1
TM124	1	1	3	2	2	1	1	2	1	1	1
TM125	1	1	3	2	2	1	1	2	1	1	1
TM126	1	1	3	2	3	1	1	2	1	1	2
TM127	1	1	3	2	2	1	1	2	1	1	1
TM128	1	1	4	2	5	1	1	2	1	3	3

Limitation Ratings

erosion	depth	moisture	permeability	drainage	consistence	soil reaction	nutrients	salinity	inundation	flood hazard
e	d	m	p	w	t	a	n	s	i	f
O	1	2	O	1	O	1	O	O	O	O
O	1	2	O	O	O	O	O	O	O	O
O	O	1	O	O	O	O	1	O	O	O
O	O	1	O	O	O	O	1	O	O	O
O	O	1	O	O	O	O	1	O	O	O
O	O	1	O	O	O	O	1	O	O	O
O	O	2	O	3	O	O	1	O	O	O

Count	Max	Sum	Sum + 2	Initial Rating	First Check	Second Check	Soil Rating	GIS Figure
4	2	5	7	S3	S3	S3	S3	3
2	2	3	5	S2	S2	S2	S2	3
2	1	2	4	S1	S1	S1	S1	1
2	1	2	4	S1	S1	S1	S1	1
2	1	2	4	S1	S1	S1	S1	1
2	1	2	4	S1	S1	S1	S1	1
3	3	6	8	S3/S4	S3	S3	S3	3

Count - Counts the number of non-zero limitation rating values

Maximum - Determines the maximum limitation rating value

Sum - Adds all the values together

Sum + 2 - Adds 2 to the above figure for use in the look-up table

Initial Rating - Taking the Maximum value and the sum + 2 value, the look-up table below provides the initial soil suitability figure.

First Check - If the Initial Rating is S3/S4, a single figure has to be determined, most figures can be determined using the Count value. If the Count = 2 or 4 the Rating is S4, if the Count = 3, the Rating is S3.

Second Check - The remainer could be determined utilising the following logical expressions:

if Count = 6, Max = 3, & Sum = 8 then Rating = NS
if Count = 5, Max = 3, & Sum = 8 then Rating = S4
if Count = 3, Max = 3, & Sum = 8 then Rating = NS
if Count = 5, Max = 3, & Sum = 9 then Rating = NS
if Count = 6, Max = 3, & Sum = 9 then Rating = S4
if Limitation Rating Product = 9, Max = 3,
& Sum = 8 then Rating = NS
if Limitation Rating Product = 12, Max = 3,
& Sum = 8 then Rating = S4
else, use First Check figure,
to provide the - Soil Rating.

Table 8.7 Crop Suitability Soil Limitation Ratings (Rainfed)

Brammer (1987)

Table 8.8 Format of a Limitation Rating 'Look-up' Table

		Land Factor Ratings (wheat)					
		1	**2**	**3**	**4**	**5**	**6**
a	(Soil reaction)	0	0	1	3	3	na
d	(Depth)	0	1	1	2	3	2
e	(Erosion)	0	2	3	4	4	4
f	(Flood Hazard)	0	0	0	0	2	na
i	(Inundation)	0	0	0	0	0	0
m	(Moisture)	0	0	1	2	3	na
n	(Nutrient)	0	1	na	na	na	na
p	(Permeability)	0	0	1	na	na	na
s	(Salinity)	0	1	2	3	4	na
t	(Consistence)	0	1	2	2	na	na
w	(Drainage)	0	0	0	1	3	4

would therefore provide the limitation rating 0, representing the erosion (e) land factor with a rating 1. Thus, the spreadsheet was able to generate a series of 11 limitation ratings with values ranging from 0 to 4 for each soil unit. The actual limitation ratings for the example soil association units are provided in the second section of Figure 8.1 labelled 'Limitation Ratings'.

A problem was experienced when extracting the land factor ratings from the SODAPS database. Despite the 11 land factor classes matching those used by the FAO, a disparity existed between the methods of allocating the limitation ratings. In certain instances the FAO adopted a different limitation scheme, containing the same classes, but in a different order. Appendix A4 provides a worked example of how this problem was overcome and a table detailing the corresponding values for the SODAPS and the FAO methodology. To avoid unnecessary complication, the remainder of this section assumes that the limitation ratings extracted from the spreadsheet have been converted to the same scheme as that adopted by the FAO.

Having established 11 limitation ratings for each soil association, the FAO methodology combines the 11 figures into a single soil suitability rating, according to the following classification:

S1	where requirements are fully met, no or only slight constraints resulting in no significant yield loss
S2	sub-optimal, moderate constraints, resulting in yield losses of the order of 20%
S3	sub-optimal, severe constraints, resulting in yield losses of the order of 40%
S4	sub-optimal, very severe constraints, resulting in yield losses of the order of 60%, and
NS	unsuitable, extremely severe constraints, yield suppression would be 80% or more.
ND	data unavailable
UA	urban area

These classes were represented by the numbers 1 to 7 in the GIS.

The final soil suitability rating process was achieved by the FAO by calculating the frequency of occurrence of each limitation rating (i.e. how many 3's, 2's etc. that there were) according to the different permutations shown in Table 8.9. This provided the final single soil suitability rating figure. For example, taking the soil association unit BN179 from Figure 8.1 - the limitation ratings consist of one 2, three 1's and the rest 0's and reference to Table 8.9 provides the single soil suitability rating figure S3. The FAO previously undertook this soil rating process for every soil unit using either a computer program or manually. Instead, it was intended to develop an alternative methodology using the spreadsheet.

In order to replicate this process the following values had to be determined:

- the maximum soil ratings value
- the sum of the limitation ratings values, and
- a count of the number of non zero limitation ratings.

Table 8.9 Relationship Between Suitability Rating and Number and Degree of Limitations

Source: FAO (1988)

Table 8.10 Soil Rating 'Look-up' Table

		Sum																				
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
		Sum + 2																				
		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
Max Value	0	S1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	1	NS	S1	S1	S2	S2	S3	S3	S4	S4	S4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	2	NS	NS	S2	S2	S2	S3	S3	S4	S4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	3	NS	NS	NS	S3	S3	S3	S3/4	S4	S4	S4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
	4	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS

It was found that based upon the permutations of the 'sum' and 'maximum' limitation rating values, shown in the look-up table in Table 8.10, the vast majority of soil ratings could be successfully rated by this process. Careful checking however, revealed that one permutation with a maximum value of 3 and a sum value of 6 provided a class of either S3 or S4. This class was therefore accounted for with the 'first check', using the 'count' value in addition to the 'sum' and 'maximum' values. If the 'count' value was 2 or 4 this rating was S4, if the 'count' value was 3, the rating was S3. This logical expression was presented for an example cell 'CD27' in the spreadsheet as:

= IF (AND (CC27 = "S3/S4", BY27 = 3)), "S3", IF (AND (CC27 = "S3/S4", BY27 = 4)), "S4", IF (AND (CC27 = "S3/S4", BY27 = 2)), "S4", CC27)))

when: cell CC27 contains the 'Initial Soil Rating'
cell BY27 contains the 'Count' value

- providing the rating S3 or S4 in the 'First Check' cell.

With additional checking it became clear that a small minority of permutations could theoretically be generated that would be incorrectly classed as 'S4'. To cater for these (if in fact they should ever occur), a 'second check' was introduced. This relied upon applying logical operations to the 'count', 'max' and the 'sum' values according to the following rules:

If count = 6, max = 3 and sum = 8, then rating = NS
If count = 5, max = 3 and sum = 8, then rating = S4
If count = 3, max = 3 and sum = 8, then rating = NS
If count = 5, max = 3 and sum = 9, then rating = NS
If count = 6, max = 3 and sum = 9, then rating = S4

It was found however that:

If count = 4, max = 3 and sum = 8, then rating can be either NS or S4, therefore an additional calculation was made if these instances ever arose, using the 'product' of the limitation ratings:

> If product = 9, max = 3 and sum = 8, then rating = S4
> If product = 12, max = 3 and sum = 8, then rating = NS
>
> ELSE use the figure provided by the 'First Check'.

This 'Second Check' logical expression was presented for an example cell 'CE27' in the spreadsheet as:

= IF (AND (BZ27 = 3, CA27 = 8, BY27 = 6)), "NA", IF (AND (BZ27 = 3, CA27 = 8, BY27 = 5)), "S4", IF (AND (BZ27 = 3, CA27 = 8, BY27 = 3)), "NA", IF (AND (BZ27 = 3, CA27 = 8, PRODUCT (BM27:BW27) = 9)), "NA", IF (AND (BZ27 = 3, CA27 = 8, PRODUCT (BM27:BW27) = 12)), "S4", IF (AND (BZ27 = 3, CA27 = 9, BY27 = 5)), "NA", IF (AND (BZ27 = 3, CA27 = 9, BY27 = 6)), "S4", CD27)))))))

when: cell BZ27 contains the 'Maximum' value
cell CA27 contains the 'Sum' value
cell BY27 contains the 'Count' value, and
cells BM27 to BW27 contain the 11 limitation ratings

The actual values for the 'count', 'sum' and 'max' can be seen to the top right of Figure 8.1, together with the results of the various checks and the final soil rating figures. In the Bangladesh, only one permutation of this type was actually found.

It must be noted that in the spreadsheet the 'sum' value has 2 added to it. This is to remove any 0's or 1's from the figures, which interfere with the look-up table function.

The spreadsheet was therefore established to import a file containing the limitation ratings for an individual crop, extract the relevant 11 land factors and to generate the final soil suitability rating as an integer value (as above) to allocate to the soil maps of Bangladesh in the GIS.

The final stage was therefore to cut the soil association units and the corresponding soil suitability ratings from the spreadsheet for allocation to the soil maps of Bangladesh. The allocation of the values is achieved by creation of an 'attribute values file'. This file format consists of two columns of numbers separated by one or more spaces. The left column specifies the feature codes corresponding to features in the feature definition image in the GIS (in this case the Soil Association maps) and the right column specifies the data values to be assigned to these features (1 to 7, for the soil ratings S1, S2, S3, S4, N, no data and urban area). Having created the attribute values file, the *assign* command was used to undertake the processing to allocate the values to the maps. This process was repeated for each of the mapped areas both before and after the climate change scenario for each crop.

Thus, the soil suitability for each soil unit and each land use type for each of the map sheets of Bangladesh were established. The final soil suitability maps for wheat are presented in the results Appendix A6, Figures A6.6 and A6.7 together with the areal extent of the classes for the remaining crops in Table A6.8.

Having established the soil suitability ratings, the next step was to combine the agro-ecological ratings described in the previous section to complete the land suitability classification.

8.7 Land Suitability Classification

The final stage in the suitability process requires combination of the soil suitability ratings maps and the agro-climatic suitability ratings map, to provide the completed land suitability assessment. The land suitability assessment brings together all the physical constraints and limitations likely to affect crop performance. The assessment takes account of all inventoried attributes of the land (climate, inundation, soil and landform) relevant to the crop being assessed and compares them to the crop's requirements, to provide a measure of the suitability of the land for the production of the crop.

Using the same methodology to that for the soil suitability assessment mapping the combination of the two suitability ratings was achieved by cross classifying the soil suitability maps with the agro-climatic suitability maps, using the *crosstab* facility within the GIS. The resultant map was then reclassified according to the combinations shown in Table 8.10 and the user-defined *reclass* facility. This process was repeated for each individual map sheet and for each crop. The final result was a series of digital maps depicting the suitability of the land according for each individual soil association unit, represented as one of 7 classes, similar to those presented in the agro-climatic suitability section:

1	=	**VS**	very suitable - yield is 80% or more of maximum attainable
2	=	**S**	suitable - yield is 60 to 80% of maximum attainable
3	=	**MS**	moderately suitable - yield is 40 to 60% of maximum attainable
4	=	**ms**	marginally suitable - yield is 20 to 40% of maximum attainable
5	=	**NS**	not suitable - yield is less than 20% of maximum attainable
6	=	**ND**	no data
7	=	**Urban**	urban area unsuitable for agriculture

The final land suitability maps for wheat are presented in Figures A6.9 and A6.10 in Appendix A6, together with the areal extent in km^2 of these 7 classes for the remaining land use types in Table A6.10.

Having established the percentage reduction that may be applied to the maximum attainable yield figure, from the land suitability rating. The maximum attainable yield figures had to be determined, the following section describes this part of the methodology.

Table 8.11 Relationship Between Agro-climatic, Soil and Land Suitability Classification

Source: FAO (1988)

III. Yield Calculations

8.8 Introduction

The following section outlines the methodology used to calculate the constraint free crop yield, for the 18 land use types listed in Table 2.4 and the methodology used to optimise the calorific output of competing staple crops.

The constraint free yield may be defined as:

> *the yield that may be expected from a particular crop, based upon ideal climatic phenological conditions, assuming that no further constraints to production from other yield reducing factors are acting, such as climatic (water stress, temperature), edaphic (low soil fertility, salinity) or biotic (pests, disease, weeds).*

The methodology is based upon the Report on Agro-Ecological Zones Project Vol. I - Methodology and Results for Africa (FAO, 1978a). The constraint free yield was calculated for the individual crops during the appropriate growing periods. This was achieved by considering the generalised photosynthesis responses of different groups of crops to the average climatic factors of: radiation (i.e., average daily radiation), temperature (i.e., average day time temperature) and generalised response of respiration to temperature (i.e., average 24 hour mean temperature). These climatic data were available from FAO (1994).

8.9 Procedure to Calculate the Potential Yield

8.9.1 The Yield Spreadsheet

The FAO AEZ methodology for the calculation of potential yields is provided by Kassam (1977). The necessary calculations have been incorporated for the first time into an Excel spreadsheet, based upon the work of Chidley (1992, pers. comm.) and specifically developed to simplify the process. Briefly, the crop type (represented as a number between 1 and 14, detailed in the spreadsheet) and the site number can be entered into two pre-determined cells within the spreadsheet. Utilising the equations from Kassam (1977) the spreadsheet was designed to automatically calculate the required values for yield etc., detailed below. The spreadsheet was intended to remove the necessity for manual calculations or the use of inflexible yield modelling programs.

The entire methodology is based upon evaluating the climatic variables during the rabi and kharif growing periods. The first step was to determine whether the growing period start and end dates originally determined by the FAO (1988) for each climate station, could be substituted with one of the 12 corresponding growing period (K) zones. For example, a station in zone K2, has a generalised rabi start date of the 15th October and an end date of the 12th February (Table 6.4) Without the K zones, the actual derived start and end dates would have to be allocated to each climate station individually. If the data were unavailable (which is highly likely), the map of the K zones may provide a possible alternative. To determine the reliability of this substitution, the yield calculations were repeated with both the actual site specific start and end dates and also the generalised start and end dates provided by the growing period (K) zones for the wheat crop. Comparison of the two sets of yield results revealed a less than 5% variation on average. This was considered to be a reasonable variation, since for continuity in the future it would be sensible to adopt this methodology. Consequently, for the full yield evaluation the growing period zones were used to determine the length of the growing period instead of the actual dates. Allowing further researchers to undertake similar studies without requiring access to the specific growing period start and end dates, by using the climatic resources inventory map (see Figure 6.3) instead. Thus, further modifications were made to the spreadsheet to accept the agro-climatic zones and to use the generalised start and end dates rather than the individual station growing period dates required originally. By typing the number of the site into the spreadsheet, the *hlookup* function allows the corresponding K zone to be derived together with the appropriate start and end dates. These dates can then be applied later in the spreadsheet to determine the length of the growing period.

To calculate the yield for the 26 climate stations within the spreadsheet, the parameters necessary for the yield estimation where:

- Site Name, Number & Location (degrees N & E)
- Altitude
- Start & End of Growing Period Date
- Moisture & Thermal Zone
- Crop
- Growing Period Type
- Input Level
- Number of Days to Maturity
- Leaf Area Index
- Harvest Index
- Crop Adaptability Group
- Photosynthesis Rate at Average Daytime Temperature (Pm)
- Legume or Non Legume
- Yield Reduction for Actual Leaf Area Index

The spreadsheet was then able to calculate the following, based upon the FAO methodology:

- Length of the Growing Period (N)
- Average radiation over the Growing Period (Rg)
- Average Temperature over the Growing Period (DTemp)
- hr Mean Temperature over the Growing Period (TMean)
- Difference in Actual Pm relative to Pm = 20 (Y)
- Average Amount of Photosynthetically Active Radiation over the Growing Period (Ac)
- Fraction of the Day Overcast (F)
- Average Rate of Gross Biomass Production for Perfectly Clear Days at Pm = 20, Over the Growing Period (bc)
- Average Rate of Gross Biomass Production for Perfectly Overcast Days at Pm = 20, Over the Growing Period (bo)
- Rate of Gross Biomass Production (bgm) at LAI = 5 & Actual Pm
- Maintenance Respiration at TMean
- Net Biomass (Bn)
- Unconstrained Yield

The following section details how the spreadsheet calculated these values.

For the yield evaluation, the prevailing climatic data from CROPWAT (FAO, 1993) for *daily* temperatures, solar radiation etc., were required for the growing periods only, not the average monthly figures provided. The spreadsheet was therefore used to facilitate interpolation of these average monthly climate figures over the growing periods. This was achieved by allocating the monthly temperature, radiation and biomass production figures across the 365 days of the year to determine daily figures. Those days that only belonged to the growing period were then summed. The calculations in the spreadsheet may be better described by reference to an excerpt from the yield spreadsheet shown in Figure 8.2 and the accompanying description of the contents of the key columns and cells:

Column:

A Actual day of the year.

B Day of the year represented as a number from 1 to 365.

C Average rate of gross biomass production on perfectly overcast days (bo) for that day (in B above). Based upon interpolation of monthly FAO gross biomass production data provided in the table in the spreadsheet.

D Average rate of gross biomass production on perfectly clear days (bc) for that day (in B above). Based upon interpolation of monthly FAO gross biomass production data provided in the table in the spreadsheet.

E Average amount of photosynthetically active radiation on that day (Ac). Based upon interpolation of monthly FAO photosynthetically active radiation data provided in the table in the spreadsheet.

F Average radiation (Rg) on that day. Based upon interpolation of monthly FAO radiation data provided in the table in the spreadsheet.

G If the day falls within the growing period a '1' is entered into this column, using the expression:

Figure 8.2 Excerpt from the Yield Spreadsheet

Cell Address	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
178																	
179									Incoming	Radiation				Mean		Mean	
180			Interpolation Over Growing				1 displayed							Day		24 Hour	
181				Period			if in	*172.12*	*337.90*	*253.93*	*408.92*			Temp:	**23.75**	Temp:	**21.64**
182	Station						growing										
183	No.	1	**bo**	**bc**	**Ac**	**Rg**	period	**bo**	**bc**	**Ac**	**Rg**						
184																	
185	Jan 1	1	158.99	316.47	229.52	393.31	1	158.99	316.47	229.52	393.31	1	Jan 1	21.49	21.49	19.19	19.19
186	2	2	159.20	316.78	229.89	393.92	1	159.20	316.78	229.89	393.92	2	2	21.47	21.47	19.16	19.16
187	3	3	159.40	317.10	230.25	394.53	1	159.40	317.10	230.25	394.53	3	3	21.45	21.45	19.14	19.14
188	4	4	159.60	317.41	230.61	395.15	1	159.60	317.41	230.61	395.15	4	4	21.43	21.43	19.11	19.11
189	5	5	159.80	317.72	230.97	395.76	1	159.80	317.72	230.97	395.76	5	5	21.41	21.41	19.08	19.08
190	6	6	160.00	318.04	231.34	396.37	1	160.00	318.04	231.34	396.37	6	6	21.39	21.39	19.06	19.06
191	7	7	160.20	318.35	231.70	396.98	1	160.20	318.35	231.70	396.98	7	7	21.37	21.37	19.03	19.03
192	8	8	160.40	318.66	232.06	397.60	1	160.40	318.66	232.06	397.60	8	8	21.35	21.35	19.01	19.01
193	9	9	160.60	318.98	232.43	398.21	1	160.60	318.98	232.43	398.21	9	9	21.34	21.34	18.98	18.98
194	10	10	160.81	319.29	232.79	398.82	1	160.81	319.29	232.79	398.82	10	10	21.32	21.32	18.95	18.95
195	11	11	161.01	319.61	233.15	399.44	1	161.01	319.61	233.15	399.44	11	11	21.30	21.30	18.93	18.93
196	12	12	161.21	319.92	233.51	400.05	1	161.21	319.92	233.51	400.05	12	12	21.28	21.28	18.90	18.90
197	13	13	161.41	320.23	233.88	400.66	1	161.41	320.23	233.88	400.66	13	13	21.26	21.26	18.88	18.88
198	14	14	161.61	320.55	234.24	401.27	1	161.61	320.55	234.24	401.27	14	14	21.24	21.24	18.85	18.85

= IF (B183 <= E550, 1, IF (B183 >= E551, 1, 0)) when,

B183 = the station number
E550 = the day number representing the end of the growing period (see below)
E551 = the day number representing the start of the growing period (see below)

To determine the day numbers used to represent the start and end of the growing period, the following routine was included for the end day number:

= HLOOKUP (D550, DAYS, 2) + C550 when,

D550 = the number of the end of the growing period
month = e.g. March is 3
C550 = the day of the end of growing period date.
DAYS = the range:

1	2	3	4	5	6	7	8	9	10	11	12
0	31	59	90	120	151	181	212	243	273	304	334

... and to determine the day number to represent the start of the growing period:

= HLOOKUP (D551, DAYS, 2) + C551 when,

D551 = the number of the start of growing period month e.g. March is 3
C551 = the day of the start of growing period date.
DAYS = the range above.

Based upon the growing period start date 15th October (15th of the 10th) and end date 12th February (12th of the 2nd) the range above can be used as a horizontal lookup table to derive the actual start and end days of the growing periods. The 10th month is the 273rd day plus 15 gives an end day number 288 and the 2nd month is day 31 plus 12 gives a start day number of 43.

These day numbers can then be used to determine whether the day in question falls within the growing period and is therefore flagged with a '1' in column G (see above).
Therefore in Column:

H If the day falls within the growing period, the bo value is multiplied by the 1 in column G.

I If the day falls within the growing period, the bc value is multiplied by the 1 in column G.

J If the day falls within the growing period, the Ac value is multiplied by the 1 in column G.

K If the day falls within the growing period, the Ac value is multiplied by the 1 in column G.

N Mean daily temperature

O If the day falls within the growing period, the mean daily temperature value is multiplied by the 1 in column G.

P Mean 24 hour temperature.

Q If the day falls within the growing period, the mean 24 hour temperature value is multiplied by the 1 in column G.

The days falling within the growing period from the 365 days of the year can therefore be identified. Having identified the average daily figures for each of these days, a simple summation process allows the variables above to be quantified for the whole growing period. The required figures are presented in cells:

H181 Average rate of gross biomass production on perfectly overcast days (bo) across the growing period. From summation of values in column H.

I181 Average rate of gross biomass production on perfectly clear days (bc) across the growing period. From summation of values in column I.

J181 Average amount of photosynthetically active radiation across the growing period (Ac). From summation of values in column J.

K181 Average radiation across the growing period (Rg). From summation of values in column K.

O181 The mean daily temperature over the growing period. From summation of values in column O.

Q181 The mean 24 hour temperature over the growing period. From summation of values in column Q.

8.10 Example Calculation of Constraint Free Yield

This section provides an example data set taken from the climate station at Bogra, adopting an example crop of rainfed wheat grown under traditional low input conditions. To demonstrate how the calculations were made, the methodology used to calculate the potential yield utilising the spreadsheet is provided. This methodology was applied to each of the land use types listed in Table 2.4. The results are presented in Tables A6.1 and A6.2.

8.10.1 Introduction

A worked example of the methodology introduced in section 8.9 is provided. It demonstrates the procedure to calculate the constraint free yield for one of the 18 land use types (wheat) at each of the 26 climate stations.

The following data were necessary for the yield calculations, the spreadsheet was finally refined to accept just two items of information, firstly the Site Number (see Figure 7.2) and secondly the crop identification number (Table 2.2). The spreadsheet then generated the figures shown below, the derivation of which are further detailed later in the section. The main sources of the information if not readily available in FAO Report 6 (1988) or described later, are provided in parentheses after the figures.

i Climate Information

Climate Station:	**BOGRA (3)** (Table 7.1)
Location:	**24.51° N** **89.22° E**
Altitude:	**20m**
Moisture Zone:	K5P4
Thermal Zone:	T4e2
Date of Emergence:	**1 December** (FAO, 1994)
Date of Physiological Maturity:	15 March (FAO, 1994)

Rg - Average Radiation over the Growing Period: (cal/cm^2/day)	396.8	
DTemp - Average Daytime Temperature over the Growing Period:	23.4 °C	
TMean - Average 24 hr Mean Temperature over the Growing Period:	21.2 °C	

ii Crop Information (wheat)

Crop Number:	3	(Table 2.2)
Days to Maturity:	105 days	
Leaf Area Index (LAI) at time of maximum growth rate:	4.5	
Harvest Index:	0.45	
Crop Adaptability Group:	I	
Growing Period start date:	15 October	
Growing Period end date:	22 February	

8.11 Estimating the Unconstrained Yield of Crops

The first step towards evaluating the crop yield potential was to calculate the net biomass production (total plant dry matter) under prevailing climatic conditions and to reduce this figure to the yield producing fraction (the economically useful portion). Thus, the net biomass had to be evaluated.

8.11.1 Gross & Net Biomass Production

Solar radiation provides the energy for biomass production, although only a fraction of this radiation is used for photosynthesis. Of this fraction, a portion is used for maintenance respiration (R) to maintain the plant's functions, the remainder is converted into plant biomass. Therefore:

net biomass production (Bn) = gross biomass production (Bg) plant maintenance (R) - eqn 8.1

The equation relating the 'rate' of net biomass production (bn) to the 'rate' of gross biomass production (bg) and respiration 'rate' (r) is:

bn = bg x r - eqn 8.2

The FAO model assumes that the study crop follows the predetermined stages of planting, growth, maturation, yield formation and harvesting. Growth rates are initially slow, accelerate to a maximum, and reduce to zero as harvesting approaches (see Figure 8.3). It is assumed that the period allowed for these phases permits full phenological stages of growth, i.e., sufficient time and correct temperature conditions, day length and energy are provided.

The maximum rate of net biomass production (bnm) is reached when the crop fully covers the ground surface. The cumulative crop growth curve for a typical crop is shown in Figure 8.4 below, bnm is the point of inflection on the growth curve. It has been estimated that over a growing period of N days, the total net biomass production (Bn) is 0.5 times the maximum net rate of crop growth (bnm) for a crop with a growth cycle of the type shown above:

Bn = 0.5 bnm x N - eqn 8.3

Therefore, if bnm can be calculated, Bn can be computed from equation 8.3 using the appropriate value of N (growing period length). To calculate the maximum net rate of crop growth (bnm) we need to know the maximum rate of 'gross' biomass production (bgm) and the respiration rate at that time (r).

Figure 8.3 **The Normal Shape of the Curve of Crop Growth Rate Plotted Against Time**

Time (t)

Source: FAO (1978a)

Figure 8.4 **Typical Cumulative Crop Growth Curve Showing the Point of Inflection During the Period of Maximum Growth When the Slope dB/dt is Equivalent to the Maximum Rate of Net Biomass Production (bnm)**

Source: FAO (1978a)

8.11.2 Estimating Maximum Net Growth Rate (bgm)

The procedure for calculating the net growth rate is based upon estimating two separate growth rates, **bo** and **bc**, the former being the maximum growth rate on overcast days, the latter, the maximum growth rate on clear days. The values of bo and bc are dependent upon **Pm**, the maximum net rate of CO_2 exchange (photosynthesis rate) of the leaves (kg/ha/hr) determined according to the crop group. Table 8.12 provides the relationship between Pm and photosynthesis rate, Table 8.13 provides the variation of bo, bc and incoming solar radiation (Ac) with latitude :

Table 8.12 Relationship Between Maximum Leaf Photosynthesis Rate Pm (kg CH_20/ha/hr) and Temperature

	Mean Daytime Temperature (° C)				
Crop Group[1]	**10**	**15**	**20**	**25**	**30**
I	15	20	20	15	5
II	0	15	32.5	35	35
III	0	5	45	65	65
IV	5	45	65	65	65

1 see Table 8.1

These tables were input into the spreadsheet, so that the relevant data could be accessed when required. Having established the variation of the climatic variables with latitude, the methodology required the values of bo, bc and Ac for the duration of the growing period only, instead of the monthly figures from the tables. To achieve this the spreadsheet contained a routine using the figures above. Based upon the monthly figures of Table 8.12, the spreadsheet averaged the values for bo, bc and Ac for each of the 365 days in the year, and summed the days that fell into the growing period identified by the growing period (K) zone.

Table 8.13 **The Variation of bo, bc and Incoming Solar Radiation (Ac) with Latitude**

Table 8.13a **Variation of Gross Dry Matter Production Rate (kg/ha/day) on Overcast Days (bo) with Latitude, For Crops With Pm = 20 &**

Table 8.13b **Variation of Gross Dry Matter Production Rate (kg/ha/day) on Clear Days (bc) with Latitude, For Crops With Pm = 20 & LAI = 5**

Table 8.13c **Variation of Maximum Photosynthetically Active Shortwave Radiation (Ac) ($cal/cm^2/day$) with Latitude**

Source: FAO (1978a)

Thus the following figures and the figures for bo and bc in the section below, were determined.

Pm Photosynthesis Rate at 23.4 °C: **16.6** kg/ha/hr

Ac Average maximum amount of photo synthetically active radiation on <u>Clear Days,</u> over the growing period: **242.4** cal/cm^2/day

8.11.2.1 Determination of Maximum Rate of Gross Biomass Production (bgm_{20})

The next stage required deriving a value representing the fraction of the day with an overcast sky:

$$F = (Ac \;\; 0.5\, Rg)/0.8\, Ac \qquad \text{- eqn 8.4}$$

F Fraction of the daytime when the sky is overcast, the value of F can be estimated by assuming that the photosynthetically active radiation is 50% of actual short-wave radiation arriving at the earth's surface (Rg) according to FAO (1978a).

Ac Average maximum photosynthetically active incoming short-wave radiation (cal/cm/day) on clear days, over the growing period

Rg Average short-wave radiation over the growing period (cal/cm/day) from the monthly climate data

Example calculation using equation 8.4:

$F = (242.4 \;\; 0.5 \times 396.8)/0.8 \times 242.4$

$F = 0.23$

The values of **bo** and **bc** are given for a standard crop for Pm = 20 kg/ha/hr and a Leaf Area Index (LAI) of 5. However, the maximum rate of CO_2 exchange (Pm) is dependent upon both temperature and photosynthetic pathway of the species (Table 8.1).

A increase in Pm of 'Y' percent relative to Pm = 20 kg/ha/hr corresponds to a (Y x 0.2) and (Y x 0.5) percent increase in bo and bc respectively. Whilst, a decrease of 'Y' percent in Pm relative to Pm = 20 kg/ha/hr would give a (Y x 2.5) and (Y x 1) percent decrease in bo and bc. Hence, bgm as calculated by equation B below had to be modified in accordance with the above. Assuming the values of bc and bo:

bc Average rate of gross biomass production of a standard crop for perfectly clear days at Pm = 20 kg/ha/hr over the growing period: **327.8** kg/ha/day

bo Average rate of gross biomass production for a standard crop for totally overcast days at Pm = 20 kg/ha/hr, over the growing period: **165.8** kg/ha/day

bgm_{20} Maximum rate of gross biomass production at Pm = 20 kg/ha/hr at LAI of 5:

The FAO crop model estimates the value of bgm_{20} as:

$$\mathbf{bgm_{20} = F \times bo + (1 - F)\, bc} \quad \text{- eqn 8.5}$$

Example calculation using equation 8.5:

$$bgm_{20} = 0.23 \times 165.8 + (1 - 0.23) \times 327.8$$
$$= 291 \text{ kg/ha/day}$$

Since actual Pm = 16.9 kg/ha/hr, this represents a 17.05% (Y) difference from Pm = 20 kg/ha/hr.

To calculate **$bgm_{16.6}$** the maximum rate of gross biomass production at Pm = 16.9 kg/ha/hr at LAI 5 bgm_{20}, has to be modified as indicated above.

When Pm is <u>GREATER</u> than 20 kg/ha/hr, bgm is <u>increased</u> by:

Y/500 x F x bo + Y/200 x (1 - F) x bc - eqn 8.6

When Pm is <u>LESS</u> than 20 kg/ha/hr, bgm is <u>decreased</u> by:

Y/200 x F x bo + Y/100 x (1 - F) x bc - eqn 8.7

Where 'Y' is the percentage difference between Pm = 20 kg/ha/hr and the actual value of Pm.

Since photosynthesis rate (Pm) is less than 20 kg/ha/hr, use equation 8.7:

= *17.05/200* x *0.23* x *165.8* + *17.05/100* x *(1 - 0.23) x 327.8*
= ***46.3*** kg/ha/hr

Taking 46.3 kg/ha/hr from bgm_{20} = 291 kg/ha/hr, leaves the rate of gross biomass production at LAI = 5 and Pm = 16.6 ($bgm_{16.6}$) as:

245 kg/ha/hr

8.11.2.2 Calculation of Total Net Biomass Production (Bn) and Yield (Yp)

At a given Pm value the magnitude of bgm is determined by the leaf area index (LAI). The effect of leaf area index on bgm is small when LAI is greater than 5, but for LAI less than 5, the maximum growth rates must be reduced according to the figures below:

Table 8.14 Ratio of Maximum Growth Rate at Leaf Area Index Less than 5

LAI	**0**	**1**	**2**	**3**	**4**	**5**
Factor (L)	0	0.3	0.58	0.75	0.91	1

Source: FAO (1978a)

(Bn) Net Biomass:

$$\mathbf{Bn = (0.36\ bgm_{16.6} \times L)/(1/N + 0.25\ Ct)} \quad \text{- eqn 8.8}$$

L Maximum growth ratio factor, equal to the ratio of $bgm_{16.6}$ at actual LAI to bgm_{20} at LAI 5. Since the LAI is actually 4.5 (see Table 8.2), $bgm_{16.6}$ must be reduced in line with Table 8.12 above:

The LAI is 4.5, therefore **L** is 0.95

N Length of crop growth cycle

Ct Maintenance respiration coefficient, dependent on both crop and temperature, given by the relation:

$$\mathbf{Ct = C_{30}\ (0.0044 + 0.0019\ T + 0.0010\ T^2)} \quad \text{- eqn 8.9}$$

T Average 24 hr Mean Temperature (TMean)

C_{30} At 30 °C, C = 0.0283 for a legume crop and 0.0108 for a non legume crop

Example calculation using equation 8.9:

Ct $= 0.0108(0.0044 + 0.0019\ (21.2) + 0.0010\ (21.2^2))$
$= 0.0053$

Ct Maintenance respiration coefficient at 21.2 °C: **0.0051**

Therefore, from equation 8.8:

$$Bn = (0.36 \times 245 \times 0.95)/(1/105 + 0.25(0.0053))$$
$$= 83.79 / 0.00952$$
$$= 8798 \text{ kg/ha}$$
$$= 8.8 \text{ t/ha}$$

(Yp) Potential yield is calculated from the net biomass, from the equation:

Yp = Hi x Bn - eqn 8.10

Yp Potential Yield

Hi Harvest Index (proportion of the crop that is economically useful - see Table 8.2)

Example calculation using equation 8.10:

$$Yp = 0.45 \times 8.8$$
$$= 3.96 \text{ t/ha}$$

Thus, the potential yield from the site at Bogra is **3.96 tonnes of wheat per hectare.**

The above methodology quantifies crop yield under 'ideal' conditions, essentially free from constraints (agro-climatic or soil) throughout the growing period. Having established this figure the reduction in yield as a consequence of agroclimatic constraints can be applied from Section 8.2 and the final stage in the land suitability assessment can be performed to provide the final productivity potential figure for each land use type.

This procedure was repeated for each of the crops, under the current climatic conditions and the IPCC estimated (Houghton *et al*, 1990) climatic conditions. The productivity potential figures for each land use type were then determined. The actual unconstrained yield figures are presented in Table A6.1 for before the climate change scenario and Table A6.2 for after. The difference in the productivity potential figures then provided the final quantification of the impact of climate change on crop productivity in Bangladesh (see

Table A6.3). The results were then incorporated into the GIS using the *reclass* command as described previously.

8.12 Application of the Productivity Figures to the GIS

Having established the potential yield as point data for each of the 26 climate stations, the GIS was employed to interpolate these figures onto a surface across Bangladesh. Having allocated the yield figures to the stations within the GIS, the *interpol* command was used to achieve this. The command uses a distance decay function based upon $1/d^2$. The *interpol* command required an exceptionally long time to run, this process took several days to complete.

At this stage the GIS contained digital maps representing the land suitability for each land use type and the maps presenting the maximum attainable yield figures. The former of these maps correspond to the percentage reduction that may be expected from the maximum attainable yield figures. The remaining step therefore was to combine these two sets of maps to provide a quantification of the yields that may be expected, under each climate scenario and for each land use type.

8.13 Application of the Land Suitability Reduction Factors to the Potential Yield Figures in the GIS

Having established the yield at a particular site in tonnes/hectare, all that remained was to determine the yield for the individual cells. A cell resolution of 200m x 200m corresponds to four hectares, thus the *scalar* command was used to multiply the yields in tonnes/hectare by four to get tonnes per cell.

The final stage was to take the land suitability maps (Figures A6.6 and A6.7 for Wheat) providing the suitability classes as five values, from very suitable (S1) to unsuitable (NS), representing the percentage reduction to be applied to the maximum attainable yield figures/cell defined above, i.e.,

VS *very suitable*, crop yield is 80% or more of the maximum attainable.
S *suitable*, yield is 60 to 80% of the maximum attainable
MS *moderately suitable*, yields of 40 to less than 60%
ms *marginally suitable*, yield of 20 to less than 40%
NS *not suitable*, yields of less than 20%

To multiply the suitability classes by the yield figures, the ranges suggested by these percentage figures had to be converted into a single figure. It was decided to adopt the lowest percentage limit as illustrated below, in order to provide a conservative estimate for yield (although the more optimistic view could quite easily have been chosen). Thus for example, **MS** corresponded to 40% of the maximum attainable yield or multiplying the yield by 0.4. Each of the suitability classes was then reclassified to correspond to the appropriate multiplier, thus:

VS = 0.8
S = 0.6
MS = 0.4
ms = 0.2
NS = 0

Finally, to derive the final attainable yield (with constraints) within each cell, the cell yield figure was multiplied by the corresponding suitability cell, by overlaying the two maps within the GIS. This was achieved using the *overlay* command and the *multiply* option. This process produced a new map presenting the new attainable yield figures for each cell after the imposition of the constraints. This process was repeated for all land use types and both scenarios, which took several days to complete. Utilising the routine detailed in Appendix A5 the total yield for each of the study regions was then determined by the summation of the yield in every cell of the map and then repeated for every crop. These yield results are presented in Table A6.12, providing the final figures to illustrate the impact that the climate change scenarios have on crop productivity.

8.14 Nutritional Values & Calorific Optimisation

In an attempt to illustrate the utility of the GIS for the crop optimisation process and to determine the maximum calorific output that could be attained if, from all alternative crops the most suitable crops were grown in each cell of the GIS. The following section details the methodology used to make this comparison, enabling quantification of the maximum number of people that could be sustained at present and potentially sustained in the future. The results from this section will give an indication whether Bangladesh 'theoretically' had the capacity to feed its population in 1988 and whether it will have the 'theoretical' capacity to support its future population. For the comparison, the major staple food crops wheat, potato and the three varieties of rice were chosen, since together they constitute approximately 85% of the cultivated staple crops fundamental to feed the population in Bangladesh (Hossain, 1991). Jute, mustard, lentil, spices etc. provide the remainder, which are non-staple crop varieties.

Having identified the yield per cell for each crop, as detailed in section 8.13 above, it was then possible to determine the number of calories provided by a particular crop based upon the figures shown in Table 8.14.

Table 8.14 **Nutritional Value per kg of Edible Portion**

Source: Data Composition of Foods, USDA Handbook No. 8 (1975) USDA Washington DC.

The number of calories per tonne of crop was determined by multiplying the values in kilograms in Table 8.14 by 1,000. These calorie figures could then be multiplied by the yield produced per cell using the *scalar* function in the GIS. The final maps produced represented the total number of calories available in each (200m x 200m) cell for each crop. This process was undertaken on the four individual map sheets for each crop, prior to the final stage the four map sheets had to be *concatenated* into the complete maps of Bangladesh.

The next step was to compare the number of calories in each cell with the corresponding cells for the alternative crops grown during that particular growing period. This would allow the identification of the most calorifically productive crop from those being compared. For the purpose of this final map comparison, the maps representing the number of calories per cell for the appropriate crops were imported from IDRISI into the GRASS GIS (originally unavailable at the start of the project). This was achieved using the IDRISI *grassidris* conversion command. GRASS was chosen for this stage of the project since it has a powerful map calculation facility ideally suited to this type of comparison, which was not readily available in IDRISI. Optimisation was only undertaken between crops grown during the same growing period, thus for example the calories in each cell were compared for HYV wheat (01) and potato (02), for the rabi season.

Using the *r.mapcalc* command in GRASS the crop with the maximum number of calories from each pair of cells was identified using the following command:

r.mapcalc best.cals = 'if (01cals > 02cals, 1, if (01cals = = 02cals, if (01cals = = 0, 0, 3), 2))'

when 'best.cals' is the name of the new image produced, 1 in the output image represents wheat, 2 potato and 3 either wheat or potato.

For the kharif season, the five rice alternatives of aus and aman were compared in a similar manner, using one pair of crops at a time.

This maximisation process was repeated before and after the climate change scenario and the most calorifically significant crops were determined in each comparable cell. An image was generated within the GIS that identified the optimum crops available per cell. An example of an optimised map comparing the crops of wheat and potato and indicating which is calorifically more productive in each cell, is presented in Figure A6.8.

The next step then was to quantify the optimum number of calories available when the crops were optimised. Again using *r.mapcalc* in GRASS, the maximised number of calories between wheat and potato can be determined using the following command, when the wheat calorie map is named '01cals', the potato calorie map is named '02cals' and the new maximised map is named 'rabi.max':

```
r.mapcalc rabi.max = 'max ( 01cals, 02cals )'
```

The five rice alternatives were maximised using the command:

```
r.mapcalc rice.max = 'max ( 08cals, 09cals, 10cals, 13cals, 14cals )'
```

when the five rice alternatives are identified by the numbers 08, 09, 10, 13 and 14 and the new maximised map is named 'rice.max'.

A small routine was then used to calculate the product of the calories contained in each individual cell for the whole study region, this provided the total number of calories 'theoretically' available to feed the population for that year. This routine for the optimised rice comparison above ('rice.max') was:

```
r.stats -c input = rice.max | gawk ' {print$1, $2, prod = $1 * $2, sum + =
        prod } end { print "\n total = ", sum }'
```

The total number of calories provided by each crop across the study area are provided in Table A6.14.

Finally, the effect of combining the optimum crop between HYV and local t. aus and the HYV t. aman output was determined, in order to see how much additional output could be generated by adopting a three crop system. This comparison routine was undertaken both before and after the climate change scenario, using the *r.mapcalc* command and adding the cell contents of the two appropriate maps.

Assuming that an average man requires 2273 calories per day to survive (INFS, 1983) 365 days per year, the total annual requirement is 829,625 calories. Division of the total number of calories available across the country by this yearly requirement provided the theoretical maximum supporting capacity. The results from this evaluation are presented and discussed in Chapter 9.

Chapter 9

Discussion of Results

9.1 Introduction

The following section discusses the results presented in Appendix A6. The full set of maps from the GIS for wheat are also included in the Appendix to provide an example of the digitally mapped output. For the remaining crops, the areas dedicated to each category are presented in tabular form only. The reader is referred back to Figure 7.1 illustrating the areas covered by the 4 study regions described in the tables, and Section 8.7 for an explanation of the various suitability classes used, if required.

The results are discussed according to the following headings:

- Unconstrained Yield
- Thermal Suitability
- Growing Period Suitability
- Agro-Climatic Suitability
- Soil Suitability
- Final Land Evaluation Classification
- Final Crop Yield Output

9.2 Unconstrained Yield

The results from the application of the crop model described in Chapter 8III are presented in Tables A6.1 and A6.2 and summarised in Table A6.4. In addition, the figures in Table 2.8, which provide examples of predicted crop yields for Bangladesh, are compared to the unconstrained yield figures.

The model reflects the impacts of climatic factors only and excludes the influence of soils at this stage. Clearly, the results are site specific, although trends may be identified. Essentially, those kharif crops subjected to the increased temperature and decreased solar radiation scenario (aus rice and jute), experience a decrease in yield of approximately 5%, this may be attributed to a reduced rate of biomass production, in response to decreased incoming solar radiation. No direct impact is produced from the increased temperature on photosynthesis rates, since the new higher temperature remained within the optimum temperature range for maximum photosynthesis of 25-30°C for group II crops (see Table 8.1).

The rabi crops were exposed to increased temperatures <u>and</u> increased solar radiation. The aman and boro rice varieties displayed a slight increase in output, of just over 2%, which contrasted to the remaining winter crops (wheat, potato, mustard and lentil) which showed a decrease in output in excess of 10%. The increase in the boro rice crop provides an indication that perhaps climate change may have slight positive impacts for this crop, if other limiting factors were reduced (see below). The rice varieties experienced a smaller increase in productivity, since the temperature rise induced a relatively small increase in photosynthesis rate. As rice is a group II crop (see Table 8.1), with an optimum temperature for photosynthesis of 25-30°C and temperatures generally remained within the optimum range for both scenarios, there was little impact on photosynthesis rate. Thus, any yield increase may be associated solely with the increased solar radiation's impact on biomass production.

The more significant yield reduction for the remaining rabi winter crops may be ascribed to the fact that they belong to group I (see Table 8.1). They have a lower optimum temperature for maximum photosynthesis, ranging between 15 and 20°C and therefore the increased temperature generally meant that the site temperatures were above this optimum resulting in reduced photosynthesis rates. Even the increased biomass production rates in response to the increased solar radiation were unable to counter the effects of the increased temperatures.

The yield figures also reveal the magnitude of productivity potential resulting from adopting the HYV cultivars. All HYV crops on average, experience at least a doubling in output, with HYV transplanted aus rice displaying more than three times the output of the local variety. This is clearly of significance to future agricultural production potential.

Having established the changes to the yield figures induced by the climate scenarios, some comparison of the baseline figures in relation to other published data can be made. Column (d) in Table 2.8 provides results from the actual FAO Resource Appraisal of Bangladesh (1988), to allow direct comparison with the results from the spreadsheet methodology. The spreadsheet uses AEZ thermal zones as opposed to the FAO derived start and end dates for defining the growing period, described in Section 6.5. There is in fact a close relationship between these two sets of results, which may therefore provide a viable alternative for planning purposes, if detailed growing period data are unavailable.

The yield figures presented in Table 2.8, columns (a)-(c), bear considerable resemblance to those derived at this stage of the study. HYV wheat, for example, is predicted to yield 3-3.5 t/ha and is modelled in the study at 3.37 t/ha on average; wheat under low input conditions is predicted to yield between 1.3-1.7 t/ha and is modelled at 1.71 t/ha on average; mustard (no variety stipulated) predicted to yield 0.93 t/ha results in a low input yield of 0.58 t/ha and a high input yield of 1.25 t/ha. Potato presents the one significant exception, it is predicted to yield quite significantly larger yields in comparison to the other crops suggested (10 t/ha predicted, 4.32 t/ha modelled).

The yield results for potato are in fact larger than the other crops in the study, but not of the magnitude suggested by the general literature, although they do agree with the results from FAO (1988) in column (d). It is difficult to predict why potato yield should be so different from the proposed average, one possibility rests with the fact that modern potato varieties have high yielding potential and that the harvest index of 0.6 (60% economically useful part) may need to be increased, although a harvest index of 1, would still have only increased yields to about 7.5 t/ha, or perhaps that farming conditions and methods in

Bangladesh are particularly unsuitable to its cultivation. Clearly, this does not provide the full answer and highlights a possible area of the FAO model for investigation, since the actual results do in fact agree with those of the FAO. Reference to Figure A6.8 indicates the potential area that potato would cover if yields were optimised (see Section 8.14), it indicates that despite this high productivity, the wheat crop is more significant.

9.3 Thermal Suitability

The Thermal Suitability assessment described in Section 8.2.2.1 provided the figures presented in Table A6.5. Based solely upon the prevailing thermal regime, the impacts of increased temperatures can be seen. Figures A6.1 and A6.2 provide examples of the maps used with the thermal suitability assessment.

Both before and after the temperature increase, certain crops remained highly suitable (S1), these include: mustard, aus and aman rice and both varieties of jute. The HYV transplanted aman crop cultivated after transplanted aus, showed an increase in the highly suitable category (S1) from just over 80% to almost 99%, after the temperature increase. In a similar manner, the boro rice crops also show an increase in the highly suitable category areas. The HYV boro (early and late maturing) 'highly suitable' class areas increase from 44% to just over 80%. This is significant since future application of irrigation facilities could remove the present limitations to rainfed boro crops imposed by lack of water, thus presenting a significant possibility for increasing production. None of the crops were less than moderately suitable (S3), wheat and potato experienced a decrease in the highly suitable class area, reflected in an increase in the 'suitable' (S2) and 'moderately suitable' (S3) categories. Likewise, almost 40% of the lentil 'highly suitable' class area became 'suitable' (S2).

9.4 Growing Period Suitability

The results from the growing period suitability assessment described in Section 8.2.3 are presented in Table A6.6. The moisture resources remained constant for the purpose of the project and therefore provide just one set of results. The growing period suitability map used in the project can be seen in Figure A6.3.

The limiting factors for the cultivation of rainfed boro are presented by the growing period suitability assessment, all varieties of boro rice are completely unsuitable (as expected), due to the limitations of insufficient water during the growing period. In general, few crops can be classified as highly suitable, only Mustard (14% of the area) tolerant of the dry conditions of the rabi period, belonged to this category. The remaining aus rice crops and the two jute varieties are generally 'suitable' and 'moderately suitable', although approximately 7% of the HYV transplanted aus crop is classified as 'marginally suitable' (S4). From the remaining rabi crops, most fall into the 'suitable' and 'moderately suitable' categories, although both potato and HYV transplanted aman cultivated after transplanted aus have unsuitable areas, potato has less than 4% of the area unsuitable, whilst the latter is over 70% unsuitable, since the combination with aus rice causes the crop to be planted late, therefore increasing its susceptibility to drought.

9.5 Agro-climatic Suitability

Combining both the suitability assessments described in the previous two sections, the agro-climatic suitability was undertaken (Section 8.2.4). The results are presented in Table A6.7 and example agro-climatic suitability maps for the wheat crop, are presented in Figures A6.4 and A6.5.

Due to the unsuitability in relation to the growing period assessment, all three boro rice varieties are classified as agro-climatically unsuitable across the entire country. The crops that retain a high thermal suitability rating (VS) after the applied climate change, provide agro-climatic class areas that also remain unchanged, and therefore reflect the growing period suitability limitations alone (if any). All the kharif crops fall into this category, together with the two rabi aman rice crops. However, the HYV aman crop cultivated after the transplanted aus crop, remains unsuitable across 72% of the country, with a very slight increase in the 'ms' (moderately suitable) class area, transferred from the lower 'marginal' category. This slightly improved suitability may reflect the non photosensitive nature of HYV aman, which makes it generally susceptible to cool weather, if temperatures were to increase therefore, this may be moderated. This HYV aman crop, despite being 'highly suitable' thermally across the majority of the country, is considerably reduced by the coincidence of the lower suitability growing period classes with these areas.

From those crops that do demonstrate a change in thermal suitability (the rabi crops), wheat's 'suitable' category, covering slightly in excess of 15% of the land area, becomes unsuitable, accompanied by a movement of 3% of the 'moderately suitable' category to 'unsuitable'. This reduced suitability may be attributed to the limitations imposed by the growing period, resulting in a general reduction to the next lower suitability class. In a similar manner, potato and lentil, originally highly thermally suitable, are also agro-climatically less suitable, due to the corresponding 'marginal' and 'unsuitable' categories provided by the growing period suitability. Subsequently, with the application of the altered climate parameters, a further decrease in suitability is experienced. Wheat, mustard and lentil remain agro-climatically suitable to some degree or other, whilst potato increases from 10% 'unsuitable' to just above 17%. At this stage of the research, only mustard provided any areas classified as 'highly suitable' (14%).

9.6 Soil Suitability

The soil suitability assessment detailed in Chapter 8II, allows the inclusion of the limitations imposed by the land, upon crop cultivation (excluded until now). As already discussed in Section 3.10.3 it has been assumed for the project that climate change will have little effect upon the soil. The results from the soil suitability assessment for each of the study regions are presented in Table A6.8 according to the area occupied by each suitability category. This table also provides the percentage change of the total regional area that each category represents. In an attempt to provide an indication of how soil suitability is distributed across the whole country and how it changes in response to the modified land factors (see Section 8.4.1) a countrywide summary table has been presented in Table A6.9. The percentages are calculated from the actual areas studied for the soil suitability 12,000 km^2 is actually omitted due to the missing data described in Section 7.4.1. For any countrywide comparisons between these figures and those detailed above therefore, this must be noted. The soil suitability map from the GIS for the wheat crop before and after the climate scenario are provided in Figures A6.9 and A6.10 to illustrate the output format.

In relation to overall change in soil suitability, the magnitude of any changes should be relatively small, since only the flood hazard frequency land factor was altered (Section

3.10.4). This is in fact the case, with most changes in the areal extent of the categories amounting to less than 5%.

Unlike the agro-climatic suitability, the soil suitability provides more crops with some areas of a 'highly suitable' nature, although the three boro varieties and the two jute crops have no highly suitable land. Wheat, mustard, lentil, the three varieties of aus rice and the two main aman crops, each have between 17-24% of the total land area classified as 'highly suitable'. The HYV aman crop grown after the aus crop, has less highly suitable areas, due to the reduced length of the growing season and increased risk of damaging inundation, which is increased when the flood hazard is increased, resulting in a just over 4% decrease in the area of this category. Potato represents the other extreme, just below 5% of the land area is classified as highly suitable for potato cultivation, which remains unaltered after increasing flood hazard frequency. The dry winter season rabi crops (wheat, potato, mustard and lentil) would be expected to demonstrate minimal effects from altered flood hazard frequency, as indeed is the case. Those areas that did demonstrate a slight reduction in soil suitability, were generally low lying and therefore more likely to be impacted from increased flooding frequency.

The rabi crops - wheat, mustard and lentil, have essentially similar growing requirements, thus they have similar soil suitability ratings. All require reasonably well drained, non-saline soil and low to moderate relief, to ensure ease of management and low soil erodeability. Overall, the SE region's soil is the least suitable for each of these three crops (approximately 64% 'unsuitable'), the NW exhibiting the least 'unsuitable' areas (approximately 5%) and the countrywide average around 28%. The irregular topography of the SE is a major contributor to the reduced suitability of this region. Overall, for wheat, potato and lentil, 70% of the soil area may be classified as one form of suitable or another. The areas are reasonably equally distributed across the classes S1 to S4, with slight concentrations on classes S2 and S3. Suitability decreases slightly with the increased flood hazard frequency, due to the impacts on the limiting soil factors described above, wheat and lentil's unsuitability classes increased approximately 5%, whilst mustard remained virtually unchanged.

On average the soil suitability of potato is slightly lower than the other rabi crops, this may be attributed to its increased susceptibility to excessive drainage, causing the soil to dry out without artificial irrigation. On average, approximately 40% of the soil is classified as unsuitable for potato, the SE region has the largest areas classed as unsuitable (67%) and the NW region the least 'unsuitable' area (12% unsuitable) with the remainder of the soils classified mainly between S2 and S4. Soil suitability decreased slightly (approximately 2%) with increased flood hazard, again due to its effects on the limiting soil factors described above.

The three varieties of boro rice are essentially unsuitable for cultivation, in all regions the unsuitable category area is in excess of 95%. In general, the crops are limited by poor drainage and sloped topography and in some instances experience problems with salinity. The late maturing variety of HYV boro rice is the least successful of the three, due to its increased susceptibility to flooding. A tiny percentage of the SW region (<2% each) is classified as potentially 'suitable' and 'marginally' suitable. When the flood hazard frequency is increased there is a reduction by one suitability class, also the few areas of suitable land corresponding to the other two boro varieties remain unaltered, as this land has a high enough relief to be unaffected.

The three varieties of aus rice display quite varied results. Each display some unsuitable areas, HYV transplanted aus paddy has an area of almost 50% unsuitable, the remaining area being reasonably evenly distributed amongst the suitability classes. The two local aus rice varieties are slightly more suitable overall, and are again reasonably equally distributed across the remaining categories. The variations in aus rice success, may be attributed to the variations in planting dates and the relative susceptibilities to floodwater and drought. The fixed height aus crops, are generally limited by inundation in excess of 90 cm, although broadcast (floating) aus does not become limiting until inundation is in excess of 180 cm. HYV transplanted aus varieties, require flood protection if planted later than the end of April, otherwise the damage from flooding can be a major problem. The local aus varieties are less troubled by flooding, since they are generally planted early enough to ripen before the floods begin, although, instead, they become susceptible to the impacts of drought. Aus crops generally prefer relatively poorly drained soils to prevent drying out before ripening, which indicates why some of the local variations in soil suitability occur.

Essentially, after considering the climate change scenario, soil suitability is reduced overall. Local broadcast aus is the least affected, HYV transplanted aus the most affected. Flood hazard frequency is clearly more important to kharif crops, although as suggested, those aus crops planted later in the season (HYVs) will experience an increased susceptibility to an increase in flood hazard frequency. On a regional basis, the NW appears the most suited to aus cultivation, transplanted aus may be unsuitable to approximately 20% of the soils in this region, whilst broadcast aus is less than 6%. Whilst the SE region once again is the least suitable, in excess of 70% of the soil is classified as 'unsuitable' for transplanted aus and more than 60%, for broadcast aus. Aus is essentially an upland crop, which is mirrored in the varying degrees of suitability in relation to relief for example, the lowland SE is the least suitable.

9.7 Land Suitability

Having established the agro-climatic suitability classification for each crop and the soil suitability classification, the final stage required the combination of these suitability classes, to provide the final land suitability assessment detailed in Section 8.7. The results for the land suitability are presented in Table A6.10, illustrating the areas of the land suitability classes for each study region, before and after the climate scenario. In addition, the land suitability class areas for the whole country, for each crop are provided in Table A6.11, to indicate the distribution of the land suitability classes across the country. The maps representing the land suitability classes for wheat are presented in Figures A6.6 and A6.7.

i **Boro rice** is considered wholly unsuitable for rainfed cultivation, due to the growing period limitations described above.

ii **Wheat** displays an overall reduction in suitability after the climate change scenario. On a regional scale, the SE is the least suited to wheat cultivation, 85% of the land area is classified as unsuitable, increasing slightly to 87% after the climate change scenario, with the remaining land essentially classified as 'marginal'. The NW region, in contrast, is the most suitable, only 12% of the land is classified as being unsuitable, increasing to about 19% after the scenario. None of the regions are classified as 'highly suitable', although some 15% of the NW region is classified 'S2', this is reduced after the scenario though, as is the S3 class, resulting in an increase in the 'marginal' category of some 26%. The NE region demonstrates the largest increase in the 'unsuitable' category, increasing 15.8%, to cover in excess of 50% of the region's area, after the scenario. Countrywide, 53% of the land is classified as suitable to some degree or other (classes S1-S4), reduced slightly to 44.5% after the scenario, the S2 suitability class experienced a 4% decrease, resulting in a 4% increase to the 'marginal' class and the S3 class fell 8.5%, increasing the unsuitable land area accordingly. Overall, wheat is influenced mainly by changes in the prevailing soil climate.

iii Potato is generally classified as a low suitability crop, no areas are classified as S1, S2 or S3 (less than 1% of the NE region is classed as S3). Overall, less than 20% of the land area has any form of suitability, essentially being S4 (marginal) and little change in the classification is seen after the scenario (approximately a 1% reduction). Potato cultivation appears to be most affected by the low growing period suitability of the country as a whole.

iv Mustard too is most suited to the NW region, although areas of S1 appear in both the SW and NW. The main highly suitable area, covering 16% in the NW region remains unaltered after the scenario. Of the remaining regions the SE is again least suited, 65% of the area is classified as unsuitable, 25% as marginal. Overall, 70% of the land may be classified as some form of suitable, distributed across the range S2-S4. The scenario has no significant effect upon any of the classes and no single factor can be attributed to the final land suitability classification, although 'thermally' the crop remains highly suitable at all times.

v Lentil too is least suited to the SE region, 85% of the land is classified as unsuitable, 12% as being 'marginal', with little impact from the climate scenario. The SW region is slightly better, 53% of the area is classified as 'unsuitable', increasing 10% to over 60%, after the scenario. The NW is most suited, less than 10% of the area is classed as 'unsuitable' rising 9% after the scenario, due to the reduced suitability of previously S2, S3 classified areas. Countrywide, just less than 60% of the area has some degree of suitability (S1-S4) falling 8% after the scenario.

vi **Local transplanted aman rice**, in similar form to those described above, 74% of the SE region is classed as 'unsuitable', 53% of the NE and only 22% of the NW. The remaining classes are relatively equally distributed across the area, although no 'highly suitable' (S1) areas exist. Overall, nearly 60% of the land area has some suitable areas (S2-S4) falling just 2% with the scenario. With the main reclassification occurring between classes S2/S3 and S4. The land suitability classes are essentially influenced by the soil suitability classification.

vii **HYV aman rice** when compared to the local aman rice above, is generally less suitable, just above 45% of the land is classified as being suitable (S1-S4) and on average, the regional distribution although similar (i.e., the NW the most suitable, the SE the least), has larger areas classified as S3, S4 and unsuitable, and a larger increase in those areas classified as unsuitable, after the climate scenario (almost 15%, compared with just 2% above). The total suitable area is reduced from about 45% to 30%, a much greater reduction than that above. Both crops have similar agro-climatic suitability, but the influences of the soil suitability assessment affect the variation in final land suitability, due to differing responses to inundation, flood hazard and the effects of an increased flood hazard frequency.

viii **HYV aman rice after HYV or local transplanted aus rice**, the last of the rabi crops, is the least suitable crop for rainfed cultivation. Countrywide, 90% of the land is classified as 'unsuitable', rising to 96% after the scenario, as those areas formerly classed as 'marginal' become 'unsuitable'. The relatively low growing period suitability and a similar soil suitability, combine to produce this poor land suitability classification.

ix **Broadcast aus rice**, a kharif crop, provides a close second as a crop with almost 70% of the land area considered 'suitable' (S2-S4), which remains virtually unaltered after the scenario, although a minute rearrangement of the S2/S3 classes can be seen. The NW region is most suitable, with less than 6% of the area classified as 'unsuitable', 46% as 'moderately suitable', the remaining area allocated equally between S4 and S2. The climate scenario has virtually no influence on the land suitability of the NW region. In fact, across all regions, the vast majority of changes in the area's of the suitability classes are less than 1%. This is to be expected for all the kharif crops, since the influence of the increased flood hazard frequency should be minimal.

x Local transplanted aus. The class S2 'suitable' occurs most frequently across the regions, the SE region has a small fraction of its area classified as this, although the NW with 16% and the NE with 4%, are the most significant. The 'unsuitable' class has the largest area, 74% of the SE region is classed as this, increasing slightly (2%) after the scenario, the NE region is classified as just over 50% 'unsuitable', with a tiny increase in the S4 category area from those previously classified as S2 and S3. After the scenario, the SE region demonstrates a shift of 20% of the S2-S4 areas into the 'unsuitable' class.

The soil suitability classification, influenced by the growing period classification, generally imposes the overall limitations to the final land suitability classification. Overall, approximately 50% of land can be classified as some level of suitability (S2-S4), decreasing approximately 5% after the scenario, from classes S2/S3 to class S4.

xi HYV transplanted aus is equally unsuitable to the SE region, some 83% of the land area is classified as such, increasing slightly after the scenario. The SW region is classified as 70% 'unsuitable' and the NE 57%, these regions however, show an increase in excess of 10% in the 'unsuitable' category. The NW has just 30% of the area classed 'unsuitable', also increasing 13% after the scenario. Small areas of 'suitable' (S2), occur in the NE, NW and SW, although after the 'unsuitable' areas, most land is classified as S4 'marginal' and S3 'moderately suitable'. When compared to local transplanted aus (above), there is generally less suitability across all areas, only 40% of the land area has some degree of suitability (compared to 55% above), which falls to 30% after the climate change scenario (50% above). The overall 'unsuitable' class areas are also larger, covering 58% of the study area before the scenario and 69% after. As described above, HYV aus is more susceptible to inundation, reducing yields and also increasing the relative impacts of the increased flood hazard frequency under the scenario.

xii Jute (*Capsularis and Olitorius*) has a generally low suitability in comparison to the other study crops, approximately 35% of the study area is classified as some form of suitable, under Jute (*Cap.*), the majority under class S4, the remainder S3. In comparison, just over 30% of the land area may be classed accordingly under Jute (*Olit.*) falling to 26% after the scenario. Jute (*Olit.*) also possesses no 'suitable' (S2) or 'highly suitable' (S1) areas. Regional distribution of jute suitability mirrors the pattern demonstrated in all the previous crops; relatively more suitable in the NW region and least suitable in the SE.

The two varieties are essentially similar in agro-climatic terms, but may be differentiated due to Jute (*Olitorius*) being less resistant to inundation levels and to sites with poor drainage, therefore producing the lower land suitability, when compared to the *Capsularis* variety.

9.8 Crop Yield Output

Having established the land suitability classes, (S1, S2 etc.), the unconstrained yield figures presented in Table A6.2 were reduced in accordance with the suitability rating (see Section 8.13). The final regional yield output for each crop is presented in Table A6.12, together with a summary of the average countrywide percentage change in yield, due to the climate scenario in Table A6.13. These figures present a possible indication of the significance of a 1.5°C, an increase or decrease in incoming solar radiation and an increase in flood hazard frequency.

From the summary statistics, it is clear that overall, the climate scenario has a deleterious effect upon all the study crop yields. HYV transplanted aman rice planted after the aus crop, illustrates the most severe percentage reduction in yield, some 65%, from just over 1mt to 0.3 mt. This crop is already risky; prone to pollen sterility if planted later than the second half of August and a shorter growing period. Modelling suggests therefore, that this crop would suffer most with climate change. Wheat, HYV transplanted aus rice and lentil, each provide a yield reduction in excess of 30%. In output terms HYV wheat provides the greatest yield output, 6.8 mt before the scenario, 4.1mt after, the low input varieties yielding approximately half these figures. Local broadcast aus rice and mustard, provide the least reduction, with -6% and -10% respectively, with the remaining crops falling between 15-30%.

9.8.1 Crop Calorific Optimisation

Having determined the yield available per 200 x 200 km cell for each of the crops before and after the climate scenario for the study regions, the optimisation process discussed in Section 8.14 was undertaken. It attempted to provide some indication of the 'theoretical' maximum number of people that could be sustained if crop cultivation was optimised in each cell according to calorific productivity alone. The number of calories theoretically available from each crop is provided in Table A6.14 - wheat for example, is calculated to have the potential to provide 56 billion[1] calories for the baseline scenario, falling to 49 billion calories after. The remaining results presented in the Table suggest that the land provides a significant food resource both before and after the climate change scenario, easily able to support the current population and the population well in excess of the 200 million plus estimated for the future (Section 2.3.1).

If each of the crops is considered in isolation (Table A6.14), local broadcast aus is the most 'calorifically' productive both before and after the climate change scenario, providing 972 billion[1] calories across the country before the scenario and 753 billion calories after, representing a reduction of 219 billion calories. Local transplanted aus provides 548 billion calories before the scenario and potentially provides 435 billion calories, a reduction of some 113 billion calories. Whilst HYV transplanted aus provided 333 billion calories, falling 155 billion calories to 178 billion after the scenario. In general, a significant reduction in the number of calories potentially available from each crop is experienced after the scenario. HYV potato, the least productive of the staple crops however, demonstrates an increase of some 46 billion calories from 153 to 199 billion before and after the scenario respectively, the low overall productivity for potato may be influenced by the rainfed conditions, since potato is more suited to irrigation. In a similar manner, HYV transplanted aman experiences an increase of some 3 billion calories from 167 to 170.

When the crop optimisation routine was applied (i.e. by comparison of corresponding cells for the alternative crops grown in a particular growing period, and choosing the most calorifically productive from the alternatives) for the rabi and kharif seasons, the results in Table A6.15 were produced. Optimising the number of calories per cell for wheat and potato before the scenario could theoretically sustain some 73 million people, whilst after the scenario 66 million people could be supported (see Figure A6.8), a fall of 7 million people, yet still sufficient to accommodate estimated future populations when considered in association with the rice crops. Whilst, optimisation of the 5 rice varieties in the kharif season could support a staggering 1346 million people, falling 255 million to 1091, well in excess of the projected future requirements. Whilst the simple three crop rotation, optimising upon local or HYV transplanted aus combined with the HYV aman crop could

[1] The UK billion = 10^{12}

sustain an additional 806 million people before the scenario and some 549 million people after.

In conclusion, combining the rabi and kharif figures would theoretically allow some 1419 million people to be supported before the climate change scenario each year and 1157 million people to be supported after the scenario each year, an overall reduction of 262 million people no longer sustainable each year, but still well in excess of the projected population figures.

It must be remembered however, that the figures are provided as theoretical maxima only, the optimisation routine is clearly artificial, since the sub-optimal farming techniques practised in Bangladesh are far from ideal, as previously mentioned in Section 2.7, Bangladesh farmers are unable to optimise solely upon calorific output, due to the pressures of low crop reliability and climatic catastrophes, whilst the logistics of housing such a massive population on the land surface alone would be totally impractical. Despite the cropping patterns being far more complex than those replicated in the optimisation routine, the potential utility of the GIS for this type of optimisation for land use planning is clearly apparent. The figures do however, provide a benchmark against which the potential for agricultural production can be compared and which indicates that there is tremendous scope for future productivity improvement, if some of the limiting factors to production, such as those influencing cropping reliability could be reduced. Without this scope Bangladesh would have little hope for the future.

9.9 Summary

In relation to unconstrained yield data, the kharif crops indicate a slight decrease in yield, the rabi rice varieties showed a slight increase in output, whilst the remaining rabi crops demonstrated a more significant decrease, of the order of approximately 10%. The influence of temperature is particularly important to group I crops, when increased, temperature exceeds the optimum range for maximum photosynthesis and reduced yields result. Increasing incoming solar radiation has minimal effects in ameliorating this effect. In contrast, Group II crops remain within the optimum temperature range, with little impact on increasing yields, in response to the reduction in net biomass induced by decreased solar radiation. Generally, the predicted yields compare well to those published in the literature, with the exception perhaps of potato.

It must be noted however, that when the margins of error of the input parameters are considered, it would appear to be sensible to regard any observed changes less that approximately 10% with a ceratin degree of caution.

Each of the kharif crops were classified as thermally suitable, of the rabi crops the various varieties of rice displayed an increase in thermal suitability with increased temperatures, whilst remaining rabi crops showed a slight decrease in thermal suitability. The growing period suitability basically determines the agro-climatic suitability in those crops classified as highly thermally suitable. From the remaining crops, there was a general reduction in the agro-climatic suitability after the climate change scenarios, in response to the limitations imposed by the growing period suitability at otherwise quite suitable sites.

The growing period limitations imposed by lack of water on the boro crops, but the general suitability in relation to other factors, present considerable theoretical scope for future production, if irrigation were to increase and farming techniques were improved. The consequences of this are discussed in Chapter 10.

The obvious disparity between the suitability of the NW and SE regions of the country, illustrates the strong influence that the relief and variations in climate have upon agriculture. The NW, generally more suitable in all respects for all the study crops, is generally highland, less impacted by flooding, experiences slightly less rainfall than in the west and the rains generally start later. Whilst the SE provides the opposite scenario, restricted by unfavourable relief, irregular topography, with the rains starting earlier.

The land suitability assessment, appears to have provided a fair indication of the potential impacts of climate change upon land suitability. The FAO methodology has successfully facilitated comparison in relation to land suitability classes. HYV transplanted aman planted after aus rice provides the least suitable crop for cultivation, yields approximately 1mt and experiences the largest percentage decrease after the scenario, some 77%. This is obviously a very risky crop to cultivate; prone to failure and most susceptible to the changes imposed by the climate scenario, despite having one of the highest potential yields. Wheat yields the highest total output, nearly 7 mt, but experiencing a significant percentage reduction to 4.2 mt after the scenario, indicating the potential that climate change may have upon rabi crops.

The crop optimisation routine indicates that Bangladesh theoretically possessed the capacity to easily support its population of just over 100 million for the 1988 baseline and even the projected populations in excess of 200 million may be theoretically sustained in the future. A staggering 1419 million people were estimated to be sustainable before the scenario and 1157 million people to be sustainable after, each year, with an additional 806 and 509 million people respectively sustainable with the introduction of a third rice crop into the crop rotation. The figures are not intended to represent absolutes, but to reveal that significant potential for agricultural production improvements does exist, which provide hope for the future of the country. Whilst the relative simplicity of applying GIS technology to the crop optimisation routine indicates that GIS will significantly benefit future land use planning and optimisation research projects.

Chapter 10

Agricultural Outlook

10.1 Introduction

Throughout this project it has been assumed that sufficient time has passed to allow a significant change in climate, whilst (artificially) no allowance has been made for future technological change, government policies or developments in agricultural practices. This chapter considers some of the possible changes that might be experienced within the agricultural sector of Bangladesh that may affect agricultural productivity and will determine the relative significance of the reductions in yield suggested by this research. The major schemes that could be undertaken are discussed, for example: crop diversification, improvements in seed stock, the efficient use of pesticides and fertilisers and the potential for increased irrigation. Quantification of these changes in a predictive manner is clearly academic, the chapter is intended instead to highlight the importance of these other factors placing the modelled yield reductions into context.

10.2 Increasing Agricultural Productivity

Various opinions exist regarding the way forward for agriculture in Bangladesh, in 1984 Bayes proposed that new technology, gradual development of irrigation and drainage facilities and relaxation of institutional barriers would bring about a four fold increase in agricultural output by the turn of the century. These changes are gradually occurring, although government restrictions regarding importing fertilisers (for example) have only recently been relaxed and still remain restrictive. The efficacy of these adjustments on production levels will influence the impacts of any change in climate. Adjustments will depend upon world prices, national policy, demand and the adoption rate of technology, all of which remain virtually impossible to predict. Certain adaptations at farm level however may be instituted with less influence from government policy. Since there is little scope for bringing new land under cultivation, intensive methods of cultivation, changes in cropping patterns and efficient use of scarce resources, including irrigation water, need to be pursued. These adaptations are discussed later. The following section assumes that optimisation for maximum output is sought, although one of the fundamental features of the Bangladesh agricultural system is pursuance of other agricultural goals, in particular risk avoidance. It is more sensible to have at least some proportion of a lower yielding crop survive, rather than have all of a higher yielding crop lost to excessive flooding for example.

10.2.1 Changes in Crop Variety

If the growing season were to become warmer, a change from quick maturing cultivars would allow full advantage to be taken of the longer and more intense growing season. Later maturing varieties requiring higher temperatures for cultivation would be more suited to exploit these new conditions. Quick maturing rice varieties, such as the HYV boro (if sufficiently irrigated), should produce higher yields with increased temperature, which is indicated in the project as average potential yields increase nearly 2.5% from 5.00 to 5.11 t/ha. Whilst the late maturing rice varieties could provide a greater yield under the new conditions (5.57 to 5.69 t/ha). Varieties with higher drought and heat resistance may also be substituted in a similar fashion.

When moisture, rather than temperature is the climatic constraint to output, or when increases in temperature could lead to higher rates of evapotranspiration and thus to reduced levels of available soil moisture, a switch to crops with lower moisture requirements may occur. Unfortunately, the lack of current information regarding future changes in rainfall makes prediction of these areas difficult. The movement of the suitability zones as demonstrated in Section 6.8, should bring about changes in crop location. If these potential suitability classes could be communicated to farmers, the most appropriate locations, in addition to the most appropriate varieties, could be cultivated to produce higher yields.

In conjunction with the herbicide measures described in Section 10.2.2.2, plant breeders are trying to develop rice cultivars that compete well against weeds, although these varieties may require some 20 years for development (Holmes, 1994).

10.2.1.1 Crop Diversification

The global trend of declining cereal prices has lowered the value of the scarce land and water resources used in cereal production. Bangladesh is faced with two alternatives to increase the value of land resources: either to increases economic output of rice, or to diversify towards production of higher value non-rice crops. Rice will almost certainly continue to be grown on almost all areas in the wet season, so there is an increased need to intensify other, more profitable options for the dry season, when water supplies are scarce but conditions for other crops are suitable. According to Biswas (1991) over 100 other crops are actually grown on the 28,000 km^2 or so not currently under rice cultivation. Crop diversification could be an effective way to improve agricultural performance in Bangladesh (Mandal, 1991).

The Fourth Five-Year Plan (1991) emphasised the importance of crop diversification for agronomic, nutritional and economic reasons. In response, the Crop Diversification Programme (CDP) was initiated, a joint effort between Canadian and Dutch International Development Agencies and the Bangladesh Ministry of Agriculture. The project was first implemented in Autumn 1990 and divided into two five-year phases. The CDP consists of three crop specific sections: tubers, oil-seeds and pulses, within which research was undertaken into: seed production, extension and marketing. The aim of the project was to assist the Bangladesh government in attaining its objectives of food-self sufficiency and improved nutritional standards. The project was also initiated in response to decreasing soil fertility caused by rice monoculture (Biswas & Sarker, 1987; Bhuiyan, 1989; Miranda, 1989) and the decreasing profitability of rice production under improved seed, fertiliser, and water technology, as a result of increased costs of production because of the withdrawal of subsidies and decline in rice yields (Mandal, 1988a). The expected outputs of the programme include an increase in CDP crops from seasonally fallow lands, increased yields and increased consumption (Fabbri, 1992).

The major opportunities for crop diversification occur during the dry months (Mandal, 1991) which have both brighter days and longer active day length when compared to the wet months, facilitating greater photosynthetic efficiency in growing plants. A lower incidence-level of pests and disease also occurs during the dry season, due to low temperature and humidity. These factors also favour uninterrupted crop growth and development for satisfactory yield performance. All of these factors are said to favour not only HYV rice and wheat crops, but also vegetables, pulses, oilseeds, tobacco and quick-growing fruits, provided that the crop growing water requirement is met artificially by irrigation .

Biswas and Sarker (1987) suggested there are physical, technical, organisational and institutional constraints to achieving higher levels of crop diversification in this manner. Whilst, Bhuiyan (1989) considered that economic returns are the preconditions for popularising a crop diversification programme, thus requiring massive price support for non-rice crops to compete with irrigated Boro rice (Mandal 1988b). The ultimate popularity of crop diversification remains questionable, although essentially agro-climatic factors dictate cropping patterns, the socio-economic factors (especially individual farmer's preferences) significantly influence these decisions. Subsistence farmers prefer cropping patterns that minimise risks, rather than maximising profits, thus potentially hindering the uptake of crop diversification on a large scale.

10.2.2 Changes in Crop Management

It is reasonable to expect that certain changes in management practices will result, when changes in climate are perceived. As discussed below the need for (but also the cost of) irrigation will increase, this will undoubtedly increase the cost of production, possibly altering the system towards less water demanding uses or taking it beyond the pockets of the subsistence farmers. Changes in management could include changes in planting and harvest dates, tillage and rotation practices, increased fertiliser and pesticide applications and improved irrigation and drainage systems. Simple management changes such as these have the potential to increase yields considerably, although labour availability at critical planting/harvesting periods can impose considerable limitations and needs consideration.

10.2.2.1 Fertiliser use

More use of fertilisers may be necessary to maintain the soil fertility in the future. Yields are already found to be falling as soil fertility declines in response to zinc and sulphur deficiencies (Hossain, 1991). Soil fertility also becomes problematic if cropping patterns becomes too intensive and soil nitrogen is depleted, although due to the flooding regime Bangladesh does not experience the chronic leaching of nutrients currently seen in other countries. The actual future fertiliser use requirements are affected by several aspects of the climate system, for example the extent that higher CO_2 levels make nutrients more limiting (thus requiring increased fertiliser usage) is one area for consideration and research, whilst future energy prices will have a direct effect on the cost of fertilisers and therefore upon their rate of uptake. The IRRI is now trying to develop a new rice plant to withstand reduced nitrogen levels in the soil, but this is unlikely to reach the farmer's fields this century.

10.2.2.2 Control of Pests & Diseases

In the past, chemical control of pests and weeds, when available, has been haphazard and sometimes dangerous. Recent research in Asia (described by Holmes, 1994), is attempting to minimise the use of herbicides, minimise environmental risks and slow the evolution of herbicide-resistant weeds. Throughout Asia weeds are the rice farmer's most damaging adversary, according to studies by IRRI, weeds reduce harvests by an average of 10-15%, despite farmer's efforts. Left unchecked weeds could wipe out as much as 95% of a crop. With the introduction of HYVs, herbicides are poised to dramatically increase in use. The traditional method of sowing rice into nursery beds and then 'transplanting' the young seedlings into paddies, allowing the seedlings an improved chance of survival against the weeds, is now under pressure from herbicides. They offer an alternative to the back-breaking de-weeding practices associated with this method of cultivation, thereby releasing labour for other purposes. The problem of herbicide resistant weeds is a serious threat however. Research is therefore being directed towards ecologically based and non-chemical methods. Clean seed is one area for improvement, this alone has the potential to boost yields by 10% and seeds saved from the previous year are far from ideal in this respect. In addition, careful tillage and levelling before sowing, to eliminate the patches where weeds thrive and choosing wisely when to flood paddies; so that weed germination is suppressed and growing weeds drown, unlike the more water tolerant rice, both provide possible strategies. Biological control of weeds using fungal diseases that infest important weeds of rice, killing or weakening them enough to give rice the competitive edge, look promising, but like new weed-resistant crop varieties they may not be ready for many years.

Insecticides, more environmentally damaging than herbicides, are also undergoing similar scrutiny. HYV rice in Asia was originally sustained with great doses of chemical fertilisers, herbicides and insecticides, but as yields began to decline, even the introduction of more resilient rice strains had little effect. Thus, in a similar manner to that described for herbicides, the IRRI is advocating optimising existing methods and current crop varieties (Integrated Pest Management - IPM), in an attempt to avoid chemically resistant crops and declining yields in the future (Madeley, 1994: Metcalf, 1984). Indirectly therefore, more prudent use of herbicides in this manner, keeping costs down and increasing crop yields, may provide some leeway for increased productivity in Bangladesh.

10.2.2.3 Soil Drainage & Control of Erosion

Bangladesh does not currently suffer the debilitating soil degradation or the erosion of land, currently experienced in other countries. The annual flooding of the major rivers, deposits a layer of silt that maintains the fertility of the floodplains. Therefore in this respect alone Bangladesh is unusual. However, planned changes to the hydraulic regime to ameliorate the impacts of flooding, for example, may interfere with this balance, so that soil erosion could become a feature of the future. In relation to hydraulic planning, Custers (1992) considers that the flood management schemes proposed for Bangladesh are inappropriate, waste scarce resources, damage the environment and have a short life span due to poor maintenance and the absolute energy of the rivers. Clearly, which ever route is taken, ramifications exist for agriculture.

10.2.2.4 The Potential for Irrigation

In Bangladesh the critical factor for agricultural transformation is the control of water. The success of water control measures would automatically lead to an increase in productivity (Hossain 1991). Implementing plans is obviously not completely straight forward. For example, the onrush of water into the country that leads to widespread flooding and crop damage, originates outside Bangladesh. Unless a plan is drawn up jointly between the neighbouring countries, there is no possibility of avoiding flooding and ensuring adequacy of surface water during the dry season for irrigation. In the mean time, all that Bangladesh can do in isolation is to construct embankments and water control structures, like sluice gates along the rivers, deepen the channels and re-excavate the river courses which are regularly being silted up by over 2 billion tonnes of silt per year. Despite these measures, the impacts of the devastating floods that occur at periodic intervals can not be avoided, thus perpetuating the insecurity of the farmers and the prevailing risk avoidance ethos.

Secondly, there is the uncertainty of rainfall, dependence upon the monsoon means that the guarantee of unhindered operations fundamental to modern productive activity, can not be achieved. Too much or too little rain results in major crop losses. In this situation it is more sensible to increase productivity during the dry season, as suggested above. This is necessarily dependent upon increased irrigation, which is ironically in short supply during the dry season. Excessive surface water abstraction is not advocated, since this water has to be allowed to flow directly into the Bay of Bengal to control salinity intrusion, enable the inland water transport to operate, ensure the survival of fresh water fisheries and to maintain the ecological balance, not to mention support of the rapidly growing urban-industrial complexes.

Surface water is not the only source of irrigation in Bangladesh however, according to the Master Plan Organisation, several million hectares of land could be irrigated with shallow and deep tube wells (Oad & Laitos, 1989). Bangladesh is sited on one of the largest aquifers in the world, but only one 6th of its potential is currently being used

(ODI, 1980). It is estimated that groundwater reserves could irrigate about three quarters of all cultivated land in Bangladesh (USAID, 1976). However, irrigation in Bangladesh, in particular the use of pumped water, is a comparatively recent innovation. The land suitable and available for irrigation far exceeds the area which is presently irrigated, although the surface and shallow groundwater of the coastal belt has limited uses for agriculture because of salinity. Table 10.1, indicates the net cultivable areas (NCA), land suitability for irrigation, water availability, the area irrigated at present and the potential area for development.

Table 10.1 Land Available & Irrigated Area at Potential Full Development (million ha)

Source: National Water Plan Bangladesh (1986)

According to the table, from a net cultivable area of 9.03 Mha, 7.56 Mha are suitable for irrigation. At present however, only 1.92 Mha of land is under irrigation, which is only about 25% of the total land suitable for irrigated agriculture. There is a potential for development to the extent of 66%, if irrigation facilities were extended to the rest of the land suitable for irrigation. Figure 10.1 presents schematically the area of potential irrigation. The reservoirs for groundwater have sufficient storage capacity to meet the yearly changes in rainfall and flooding which provide a dependable volume of

Figure 10.1 **The Dry & Saline Zones of Bangladesh & the Area for Potential Irrigation**

Sources: MPO, *NWO*, p 10-104; Herb Weibe (1985) 'Agro-Water Resource' Vol. 2 of *A Reconnaissance Survey*, AST: Dhaka), p31.

groundwater for most uses and well technologies (Hossian, 1991). It has been estimated by the National Water Plan (1986) that the primary irrigation demand for the total irrigable area of Bangladesh including the active floodplains is about 7.98 Mha, which would require 57,223 Mm^3 of water during the dry season. The maximum demand for irrigation water occurs in March when 16,380 Mm^3 (29% of total water demand) is needed.

To maximise irrigated areas, exploitation of surface and ground water must be to its fullest extent without being indiscriminate. Land must not be irrigated without consideration for the water resources of the country as a whole and governmental control of some description is necessary to prevent the excessive prices charged by the private sector to supply irrigation to the peasants. It is clear therefore that Bangladesh does have the irrigation potential necessary to support cultivation during the dry season, but other factors influence its successful implementation.

10.2.2.4.1 Irrigation & the Boro Rice Crop

The results of the project indicate that irrigation is essential for the full growth period of boro rice and for the early part of aus rice. Boro rice has a tremendously high potential yield, it is one of the few crops to demonstrate increased thermal suitability after the climate change scenario and is essentially only limited by insufficient moisture. The FAO limitation ratings for irrigated boro, indicate that the current soil moisture limitations would be completely removed and, if not on excessively well drained ground, most levels of drainage would be suitable for its cultivation. In relation to the growing period suitability, from present classification as completely 'unsuitable', local boro may be classified as very suitable' (S1) and 'suitable' (S2), across the majority of the country, with a few 'moderately suitable' (S3) areas in the NE region. A marked improvement upon the present suitability classification.

10.2.3 Changes in Crop & Livestock Husbandry.

10.2.3.1 Mechanisation

Any attempts to increase the 'rate' of harvesting to mitigate the effects of weather induced effects, such as shattering of rice, are hindered by insufficient labour availability at critical periods (FAP 2, 1992). Similarly, shortages and constraints of draft power for land preparation have a bearing upon this, as the human demand for food increases the requirements of the animals are unfulfilled. Standards of land preparation are declining therefore and if this continues into the future, will act as an impediment to yield optimisation. The only way forward appears to be mechanisation therefore, which is not only costly, but has severe ramifications for the rural unemployment problem.

Farmers generally cultivate small plots over a large area, thus there will be limits to the adoption and use of power driven mechanical equipment for cultivation, to date there has been little advancement in this area. Reorganisation of the cadastra, to rationalise land holdings from discrete distant plots into single units may make mechanical cultivation more viable, although the likelihood of such a major project is low. From the equipment available, irrigation and threshing appear to be the most promising for technological advancement in the foreseeable future, economising labour use is not really a goal to be encouraged, with such massive unemployment. Ultimately, the bleak future for agricultural productivity and development may be attributed to the low levels of expenditure experienced within this sector.

Hand driven mechanical equipment is available for sowing, weeding, threshing etc., and substantial improvements in productivity could be achieved if this equipment were to be used by the peasantry. Crop losses due to inefficient threshing are thought to account for a 5% loss in total output (Hossain, 1991). Hand driven threshers could help to significantly lessen such losses. In both sowing and weeding, labour operated mechanical equipment could yield substantial benefits. Even though these machines are not power driven, they can facilitate the movement from primitive to modern methods of agriculture. Transplanting, application of fertilisers etc., which require substantial labour use, will continue at present, to avoid mass labour displacement and rural unemployment, at least until the industrialisation process acquires momentum.

Research studies relating to the appropriateness of mechanised equipment in Bangladesh are limited. Gill (1983) compares the performance of mechanised tillage relative to that with traditional bullock-drawn ploughs. The results on the whole do not establish the superiority of mechanical equipment over traditional ploughs. Particular problems are poor reliability, obtaining an unadulterated fuel supply, lubricants and spare parts. Draft animals are advantageous in this respect, because of their easy availability and their greater reliability, although mechanised cultivation on a larger scale may automatically solve the problems associated with this small scale uptake of technology.

10.2.4 Industrialisation & Agriculture

Bangladesh's industrialisation process provides a major determining factor for the future prosperity of a country currently so reliant upon agriculture. Hossain (1991) suggests that it is conceivable that in a few decades most of the non-viable farming households would move to better jobs in factories and adopt other professions in urban areas, if the country achieves success in its industrialisation strategy, together with consolidation of farms. Once the need for producing for home consumption had gone, farming could be organised on the basis of market processes. At present, in general, peasants are not very responsive to prices. The great majority of peasant will continue to grow rice irrespective of its rate of return vis-à-vis other crops, it seems logical therefore that initial emphasis should be directed towards HYV to replace traditional varieties. Research by Kashem (1987, Cited in Hossain, 1991) regarding the adoption of HYV rice revealed a significant positive relationship between age of cultivator and adoption; the older farmers were easier to influence to adopt innovative practices; larger households were less keen to adopt than smaller ones, and there was a significant negative relationship between farm size and adoption. Smaller sized holdings were more eager to adopt HYV (as long as the costs were not beyond their reach) and once adopted they rarely reverted to their old practices. Essentially, negative perceptions were the largest barrier to uptake. Decisions regarding cropping patterns are generally dictated by farmer's tastes, perceived economic gains and agro-climatic conditions (Biswas, 1991), although a large number of tropical crops are still grown despite their low economic returns. Bhuiyan (1988) illustrates that the system of share cropping (operative in Bangladesh) is not conducive to HYV adoption, as little incentive exists to change, since the farmer has to bear the burden of input costs. It is suggested perhaps, that cash renting (instead of a percentage of the produce) be introduced, which should technically increase the uptake of HYVs.

10.2.4.1 Effects of Technology on Yield

Future changes in yield, may well be masked by the larger effects of technological improvements. MacCracken *et al* (1990) consider that next to climate, technology is the most critical factor affecting crop yields. Yield increases in the past decade have been driven by such technical advances as mechanisation, chemical fertiliser application, development of hybrid varieties, chemical herbicides and pesticides. A major issue in projecting the impacts of future climate change is that of estimating future technological improvements. This would require numerous assumptions about population growth, rates of technical progress and resource availability. In Bangladesh however, the assumption may have to be made that certain areas of agriculture will alter with the adoption of different crop cultivars or the increased use of fertilisers etc., but the economic constraints coupled with these developments, may allow us to assume that the transition will, at best, be slow.

Known modern technologies are still under-exploited in Bangladesh. In the future not only will exploitation of known technologies increase, but new technologies are likely to be developed. Fertiliser use per hectare of crop land increased at an annual rate of 7.4% in the 1960s. In the 1970s this fell to 5.9%, and a much lower rate is expected in the future, not as a consequence of sloth, but as an outcome of biotechnical innovations (Hossain, 1991). New advances in genetic engineering, combined with cloning and tissue culture are likely to be forthcoming for yield increases. It does appear that the high percentage of land already under cultivation (67% - Hossain, 1991) means that any increase in agricultural output will have to come from technological advances, the potential of which has already been demonstrated in Section 10.2.3.1.

10.2.5 Effects of Carbon Dioxide Enrichment on Crop Yields

As discussed in Section 4.3.1, the extent to which CO_2 enrichment can offset detrimental impacts on yields has not been satisfactorily determined. This is one of the few areas where some positive effect may be gained by C3 plants, although as previously discussed, some researchers remain sceptical as to whether these impacts would ever be felt at farm level. Whether it will be sufficient to counter reduced yields, will only be revealed by further research and ultimately, by time.

10.2.6 The Future, Agricultural Extension

Efforts have been made to implement some of the adaptations described above. For more than a quarter of a century Bangladesh has been attempting to bring about a technological transformation in agriculture and to enhance the productivity growth rate. Despite attempts, the growth rate remains low. Per capita income of the rural population remains amongst the lowest in the world and the peasants remain as averse to taking risks as their forefathers, still clinging to age-old agricultural practices, when widespread use of improved seeds and modern inputs like fertiliser, pesticides and irrigation, as well as increased cropping intensity and cultivation of more valuable crops could enable them to substantially increase their income from the land. The policy makers have still to devise an effective strategy for transforming the traditional small holding rice growing peasantry into modern agricultural entrepreneurs (Hossain 1991).

Agricultural Extension aims to transfer more productive and useful technologies to farmers, it is essential to the growth and development of the agricultural sector. Bangladesh has a large governmental and non-governmental services sector for extension work, although to date their impacts have been unsatisfactory. The mere invention and existence of highly productive and beneficial technologies such as crop rotation, organic manure, soil conservation practices, improved seeds, fertilisers, irrigation, improved breeds and feeds, use of simple tools, bio-gas, solar energy, food processing techniques etc., do not find their way to farms without considerable effort. Agricultural development is possible only when the needs of the farmers are met effectively at the right time, place, cost and in the appropriate form. Farmers need education, organisation, inputs, credit and services. Technically, agricultural extension services if properly organised can effectively meet theses needs. Whether such schemes will be successful in the future will be determined by governmental stability, policy and investment. Success, all be it limited, has already been seen and there is no reason in theory that similar success should not continue into the future (Hossain 1991).

10.2.6.1 Present Analogies Useful for the Future

Reference to relatively progressive areas of Bangladesh, already involved with agricultural improvements may well give some indication as to the future direction for agriculture across the rest of the country.

In NW areas currently sufficient in water resources, boro rice has been overwhelmingly chosen as the major irrigated crop. As rates of foodgrain production increase however, rice may be expected to command a reduced market price in the future and profitable new HYVs may well be adopted as alternatives. With the availability of new crops and varieties, farmers may replace boro paddy with two alternative crops to use land more intensively. This shift away from boro paddy to more profitable varieties can already be seen in Bogra, which has more progressive farmers and high boro yields. Similarly, Rangpur farmers with irrigated land, report higher profits with a variety of crops, including banana, sugarcane and turmeric, than with boro and aman paddy (Gisselquist, 1991).

10.2.7 Bangladesh & the World Economy

To be meaningful, the impacts of climate change need to be considered in the context of the changes in future world economic demand. If Bangladesh is to use economic development to fulfil the needs of its expanding population, this context will be vital. It has been suggested that climate change may result in significant shifts in competitive advantage (Parry, 1990), if the predictions of the project hold true, then Bangladesh is already disadvantaged by reduced land suitability, which does not bode well for the future. If prepared to ensure food security by permitting increased imports from 'advantaged' countries, it is vital that Bangladesh builds an economic framework sufficient to fund these imports. Unfortunately, physical and institutional infrastructures are still insufficient to support increased production in Bangladesh, unless this situation is addressed it will continue to constrain production in the future.

10.2.8 Social Conflict

Levels of adaptation as described above, and the efficacy of adaptive practices will ultimately remain uncertain. There may be social or economic reasons why farmers are reluctant to implement adaptation measures, for example, increased fertiliser application or improved seed stock may be advocated to improve production, but these are capital intensive, and/or may not fall within the strategies adopted by farmers, therefore the uptake could be hindered.

Currently the population stands at 120 million, providing just 0.08 ha of crop land per capita. Crop land is already desperately scarce, by 2025, the amount of available crop land will be cut in half (United Nations, cited in Homer-Dixon *et al*, 1993). Flooding and the numerous other ravages of the Bangladesh system, have already forced millions of people to migrate into the neighbouring areas of India, swelling the population of these neighbouring states by 15 million. Already a source of political friction, this safety valve may well be closed in the future, facing Bangladesh with even more problems to add to the multitude already in effect.

10.3 Sea Level Rise

As briefly mentioned in the introduction, the impacts of sea level rise have been excluded from this research. In reality however, any changes in sea level could have significant impacts in agriculture in the future. The following section therefore highlights some of the research of direct relevance to Bangladesh and indicates how a rise in sea level could impact the agricultural system.

The IPCC (1992) reported that at the current rate of emissions, mean global sea level is expected to rise about 20cm by 2030 and 65cm by 2090. Huq & Ali (1990) assessed the effects of possible sea level rise specifically on Bangladesh, based upon updated figures for contour levels. Their project considered the effects upon population, agriculture, infrastructure, forests and other activities due to a 1m sea level rise scenario. They proposed that over 12,000 km^2 of aman rice, 1,000 km^2 of aus rice and 138 km^2 of jute, may be affected. It is also suggested that salt water intrusion will effect the land above the 1m contour, decreasing the agricultural output in addition to that described above.

Tickell (1991) suggests that an average sea level rise of 30 cm would force most people in the delta region of the Ganges to migrate and would result in a loss of 25% of the land.

Local sea level increases depend upon subsidence, in a deltaic region such as Bangladesh under natural conditions it would be expected that deposition of sediment would equalise delta subsidence. Unfortunately, human activities now interfere with this balance, including channelling, diverting or damming rivers; destruction of mangrove forests; removal of groundwater, etc.. India has also diverted flow from the Ganges causing rising salinity in coastal streams in Bangladesh and considerable drilling of shallow and deep wells has resulted in subsidence of twice the normal rate (Milliman *et al*, 1989). Therefore the direct effects of global sea level rise, such as inundation of land and salt water intrusion are being worsened by the impacts from localised activities such as diversion, damming and abstraction.

10.4 Outlook

Irrigation appears to provide one of the keys to future agricultural improvement. The problems associated with surface water origins and lack of control however suggest that the way forward will make use of the significant water resource held underground. To avoid the vagaries of flood and timing of the monsoon, increased use of the winter season, in conjunction with irrigation and crop diversification provides one avenue for development. Any irrigation policy must be formulated with strict guidelines so that the livelihoods of other water users are not jeopardised.

The successful introduction of irrigation would allow boro rice to be cultivated, which would significantly supplement current rice output, with potential yields in excess of 5.5 t/ha. Areas such as Bogra already sufficient in water resources indicate that this may be the next step, although in the longer term, extension into the dry season with crop diversification techniques is possible.

The relatively high productivity potential of the high yielding crop varieties alone, provides a significant potential food reservoir for future populations. If agricultural inputs can be improved, farming techniques made more efficient and effective (protecting HYV aus from floodwaters, selective application of fertiliser or pesticide, for example), the relatively low yields can be increased. Gisselquist (1991) suggested that increased fertiliser use, adoption of new varieties, new crops and power tillers, excluding irrigation, may contribute at least 2-3% to agricultural growth.

Clearly, the prevailing farming system in Bangladesh has unique features that can not be overlooked when trying to analyse the system for the future. According to Hossain (1991):

> *"farming can never be specialised in the near future, rather it will remain small, fragmented, multiple and subsistence"* (p 254)

If this remains the case, full-scale adoption of modern farming practices will be severely hampered.

10.5 Summary

Just a few of the potential adaptations in agriculture, possible with current levels of technology, have been described above. Clearly, over the coming decades new adaptation techniques will become available and refinements will be made to current techniques. Overall, the findings of the project suggest considerable potential for improvements to the agricultural productivity of Bangladesh, and the optimisation results suggest that theoretically the maximum attainable yields are well in excess of the population supporting capacity.

It does appear however, that massive population growth, exposure to environmental hazards and the general stresses on the whole agricultural system, may prove formidable barriers. The IRRI (Madeley, 1994) calculates that rice output in Asia will need to increase 70% over the next 25 years, to keep pace with population growth, excluding any impacts from climate change. Yield increases in excess of this are by no means impossible, as illustrated in the optimisation routine. The problems faced by the Bangladesh agricultural system are essentially social, if crop yields were to be improved, a simultaneous improvement in food distribution would be essential together with a coherent, effective governmental policy with massive amounts of expenditure for construction of the infrastructure necessary to create controlled conditions in agriculture and to make adequate arrangements for the availability of fertilisers, pest control measures and technological development. New crop types are clearly essential if productivity and agricultural success are to be sustained, not only are high yielding varieties necessary, but crops tailored towards the demands of a world economy will be fundamental. Whilst the limited success of government agricultural improvement schemes to date, provides even more evidence that improvements even if apparent, will be slow.

Chapter 11

Conclusions

11.1 Introduction

This final chapter, provides a summary of the findings of the project; in particular an appraisal of the success of the methodology, indicating the main contributions to knowledge provided by the research and suggestions for further research.

11.2 Summary of Findings

11.2.1 Implications for Agriculture in Bangladesh

Despite the imprecision of regional predictions of climate change, predictions of the potential implications of climate change may help to improve current knowledge and therefore the ability to alleviate any impacts from climate change should they occur.

The yield prediction model suggests that the climate change scenario will have a deleterious effect upon the yields of all the study crops. This is in agreement with other studies that suggest that changes in temperature and solar radiation will reduce yields due to the impacts of a shortened growing period. Any reductions in yield will have severe implications for future agricultural practices in Bangladesh, not only will productivity increases have to be sufficient to support population growth, but they will also have to be able to support the reductions in yields induced by climate change. Carbon dioxide enrichment, increased rates of photosynthesis and improved plant water use efficiency may improve yields to some degree, although evidence of this remains scant. Additionally, the simultaneous effects upon the weeds, pests and diseases of the crops could have either positive or negative implications.

The effects of climate variability, in particular flood hazard frequency, are seen to have a significant influence upon land suitability, particularly for those crops grown in the summer kharif period. The reductions in land suitability in response to this increased hazard substantiate the suggestion that agricultural development efforts in Bangladesh should be concentrated in the winter rabi season, in order to avoid the flood hazard altogether.

The 'theoretical maximum' population supporting capacity is calculated to be well in excess of both the population of the base scenario in 1988 and for future population projections, suggesting that under modified conditions Bangladesh has the potential capacity to feed its population both now and in the future. Despite the massive reductions in calorific supporting capacity, resulting from the climate change scenario, the population can be accommodated. However, the agricultural system will require major modifications and improvements if this potential is to become realised. The agricultural developments suggested in Chapter 10, such as new crops and varieties with greater market value and yield success, coupled with improved agricultural practices and in particular the increased use of irrigation facilities, are fundamental to this. The prevailing agricultural ethos - based upon risk avoidance - perpetuates low yielding varieties and inappropriate cropping patterns when compared to the yield requirements of future generations.

11.2.2 Methodology Validity

The suitability of applying the Agro-ecological Zones methodology to a PC and enlisting a spreadsheet to perform the calculations formerly undertaken by an inflexible computer program (or indeed by hand) has generally proved very successful. The limitations experienced, may be solely attributed to insufficient processing capacity or lack of computer disk space. The major advances currently being made in computer technology over the past few years, have already made the necessary technology affordable, so this limitation could realistically be eliminated in future application. The problems associated with data acquisition and data verification, are also divorced from the methodology itself and do not limit the success of the technique. They do however, remain the major problems of all land evaluation techniques.

The study has provided the first endeavour at delineating new boundaries for the thermal zones from the AEZ methodology, resulting from a climate change scenario. Additionally, the substitution of the growing period (K zones) for the actual growing period start and end dates derived by the FAO (1988), will allow future researchers to adopt the zones provided by the mapped Climatic Resources Inventory, removing the necessity to acquire the actual dates from the FAO. Neither of these new delimitation experiments have been undertaken previously.

The adoption of the spreadsheet, to determine the unconstrained yield figures, was extremely successful. As hoped, the methodology was simplified and the unconstrained yield calculations compared well to those described in earlier work, indicating that the yield calculation routine functioned well. Incorporating the new climatic variables for temperature and photosynthesis was facilitated by using the 'look-up table' facility within the spreadsheet, and the interpolation of the monthly climatic figures across the growing periods was also easily achieved and uncomplicated. Having established the feasibility of adopting a spreadsheet in this manner, this provides tremendous scope for the future, due to the cheap, reliable and powerful nature of the package.

The Geographic Information System IDRISI provided many functions to facilitate the land suitability assessment. The rapid production of detailed suitability maps for all aspects of the land suitability, allowed determination of the land areas that experienced a change in suitability and a clear visual representation of their areal locations. The GIS 'overlay' function was particularly useful, eliminating the necessity for time consuming and potentially erroneous manual planimetry. The abundance of functions within the GIS for data manipulation, comparison and display, provides tremendous scope for future work. The GIS was also able to interpolate discrete site specific climatic data across the surface of the country quickly and easily. Overall, IDRISI proved to be very user-friendly, the basic principles necessary for undertaking the methodology were easy to learn with minimal prior knowledge of a GIS. With this in mind, application of this methodology to a developing country appears feasible (as indeed has been the case recently in several countries (Chidley, Pers. Comm.)). One weakness of IDRISI was the inability to readily provide an effective facility for optimisation of crop yields within corresponding cells. The GIS *GRASS* was therefore used for this instead and proved to be ideal for this purpose. Incorporation of more complex cropping patterns, closer to those adopted in reality could be readily undertaken in the future. The entire project could have in fact been undertaken using the GRASS GIS, or with IDRISI if time was taken writing additional modules and scripts, however the technique of adopting the best of each system proved very successful.

The study has tested the proposal of the Bangladesh AEZ Programme, that the SODAPS database provides a flexible information base for effective agricultural planning. Having overcome the time consuming data verification and checking necessary when using the database for the first time, and developing the methodology necessary to undertake the conversion between the two different classification methods, the SODAPS does provide the information necessary to undertake a study of this type and would be much easier to use again in the future. The database will require continuous updating if this utility is to be maintained however and the difficulties involved with actually accessing the information need to be addressed and eliminated.

However, the proposed utility of the SODAPS database alone for projects of this type is questionable when the difficulties involved with data acquisition are considered. Fortunately, even within the lifetime of the project, the availability of data in the public domain is increasing. As outlined in Chapter 7, the climatic data for Bangladesh is provided by the FAO CLIMWAT database on CD ROM and across the Internet and the FAO Soil Map of the World has now become available in digital format. This type of international data availability must be continued and actively encouraged, if global issues such as those addressed by this work are to be researched in an effective and efficient manner.

The success of adopting the areally most significant soil series code to represent the entire soil association unit was also examined for the first time (see Chapter 6). Currently used by researchers in the field without quantification, the study has indicated that this method provides a reasonable representation for simplification purposes, although the fine details relating to the unmapped areas are lost, as with any simplification. However, as computer technology improves and processing speeds increase, it will become increasingly unnecessary to adopt this simplification process.

The evidence from the results has provided an observed change in yields due to the application of a climatic scenario. It must be remembered however, that the causal relationship for this observed change may also be attributable to the adopted procedure. The delimitation of the discrete climatic zones fundamental to the land suitability methodology, for instance, may be an excessively arbitrary replication of reality and could possibly provide an unrepresentative reclassification of the land suitability classes (Chapter 5). This new delimitation could produce an observed reduction in yields potentially in excess of those experienced in reality. The reliance upon discreet boundaries for soils, climatic variables and physiography is recognised as artificial and until the capacity to store and process the highly complex data is made available and indeed the data itself is made readily available, the weaknesses must be recognised as a constraint. All good research recognises the potential areas for error, this potential is recognised here, but only further research will be able to verify whether these concerns are actually founded or not.

11.3 Further Research

This section provides a brief indication of areas for further research, prevented due to limitations of time, data or processing capacity or which emerged from the findings of the project as areas for future consideration.

The reliance upon the Agro-ecological Zones database provides a necessity to quantify its limitations and to provide some more specific quantification of its accuracy. Only then can the true utility of the database be assessed.

The obvious significance of irrigation to agriculture in Bangladesh suggests the need to repeat the entire project for irrigated crop varieties, having established the required methodology. The boro rice crop in particular, which under rainfed conditions is completely unsuitable, holds tremendous potential for improved yields when irrigated, providing a significant area for potential productivity increase. The necessary limitation ratings may be obtained from the FAO, for application to these crops. In addition to repeating the methodology for irrigated crops, other variables in the methodology could be altered to determine which factors have the most significant impact upon crop productivity. Although low confidence in regional climate predictions will remain the limiting factor for this for some time into the future. As mentioned, crop reliability is extremely important to farmers in Bangladesh. It is suggested therefor that the probability of crop failure is incorporated into the model to allow a more accurate representation of its impacts upon the system.

The exceptional problems encountered with data collection and incompatibility for this research indicate that a large problem exists with regard to data acquisition for Bangladesh (or indeed any Developing country). It is suggested therefore that an improved network for data sharing and communication is implemented, with provision for standards of data interchange, including in particular data descriptions, file formats and well defined map projections. In conjunction with increased communication and availability of public domain information on CD ROM or the Internet.

Having established the suitability of the spreadsheet for the methodology, tremendous scope exists for refinement of its functions and its useability.

With improvements in computer capability it may be possible to apply greater resolution to the GIS to provide soil maps which represent the data provided by the SODAPS database in more detail. Thus reducing the loss of information due to simplification for classification.

With improvements in the availability of very powerful GIS software such as that of GRASS, it is highly likely that the entire process could eventually be incorporated into the GIS, eliminating the use of the spreadsheet entirely. This provides an exciting area for potential advancement in the future.

The essence of the suitability process is the allocation of soils, land or climatic factors to discrete specific suitability classes. On one hand it has provided a successful way to simplify clearly complex and voluminous data, whilst it does also appear to present an over simplification to some extent. The combined effects of a soil suitability class of 'S2' and an agro-climatic suitability class 'S', may indeed provide a final land evaluation class of MS (moderately suitable), but whether this reflects reality can be questioned. Perhaps the 'fuzzy' approach advocated by Wang *et al* (1990) represents the next step in the suitability modelling process, modern technology has released the processing capacity and data availability necessary for this change, therefore the degree of simplification provided by the FAO methodology, previously necessary because of the constraints of processing capabilities, may now be expanded, as the previous constraints have been reduced. This methodology is also suitable where detailed models are not accurate enough. This research would help to establish whether the applied methodology does in fact affect the results.

Regional effects are, and will remain, the key to successfully assessing the overall impacts of a changing climate on agriculture. Pursuance of more accurate regional estimates of climate change will remain paramount in assisting improvements in this and similar research. Quantification of: the incidence of extreme events, how the moisture regime may alter, improved methods of paramaterisation in GCMs and increased model resolution, will be necessary for this increased accuracy.

Also at the regional level, agricultural development and water and land planning institutions should take future climate change into account, with attention to maintaining flexibility to the increased hazard of flooding from sea level rise in low lying coastal agricultural areas and to drought security issues and food-support needs of vulnerable regions should be addressed in light of potential climate change.

Agricultural research centres should encourage the development of effective approaches for preparing for climate change, such as the continued development of heat and drought resistant crops. Research should be directed towards determining what are the heat and drought tolerance limits of both presently grown and alternative crops and varieties.

11.4 Summary

Populations living at the margins of survival, such as those in Bangladesh, are particularly susceptible to even small changes in climatic conditions. With the threat of climate change and the potential for increased famine, now is the time to act to try and minimise the impacts, to wait until the famine has struck will be too late. The problems of high population growth, poverty, subsistence agriculture, weak governmental processes and under-developed social support systems need to be addressed with improved agricultural techniques (in particular irrigation), education, training and economic development. The research suggests that the agricultural potential exists in Bangladesh, if it can be harnessed now, the potential impacts of climate variation in the future may be ameliorated somewhat. The calculated theoretical agricultural capacity to support not only current populations, but the massive populations projected in the future, provides a tremendous incentive for development. It appears therefore that modern technologies such as GIS may play a small but significant role in simplifying the land evaluation process for planning for this future.

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Vol. 2 Inundation Resources Inventory

Report 5 - Land Resources

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Appendix A1

Description of the Columns in the SODAPS Database

Column A	**Soil Association Map Code**
Column B	**Soil Series Code**
Column C	**Soil Variant Code**
Column D	**Soil Phase Code**

<u>Landform</u>

Column E **Inundation Land Type**

1	Highland (H)	Land which is above normal inundation level and would normally not develop wetland conditions unless rainwater was retained on the surface by bunding (building small levees) on suitable soils.
2	Medium Highland 1 (MH1)	Land which is generally inundated less than 30 cm.
3	Medium Highland 1 (MH1) Bottomland	As above but remains in a wetland state throughout the year

4	Medium Highland 2 MH2)	Land which is generally inundated in the range 30-90 cm.
5	Medium Highland 2 (MH2) Bottomland	As above but remains in a wetland state throughout the year
6	Medium Lowland (ML)	Land which is generally inundated in the range 90-180 cm.
7	Medium Lowland (ML Bottomland	As above but remains in a wetland state throughout the year
8	Lowland (L)	Land which is generally inundated in the range 180-300 cm.
9	Lowland (L) Bottomland	As above but remains in a wetland state throughout the year
10	Very Lowland (VL)	Land which is generally inundated more than 300 cm.
11	Very Lowland (VL) Botttomland	As above but remains in a wetland state throughout the year

Column F **Relief**

1 Regular
2 Irregular
3 Broadly dissected
4 Closely dissected
5 Deeply dissected

Column G **Slope (%)**

1 <3
2 3-8
3 8-16
4 16-30
5 30-45
6 >45

Column H **Erosion Status**

1 Topsoil not eroded
2 Topsoil eroded

Column I	Topsoil Texture
1	Sand
2	Loamy sand
3	Loamy fine sand
4	Sandy loam
5	Fine sandy loam
6	Very fine sandy loam
7	Gravelly sandy clay loam
8	Sandy clay loam
9	Loam
10	Silt
11	Silty loam
12	Gravelly silt loam
13	Silty clay loam
14	Clay loam
15	Silty clay
16	Clay
17	Mucky clay
18	Muck
19	Peaty muck
20	Peat

Column J	Effective Soil Depth (cm)	
1	<25	Very shallow soil
2	25-69	Shallow soil
3	60-90	Deep & very firm soil
4	90-122	Deep & firm soil
5	>122	Deep & friable soil

Column K	Ploughpan
1	Absence of ploughpan
2	Presence of ploughpan

Column L **Soil Moisture Holding Capacity (mm)**

very low (<100)
low (100-200)
moderate (200-300)
high (300-400)
very high (>400)

Column M	Soil Permeability Rate (cm/day)	
1	<12	Slowly permeable
2	12-305	Moderately permeable
3	>305	Rapidly permeable

Column N	**Drainage**	
1	Well to excessively drained	
2	Moderately well drained	
3	Imperfectly drained	
4	Poorly drained but surface drains early (before mid- November)	
5	Poorly drained but surface drains late (after mid-November)	
6	Very poorly drained	

Column O	**Soil Consistency/Workability**
1	Mineral surface soil, not more than slightly firm/sticky/plastic/hard
2	Mineral surface soil, firm, very firm, sticky, plastic, hard, very hard
3	Mineral surface soil, extremely firm, very sticky/plastic/hard
4	Organic soil, organic material to at least 25cm below surface

Chemical Characteristics of Soil Series

Column P	**Soil Reaction**	
1	<4.5	Extremely acid
2	4.5-5.5	Strongly to very strongly acid
3	5.5-7.3	Neutral to moderately acid
4	7.3-8.4	Mildly to moderately alkaline
5	>8.4	strongly to very strongly alkaline

Column Q	**Nutrient Status**	
1	Low	Relatively Infertile
2	High	Relatively fertile

Column R	Soil Salinity (mmhos/cm)	
1	<2	Non saline
2	2-4	Very weakly saline
3	4-8	Weakly saline
4	8-15	Moderately saline
5	>15	Strongly saline

Column S	**Alkaline Phase**
1	Alkali phase absent
2	Alkali phase present

Column T	Calcic Phase
1	Calcic phase absent
2	Calcic phase present

Column U **Acid Sulphate Phase**

1	Acid sulphate phase absent
2	Acid sulphate phase present

Inundation/Flooding Status

Column V **Flooding Depth**

1	Highland (H)	Land not normally inundated
2	Medium Highland 1 (MH1)	Normal inundation less than 30cm
3	Medium Highland 2 (MH2)	Normal inundation 30-90cm
4	Medium Lowland (ML)	Normal inundation 90-180cm
5	Lowland (L)	Normal inundation 180-300cm
6	Very Lowland (VL)	Normal inundation deeper than 300cm

Column W **Flood Hazard**

1	Disastrous flood hazard absent
2	Disastrous flood hazard present

Column X **Erosion Hazard**

1	Disastrous river erosion hazard absent
2	Disastrous river erosion hazard present

Column Y **Storm Surge Hazard**

1	Disastrous storm surge hazard absent
2	Disastrous storm surge hazard present

Column Z **Hazard Frequency**

1	<=2%
2	2-6%
3	6-20%
4	20-50%
5	>50%

Column AA **Land Phase Area**

Column AB **Homestead & Water Area**

Column AC **Miscellaneous Land Area**

Appendix A2

Climate Station Data Format

Format of the monthly climatic data available from the CLIMWAT dataset (FAO, 1993b) for each of the 26 climate stations listed in Table 7.1 page 127.

Month	
P	Precipitation (mm)
T-Mean	Mean Temperature (°C)
T-Max	Absolute Maximum Temperature (°C)
T-Min	Absolute Minimum Temperature (°C)
T-Day	Mean Daytime Temperature (°C)
T-Night	Mean Night Time Temperature (°C)
ED	Barometric Pressure (mbar)
RH-Mean	Mean Relative Humidity
U	Average Wind Speed (m/second)
RG	Solar Radiation (cal/cm²/day)
ET-Penman	Potential Evapotranspiration (mm)

Appendix A3

Summary Frequency Data of the Thermal Zone Allocation for Each Climate Station

Bogra T4 - T3

	Baseline Climate		Baseline + 1.5°C	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	96	T4	71	T1/2
T-mean < 20°C	57	T4	22	T1
T-min < 17.5°C	115	T4	96	T3
T-min < 15°C	82	T4	68	T3

Faridpur T4 - T3

	Baseline Climate		Baseline + 1.5°C	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	99	T4	78	T2/3
T-mean < 20°C	62	T4	20	T3
T-min < 17.5°C	68	T3	63	T1
T-min < 15°C	54	T3	42	T2

Dinajpur T5 - T4

	Baseline Climate		Baseline + 1.5°C	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	110	T4/5	85	T3
T-mean < 20°C	69	T5	30	T3
T-min < 17.5°C	136	T5	127	T5
T-min < 15°C	110	T5	83	T4

Srimangal T5 - T5/4

	Baseline Climate		Baseline + 1.5°C	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	112	T5	91	T4
T-mean < 20°C	76	T5	52	T4
T-min < 17.5°C	133	T5	120	T4/5
T-min < 15°C	113	T5	94	T5

Jessore T4 - T3

	Baseline Climate		**Baseline + 1.5°C**	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	95	T4	77	T1/2
T-mean < 20°C	56	T4	22	T1
T-min < 17.5°C	113	T4	96	T3
T-min < 15°C	88	T4	68	T3

Rangpur T5 - T4

	Baseline Climate		**Baseline + 1.5°C**	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	107	T4	81	T3
T-mean < 20°C	66	T4/5	36	T3
T-min < 17.5°C	140	T5	126	T5
T-min < 15°C	110	T5	88	T4

Mymensingh T4 - T3

	Baseline Climate		**Baseline + 1.5°C**	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	96	T4	73	T1/2
T-mean < 20°C	53	T4	18	T1
T-min < 17.5°C	110	T4	91	T3
T-min < 15°C	77	T4	57	T3

Satkhira T3 - T2

	Baseline Climate		**Baseline + 1.5°C**	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	80	T2/3	53	<T1
T-mean < 20°C	38	T3	0	-
T-min < 17.5°C	101	T3	76	T2
T-min < 15°C	67	T3	44	T2

Bhola T3 - T2

	Baseline Climate		**Baseline + 1.5°C**	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	87	T3	62	T1/2
T-mean < 20°C	39	T3	0	-
T-min < 17.5°C	94	T3	76	T2
T-min < 15°C	65	T3	41	T2

Comilla T3 - T2

	Baseline Climate		**Baseline + 1.5°C**	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	84	T3	62	T1/2
T-mean < 20°C	36	T3	0	T1/2
T-min < 17.5°C	103	T3	79	T2
T-min < 15°C	70	T3	37	T1/2

Chandpur T3 - T2

	Baseline Climate		**Baseline + 1.5°C**	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	87	T3	57	<T1
T-mean < 20°C	40	T3	0	<T1
T-min < 17.5°C	94	T3	71	T1/2
T-min < 15°C	58	T3	21	<T1

Khulna T2 - T1

	Baseline Climate		**Baseline + 1.5°C**	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	0	T1	0	-
T-mean < 20°C	60	T1/2	40	<T1
T-min < 17.5°C	85	T2	58	T1
T-min < 15°C	37	<T1	0	T1

Sandwip T1 - T1

	Baseline Climate		**Baseline + 1.5°C**	
	Frequency (days)	Thermal Zone	Frequency (days)	Thermal Zone
T-mean < 22.5°C	68	T1/2	37	<T1
T-mean < 20°C	-	-	-	-
T-min < 17.5°C	68	T1	40	<T1
T-min < 15°C	16	<T1	0	<T1

Appendix A4

Soil Suitability Classification Procedure

A4.1 Introduction

The following section details how the 'soil' suitability classification was performed using to the FAO methodology (1988), the reader is referred to Chapter 8II to address the areas not detailed here.

To demonstrate the methodology, the randomly chosen soil association unit **BN179** is used in conjunction with the corresponding soil attributes taken from the SODAPS database (discussed in Section 6.7.1). As mentioned in Chapter 6 the database attributes were labelled in a different manner to those used in the FAO methodology and thus had to be converted between the two formats.

The soils classification consists of three suitability sub-divisions (agro-inundation, edaphic and landform). Within each, the FAO considered that the following 11 **land factors** were critical for the soil suitability. The column containing the appropriate figure is indicated and can be compared to Figure 6.9 in Section 6.7.1.

Table A4.1 The 11 Critical Land Factors According To the FAO Methodology

FAO Land Factor	SODAPS Database Column
Agro-inundation suitability	
i - depth of inundation	v
f - flood hazard	w
Agro-edaphic suitability	
d - effective soil depth	j
m - available soil moisture holding capacity	l
p - permeability	m
w - drainage	n
t - topsoil consistence and bearing capacity	o
a - soil reaction	p
n - nutrient availability	q
s - soil salinity	r
Agro-landform suitability	
e - slope	g

A4.2 The FAO Land Factor Ratings

For every soil association unit, each of the 11 land factors were classified using a land factor rating, the FAO rating system was as follows (FAO,1988: Report 6):

Table A4.2 The FAO Land Factor Rating System

		Land factor rating
(i)	Depth of inundation (cms)	Land factor rating
	no inundation	i1
	very shallow inundation (<30)	i2
	shallow inundation (30-90)	i3
	moderately deep inundation (90-180)	i4
	deep inundation (180-300)	i5
	very deep inundation (>300)	i6
(f)	Flood hazard (%)	Land factor rating
	no flood, river erosion or storm hazard (<2%)	f1
	slight flood, river erosion or storm hazard (2-6%)	f2
	moderate flood, river erosion or storm surge hazard (6-20%)	f3
	severe flood, river erosion or storm surge hazard (20-50%)	f4
	very severe flood, river erosion or storm surge hazard (>50%)	f5
(d)	Effective soil depth (cms)	Land factor rating
	deep and friable soil (>122)	d1
	deep and firm soil (90-122)	d2
	deep and very firm soil (60-90)	d3
	shallow soil (25-60)	d4
	very shallow soil (<25)	d5
(m)	Available soil moisture holding capacity (mm)	Land factor rating
	very high (>400)	m1
	high (300-400)	m2
	moderate (200-300)	m3
	low (100-200)	m4
	very low (<100)	m5
(p)	permeability (cm/day)	Land factor rating
	rapidly permeable soil (>305)	p1
	moderately permeable (12-305)	p2
	slowly permeable (<12)	p3
(w)	Drainage	Land Factor rating
	well to excessively drained soil	w1
	moderately well drained	w2
	imperfectly drained	w3
	early to normal draining, poorly drained, surface drained before mid-November	w4
	slow draining, poorly drained, surface drained after mid-November	w5
	very poorly drained	w6

(t) Topsoil consistence and bearing capacity

	Land factor rating
soil without tillage problems	t1
soil with moderate tillage problems	t2
soil with serious tillage problems	t3
organic soil	t4

(a) Soil reaction (pH)

	Land factor rating
medium acid to neutral soil (<4.5)	a1
mildly to moderately alkaline soil (4.5-5.5)	a2
very strongly acid to strongly acid soil (5.6-7.3)	a3
extremely acid soil (7.4-8.4)	a4
strongly to very strongly alkaline soil (>8.4)	a5

(n) Nutrient availability

	Land factor rating
relatively infertile	n1
relatively fertile	n2

(s) Soil salinity (mmhos/cm)

	Land factor rating
non-saline soil (<2)	s1
very weakly saline soil (2-4)	s2
weakly saline soil (4-8)	s3
moderately saline soil (8-15)	s4
strongly saline soil >15	s5

(e) Slope (%)

	Land factor rating
level and nearly level (<3%)	e1
gently sloping and undulating (3-8%)	e2
sloping and rolling (8-16%)	e3
moderately steep and hilly (16-30%)	e4
steep (30-45%)	e5
very steep (>45%)	e6

Reference to Appendix A1 provides the legend to the SODAPS database, those items marked with an * are classes that do not correspond exactly to the FAO classification system. The procedure used to resolve this inconsistency is explained below.

Having identified the range of alternative land factor values for each soil unit and the appropriate columns within the database, it was possible to take the example figures from the database to provide the land factor ratings. Using the soil association figure BN179, the following land factor ratings were identified from the database:

Table A4.3 Example Land Factor Values For Soil Association BN179

Land Factor	Database Column & Value
Agro-inundation suitability	
i - depth of inundation	**V** 3
f - flood hazard	**Z** 1
Agro-edaphic suitability	
d - effective soil depth	**J** 4
m - available soil moisture holding capacity	**L** 2
p - permeability	**M** 3
w - drainage	**N** 4
t - topsoil consistence & bearing capacity	**O** 1
a - soil reaction	**P** 2
n - nutrient availability	**Q** 1
s - soil salinity	**R** 1
Agro-landform suitability	
e - slope	**G** 1

As mentioned above, certain values from the database required conversion to the suitability ratings format used in the FAO methodology. This conversion procedure will be demonstrated using a worked example:
Taking the available moisture holding capacity as an example, which corresponds to **m** in the FAO methodology and column **L** in the SODAPS database, the corresponding

database value was: 2. Reference to the SODAPS database legend (Appendix A1) indicated that this represented 100-200 mm a 'low' moisture holding capacity. Reference to the FAO land factors in Table A4.3 above, indicated that a value of 100-200 mm had an **m** value of 4.

The spreadsheet was refined however to further incorporate a conversion routine to generate the corresponding figures. Having converted the appropriate figures, the following values resulted:

Table A4.4 Land Factor Rating Figures From Both Schemes

Land Factor	Corresponding Data-base Column	SODAPS Database Value	Converted Rating Figure for Methodology
i	V	3	i3
f	Z	1	f1
d	J	4	d2
m	L	2	m4
p	M	3	p1
w	N	4	w4
t	O	1	t1
a	P	2	a3
n	Q	1	n1
s	R	1	s1
e	G	1	e1

As can be seen from the worked example, not all the land factor rating classes disagree with the FAO methodology. Table A4.5 below provides the two sets of values necessary for the conversion.

Table A4.5 Conversion Table Showing the FAO Methodology Land Factor Rating Associated with Each Database Value

Land Factors	Spreadsheet	FAO Methodology
Depth of Inundation	V1	i1
	V2	i2
	V3	i3
	V4	i4
	V5	i5
	V6	i6
Flood Hazard Frequency	Z1	f1
	Z2	f2
	Z3	f3
	Z4	f4
	Z5	f5
Effective Soil Depth *	J5	d1
	J4	d2
	J3	d3
	J2	d4
	J1	d5
Available Soil Moisture Holding Capacity *	L5	m1
	L4	m2
	L3	m3
	L2	m4
	L1	m5
Permeability *	M3	p1
	M2	p2
	M1	p3
Drainage	w1	N1
	w2	N2
	w3	N3
	w4	N4
	w5	N5
	w6	N6
Topsoil Consistence & Bearing Capacity	t1	O1
	t2	O2
	t3	O3
	t4	O4

Cont...

Land Factors	Spreadsheet	FAO Methodology
Soil Reaction *	a1	P3
	a2	P4
	a3	P2
	a4	P1
	a5	P5
Nutrient Availability	n1	Q1
	n2	Q2
Soil Salinity	s1	R1
	s2	R2
	s3	R3
	s4	R4
	s5	R5
Slope	e1	G1
	e2	G2
	e3	G3
	e4	G4
	e5	G5
	e6	G6

* Represents those Land Factors that do not have the same Rating Figures in both schemes & must therefore be converted.

Having established the correct land factor ratings, the next stage was to determine the degree of limitation that the various land factor ratings impose upon crop growth, the limitation ratings had to be determined therefore.

A4.3 Determination of the Limitation Ratings

Table 8.7 details the land factor limitation ratings for the classes for each of the rainfed crops and the 4 classes (0 to 4) used to define the limitation ratings. For rainfed wheat, the following limitation ratings were identified:

Table A4.6 **The Final Limitation Ratings for Rainfed Wheat with Soil Association BN179**

Rating Figure	Limitation Rating
i2	0
f1	0
d3	2
m2	0
p2	0
w4	1
t1	0
a1	0
n2	0
s1	0
e1	0

The final stage required conversion of the 11 limitation rating figures into a single suitability rating figure. The spreadsheet described in Section 8.6, undertook this process automatically and produced the soil suitability rating figure of S3.

Appendix A5

Pascal Program to Sum Yield Values for Individual Cells in the GIS

```
program new_modules;

var

  ref_units                                   : string[3];
  val_units,title,ref_system,flag_defn        : string[66];
  val_recs,rows,cols                          : longint;
  val_fields,val_file_type                    : byte;
  legend,data_format,geo_type                 : integer;
  old_data_type,old_file_type                 : integer;
  new_data_type,new_file_type                 : integer;
  wxmin,wxmax,wymin,wymax,unit_dist           : real;
  flag_value,resolution,cellx,celly           : real;
  posn_error,val_error,min,max                : real;
  posn_error_flag, resolution_flag,
   val_error_flag, flag_flag                  : boolean;
  legend_text                                 : array [0..255] of string[66];
  path                                        : string[40];
  digi_port,plot_port,prn_port                : string[4];
  drive,units                                 : string[2];
  old_image,new_image                         : string[8];
  image_docfile_extension                     : string[4];
  image_file_extension                        : string[4];
  vector_docfile_extension                    : string[4];
  vector_file_extension                       : string[4];
  values_docfile_extension                    : string[4];
  values_file_extension                       : string[4];
```

```
 datafile                                      : real;
   filename                                    : string[8];
   i,j                                         : integer; {loop counters}
   value,sum                                   : real;    {pixel value and total}

{*********************************************************************}
procedure create_new_documentation_file;

var
   docfile                                     : text;
   docname                                     : string[80];
   i                                           : integer;

begin

   docname:=drive+path+new_image+image_docfile_extension;
   assign(docfile,docname);
   rewrite(docfile);

 if ((new_data_type=0) and (new_file_type=1)) then new_data_type:=2;

 writeln (docfile,'file title                  : ',title);
 case new_data_type of
 0 : writeln (docfile,'data type               : integer');
 1 : writeln (docfile,'data type               : real');
 2 : writeln (docfile,'data type               : byte');
 end;

 case new_file_type of
 0 : writeln (docfile,'file type               : ascii');
 1 : writeln (docfile,'file type               : binary');
 2 : writeln (docfile,'file type               : packed binary');
 end;

 writeln (docfile,'columns                     : ',cols);
 writeln (docfile,'rows                        : ',rows);

 writeln (docfile,'ref. system                 : ',ref_system);
 writeln (docfile,'ref. units                  : ',ref_units);

 {*** note that both ref_system and ref_units MUST be in LOWER CASE ***}

writeln (docfile,'unit dist.                   : ',unit_dist:9:7);
writeln (docfile,'min. X                       : ',wxmin:9:7);
writeln (docfile,'max. X                       : ',wxmax:9:7);
writeln (docfile,'min. Y                       : ',wymin:9:7);
writeln (docfile,'max. Y                       : ',wymax:9:7);

if posn_error_flag then writeln (docfile,'pos'n error : ',posn_error:9:7)
            else writeln (docfile,'pos'n error : unknown');
if resolution_flag then writeln (docfile,'resolution  : ',resolution:9:7)
            else writeln (docfile,'resolution  : unknown');
if new_data_type=1 then writeln (docfile,'min. value  : ',min:9:7)
            else writeln (docfile,'min. value  : ',min:1:0);
if new_data_type=1 then writeln (docfile,'max. value  : ',max:9:7)
            else writeln (docfile,'max. value  : ',max:1:0);
if val_units='' then writeln (docfile,'value units : unspecified')
          else writeln (docfile,'value units : ',val_units);
{*** note that val_units MUST be in LOWER CASE ***}

write (docfile,'value error : ');
if not val_error_flag then writeln (docfile,'unknown') else writeln (docfile,val_error:9:7);
```

```
 write (docfile,'flag value  : ');
 if not flag_flag then writeln (docfile,'none') else
   begin
    if new_data_type=1 then writeln (docfile,flag_value:9:7)
                else writeln (docfile,flag_value:1:0);
   end;

 if flag_defn='' then writeln (docfile,'flag def'n  : none')
            else writeln (docfile,'flag def'n  : ',flag_defn);

 writeln (docfile,'legend cats : ',legend);
 if legend<>0 then begin
   if legend>255 then legend:=255;
   for i:=0 to (legend-1) do begin
     write(docfile,'category',i:3,' : ');
     writeln (docfile,legend_text[i]);
   end; {for}
   end;
 close(docfile);
end;

{**************************************************************************}
procedure read_documentation_file;

var
   docfile                                          : text;
   docname                                          : string[80];
   description                                      : string[14];
   i,err_code                                       : integer;
   tmpstr                                           : string[66];

begin

 docname:=drive+path+old_image+image_docfile_extension;
 assign (docfile,docname);
 reset (docfile);

 read (docfile, description); readln (docfile,title);
 read (docfile,description); readln (docfile,description);
 if description = 'integer'    then old_data_type:=0 else
 if description = 'real'       then old_data_type:=1 else
 if description = 'byte'       then old_data_type:=2 else
 if description = 'word'       then old_data_type:=3 else old_data_type:=999;

 if old_data_type>3 then begin
   writeln ('Error : The ',description,' data type is not supported by this module');
   halt;
   end;

 read (docfile,description); readln (docfile,description);
 if description = 'ascii'  then old_file_type:=0 else
 if description = 'binary' then old_file_type:=1 else
 if description = 'packed binary' then old_file_type:=1 else old_file_type:=999;

 if old_file_type>1 then begin
   writeln ('Error : The ',description,' file type is not supported by this module');
   halt;
   end;

 read (docfile,description);readln (docfile,cols);
 read (docfile,description);readln (docfile,rows);

 read (docfile,description);readln (docfile,ref_system);
```

```
read (docfile,description);readln (docfile,tmpstr);
 for i:=1 to length(tmpstr) do tmpstr[i]:=upcase(tmpstr[i]);
 if ((tmpstr='M') or (tmpstr='FT') or (tmpstr='MI')
 or (tmpstr='KM') or (tmpstr='DEG') or (tmpstr='RAD')) then ref_units:=tmpstr;

read (docfile,description);readln (docfile,unit_dist);
read (docfile,description);readln (docfile,wxmin);
read (docfile,description);readln (docfile,wxmax);
read (docfile,description);readln (docfile,wymin);
read (docfile,description);readln (docfile,wymax);
cellx:=(wxmax-wxmin)/cols;
celly:=(wymax-wymin)/rows;

read (docfile,description);readln (docfile,tmpstr);
 posn_error_flag:=false;posn_error:=0;
 for i:=length(tmpstr) downto 1 do if tmpstr[i]=' ' then delete(tmpstr,i,1);
 val(tmpstr,posn_error,err_code);
 if err_code=0 then posn_error_flag:=true;

read (docfile,description);readln (docfile,tmpstr);
 resolution_flag:=false;resolution:=0;
 for i:=length (tmpstr) downto 1 do if tmpstr[i]=' ' then delete (tmpstr,i,1);
 val (tmpstr,resolution,err_code);
 if err_code=0 then resolution_flag:=true;

read (docfile,description);readln (docfile,min);
read (docfile,description);readln (docfile,max);
read (docfile,description);readln (docfile,val_units);

read (docfile,description);readln (docfile,tmpstr);
 val_error_flag:=false;val_error:=0;
 for i:=length (tmpstr) downto 1 do if tmpstr[i]=' ' then delete (tmpstr,i,1);
 val (tmpstr,val_error,err_code);
 if err_code=0 then val_error_flag:=true;

read (docfile,description);readln (docfile,tmpstr);
 flag_flag:=false;flag_value:=0;
 for i:=length (tmpstr) downto 1 do if tmpstr[i]=' ' then delete (tmpstr,i,1);
 val (tmpstr,flag_value,err_code);
 if err_code=0 then flag_flag:=true;

read (docfile,description);readln (docfile,flag_defn);
read (docfile,description);readln (docfile,legend);

if legend<>0 then begin
 if legend>255 then legend:=255;
 for i:=0 to (legend-1) do begin read (docfile,description);
    readln (docfile,legend_text[i]);
    end;                                        {for}
 end;
close (docfile);
end;
{**************************************************************************}
procedure read_env_file;

var temp                                       : text;
  env_txt                                      : string[40];
  i                                            : integer;
begin
 path:='';drive:='';
 assign(temp,'idrisi.env'); {$I-} reset(temp); {$I-}

 readln (temp); readln (temp);
```

```
  read (temp,env_txt);readln (temp,drive);
  read (temp,env_txt);readln (temp,path);

  read (temp,env_txt);readln (temp,image_file_extension);
  read (temp,env_txt);readln (temp,image_docfile_extension);
  read (temp,env_txt);readln (temp,vector_file_extension);
  read (temp,env_txt);readln (temp,vector_docfile_extension);
  read (temp,env_txt);readln (temp,values_file_extension);
  read (temp,env_txt);readln (temp,values_docfile_extension);

  read (temp,env_txt);readln (temp,ref_units);
  read (temp,env_txt);readln (temp,digi_port);
  read (temp,env_txt);readln (temp,plot_port);
  read (temp,env_txt);readln (temp,pm_port);
  close(temp);

  if path='none' then path:='';
  if drive='no' then drive:='' else if (drive[2]<>':') then drive:='';

end;

{***************************************************************************}
begin
read_env_file;                                    {get the default file names etc}

writeln (,'This program takes an IDRISI image and totals all the pixel values');
writeln ('and outputs the total., it only takes one data type');
writeln ('    - real binary - so please convert your files to that format');

old_image:='holdit';

while old_image <> '' do
 begin
 writeln;
 writeln;
 write ('File to be totalised  ');
 readln (old_image);
 if old_image <> '' then
  begin
  read_documentation_file;                        {read all the info about the file}
  filename:=drive+path+old_image+image_docfile_extension;
  assign(datafile,filename);                      {the data file}
  reset(datafile);
  sum:=0;                                         {to hold the sum of data}
  for i:= 1 to rows do
   for j:= 1 to cols do
    begin
    read (datafile,value);
    sum:=sum+value;
    end;
  writeln ('The sum of elements is ',sum:10:4);
  end;                                            {ends the if}
 end;                                             {ends the while loop}
writeln ('The program has finished press return to continue');
readln;
  {main program goes here}
end.
```

Appendix A6

Results

The following section presents the results for the project. The discussion accompanying these results is presented in Chapter 9. To aid interpretation, the reader is reminded of the various suitability classes used:

The thermal, growing period and soil suitabilities adopt the following classes:

S1	where requirements are fully met, no or only slight constraints resulting in no significant yield loss
S2	sub-optimal, moderate constraints, resulting in yield losses of the order of 20%
S3	sub-optimal, severe constraints, resulting in yield losses of the order of 40%
S4	sub-optimal, very severe constraints, resulting in yield losses of the order of 60%, and
NS	unsuitable, extremely severe constraints, yield suppression would be 80% or more.

For the agro-climatic suitability and the land evaluation, the following classes apply:

VS	*very suitable*, crop yield is 80% or more of the maximum attainable
S	*suitable*, yield is 60 to 80% of the maximum attainable
MS	*moderately suitable*, yields of 40 to less than 60%
ms	*marginally suitable*, yield of 20 to less than 40%
NS	*unsuitable*, yields of less than 20%

Table A6.1 Unconstrained Yield Figures (t/ha) at Each Climate Station Before the Climate Change Scenario (1988 Baseline)

	Sites												
Crop & Input Level	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**
Wheat High Input	3.43	3.38	3.43	3.39	3.37	3.36	3.40	3.33	3.43	3.51	3.53	3.25	3.31
Wheat Low Input	1.74	1.72	1.74	1.72	1.71	1.71	1.72	1.69	1.74	1.78	1.79	1.65	1.68
White Potato High Input	4.39	4.32	4.38	4.34	4.30	4.30	4.34	4.26	4.38	4.49	4.52	4.16	4.23
White Potato Low Input	1.67	1.65	1.67	1.65	1.64	1.64	1.65	1.62	1.67	1.71	1.72	1.58	1.61
Mustard High Input	1.28	1.26	1.28	1.26	1.25	1.25	1.26	1.24	1.27	1.31	1.32	1.21	1.23
Mustard Low Input	0.59	0.58	0.59	0.58	0.58	0.58	0.58	0.57	0.59	0.60	0.61	0.56	0.57
Lentil High Input	1.80	1.77	1.81	1.77	1.75	1.74	1.77	1.72	1.80	1.87	1.87	1.68	1.70
Lentil Low Input	0.92	0.91	0.93	0.91	0.89	0.89	0.91	0.88	0.92	0.96	0.96	0.86	0.87
Local Boro Low Input	2.94	2.93	2.87	2.96	2.97	2.97	2.98	3.01	2.90	2.92	2.92	2.95	2.96
HYV Boro (Quick) High Input	5.04	5.01	4.91	5.07	5.08	5.08	5.09	5.15	4.96	4.99	4.99	5.05	5.06
HYV Boro (Late) High Input	5.61	5.58	5.47	5.65	5.65	5.65	5.68	5.74	5.53	5.57	5.57	5.62	5.63
Local B.Aus Low Input	1.52	1.53	1.62	1.67	1.66	1.63	1.67	1.63	1.63	1.63	1.55	1.62	1.63
Local T. Aus Low Input	1.34	1.34	1.43	1.47	1.47	1.43	1.48	1.43	1.44	1.44	1.37	1.43	1.43
HYV T. Aus High Input	4.47	4.48	4.75	4.89	4.89	4.77	4.92	4.77	4.78	4.78	4.56	4.75	4.78
Jute High Input	2.46	2.46	2.61	2.69	2.68	2.62	2.70	2.63	2.63	2.63	2.51	2.61	2.63
Jute Low Input	1.23	1.23	1.30	1.35	1.34	1.31	1.35	1.31	1.31	1.31	1.25	1.31	1.31
Local T. Aman Low Input	1.81	1.79	1.76	1.82	1.82	1.82	1.83	1.85	1.78	1.79	1.79	1.81	1.81
HYV T. Aman High Input	4.54	4.51	4.42	4.57	4.58	4.58	4.59	4.65	4.47	4.50	4.49	4.55	4.56

	Sites												
Crop & Input Level	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**
Wheat High Input	3.47	3.32	3.16	3.45	3.10	3.42	3.27	3.10	3.45	3.40	3.25	3.51	3.58
Wheat Low Input	1.76	1.69	1.61	1.75	1.57	1.73	1.66	1.57	1.75	1.73	1.65	1.78	1.82
White Potato High Input	4.44	4.24	4.40	4.41	3.97	4.37	4.18	3.96	4.41	4.34	4.16	4.49	4.57
White Potato Low Input	1.69	1.62	1.54	1.68	1.51	1.66	1.59	1.51	1.68	1.65	1.58	1.71	1.74
Mustard High Input	1.29	1.24	1.18	1.28	1.16	1.27	1.22	1.15	1.29	1.27	1.21	1.31	1.33
Mustard Low Input	0.60	0.57	0.54	0.59	0.53	0.59	0.56	0.53	0.59	0.58	0.56	0.60	0.61
Lentil High Input	1.84	1.74	1.63	1.82	1.60	1.80	1.69	1.64	1.84	1.79	1.69	1.86	1.89
Lentil Low Input	0.94	0.89	0.83	0.93	0.82	0.92	0.87	0.84	0.94	0.92	0.87	0.95	0.97
Local Boro Low Input	2.89	2.85	2.92	2.87	2.89	2.94	2.90	2.87	2.89	2.87	2.87	2.91	3.00
HYV Boro (Quick) High Input	4.94	4.88	4.99	4.91	4.94	5.03	4.96	4.90	4.94	4.91	4.91	4.98	5.13
HYV Boro (Late) High Input	5.51	5.44	5.56	5.48	5.50	5.61	5.52	5.47	5.52	5.48	5.47	5.56	5.72
Local B.Aus Low Input	1.63	1.57	1.61	1.63	1.61	1.62	1.51	1.68	1.64	1.56	1.52	1.56	1.65
Local T. Aus Low Input	1.43	1.39	1.42	1.44	1.42	1.43	1.33	1.48	1.45	1.37	1.34	1.38	1.45
HYV T. Aus High Input	4.78	4.62	4.71	4.79	4.74	4.75	4.44	4.93	4.83	4.58	4.45	4.59	4.84
Jute High Input	2.63	2.54	2.59	2.63	2.60	2.61	2.44	2.71	2.66	2.51	2.45	2.52	2.66
Jute Low Input	1.31	1.27	1.29	1.32	1.30	1.31	1.22	1.35	1.33	1.26	1.22	1.26	1.33
Local T. Aman Low Input	1.77	1.75	1.79	1.76	1.77	1.80	1.78	1.76	1.78	1.76	1.76	1.79	1.84
HYV T. Aman High Input	4.44	4.40	4.50	4.42	4.46	4.53	4.47	4.42	4.45	4.42	4.42	4.48	4.62

Table A6.2 Unconstrained Yield Figures (t/ha) at Each Climate Station After the Climate Change Scenario (1988 Baseline)

Crop & Input Level	Sites 1	2	3	4	5	6	7	8	9	10	11	12	13
Wheat High Input	3.11	3.01	3.16	3.01	2.96	2.93	3.00	2.83	3.13	3.24	3.26	2.75	2.85
Wheat Low Input	1.58	1.53	1.60	1.53	1.50	1.49	1.52	1.44	1.59	1.65	1.66	1.39	1.45
White Potato High Input	3.97	3.85	4.04	3.85	3.78	3.75	3.84	3.62	4.01	4.14	4.17	3.52	3.64
White Potato Low Input	1.51	1.47	1.54	1.47	1.44	1.43	1.46	1.38	1.53	1.58	1.59	1.34	1.39
Mustard High Input	1.16	1.12	1.18	1.12	1.10	1.09	1.12	1.05	1.17	1.23	1.22	1.02	1.06
Mustard Low Input	0.53	0.52	0.54	0.52	0.51	0.50	0.52	0.49	0.54	0.57	0.56	0.47	0.49
Lentil High Input	1.65	1.54	1.63	1.54	1.50	1.49	1.53	1.43	1.61	1.68	1.69	1.39	1.43
Lentil Low Input	0.85	0.79	0.84	0.79	0.77	0.76	0.79	0.73	0.82	0.86	0.86	0.71	0.73
Local Boro Low Input	3.00	3.00	2.95	3.04	3.04	3.03	3.05	3.07	2.98	3.01	3.00	3.00	3.02
HYV Boro (Quick) High Input	5.13	5.13	5.05	5.19	5.19	5.19	5.22	5.25	5.10	5.15	5.13	5.14	5.16
HYV Boro (Late) High Input	5.71	5.71	5.62	5.78	5.77	5.77	5.80	5.84	5.67	5.73	5.72	5.71	5.73
Local B.Aus Low Input	1.45	1.45	1.54	1.59	1.58	1.55	1.59	1.55	1.55	1.55	1.48	1.54	1.55
Local T. Aus Low Input	1.28	1.28	1.36	1.40	1.40	1.37	1.41	1.37	1.37	1.37	1.31	1.36	1.37
HYV T. Aus High Input	4.26	4.27	4.52	4.65	4.64	4.54	4.67	4.54	4.55	4.55	4.34	4.52	4.54
Jute High Input	2.34	2.34	2.48	2.55	2.55	2.49	2.57	2.50	2.49	2.50	2.38	2.48	2.49
Jute Low Input	1.17	1.17	1.24	1.28	1.27	1.25	1.28	1.25	1.25	1.25	1.19	1.24	1.25
Local T. Aman Low Input	1.84	1.84	1.81	1.86	1.86	1.86	1.87	1.88	1.83	1.85	1.84	1.84	1.85
HYV T. Aman High Input	4.63	4.63	4.56	4.69	4.69	4.69	4.71	4.74	4.60	4.64	4.63	4.64	4.66

Crop & Input Level	Sites 14	15	16	17	18	19	20	21	22	23	24	25	26
Wheat High Input	3.20	2.97	2.61	3.18	2.53	3.09	2.83	2.55	3.19	3.12	2.82	3.24	3.30
Wheat Low Input	1.63	1.51	1.32	1.62	1.29	1.57	1.43	1.29	1.62	1.58	1.43	1.65	1.67
White Potato High Input	4.10	3.80	3.34	4.07	3.24	3.95	3.62	3.26	4.07	3.99	3.61	4.14	4.21
White Potato Low Input	1.56	1.45	1.27	1.55	1.23	1.50	1.38	1.24	1.55	1.52	1.37	1.58	1.60
Mustard High Input	1.19	1.11	0.97	1.19	0.94	1.15	1.05	0.95	1.19	1.16	1.05	1.21	1.23
Mustard Low Input	0.55	0.51	0.45	0.55	0.44	0.53	0.49	0.44	0.55	0.54	0.48	0.56	0.57
Lentil High Input	1.66	1.53	1.31	1.64	1.27	1.59	1.43	1.31	1.66	1.61	1.44	1.68	1.70
Lentil Low Input	0.85	0.78	0.67	0.84	0.65	0.81	0.73	0.67	0.85	0.82	0.73	0.86	0.87
Local Boro Low Input	2.97	2.92	2.97	2.95	2.93	3.02	2.96	2.91	2.98	2.95	2.93	3.00	3.09
HYV Boro (Quick) High Input	5.05	5.00	5.07	5.05	5.02	5.16	5.06	4.98	5.09	5.05	5.01	5.13	5.28
HYV Boro (Late) High Input	5.63	5.57	5.63	5.62	5.57	5.75	5.62	5.54	5.67	5.62	5.57	5.71	5.88
Local B.Aus Low Input	1.55	1.50	1.53	1.55	1.54	1.54	1.44	1.60	1.57	1.48	1.45	1.49	1.57
Local T. Aus Low Input	1.37	1.32	1.35	1.37	1.36	1.36	1.27	1.41	1.38	1.31	1.28	1.31	1.38
HYV T. Aus High Input	4.55	4.40	4.48	4.56	4.51	4.52	4.23	4.69	4.59	4.36	4.24	4.37	5.06
Jute High Input	2.50	2.41	2.46	2.50	2.47	2.48	2.32	2.57	2.52	2.39	2.33	2.40	2.53
Jute Low Input	1.25	1.21	1.23	1.25	1.24	1.24	1.16	1.29	1.26	1.19	1.16	1.20	1.27
Local T. Aman Low Input	1.81	1.79	1.82	1.80	1.80	1.85	1.81	1.78	1.83	1.81	1.80	1.84	1.90
HYV T. Aman High Input	4.56	4.51	4.58	4.53	4.53	4.66	4.57	4.49	4.59	4.56	4.52	4.62	4.76

Table A6.3 Percentage Change in Crop Productivity at Each Site

Sites

Crop & Input Level	1	2	3	4	5	6	7	8	9	10	11	12	13
Wheat High Input	-9.3	-10.9	-7.9	-11.2	-12.2	-12.8	-11.8	-15.0	-8.7	-7.7	-7.6	-15.4	-13.9
Wheat Low Input	-9.2	-11.0	-8.0	-11.0	-12.3	-12.9	-11.6	-14.8	-8.6	-7.3	-7.3	-15.8	-13.7
White Potato High Input	-9.6	-10.9	-7.8	-11.3	-12.1	-12.8	-11.5	-15.0	-8.4	-7.8	-7.7	-15.4	-13.9
White Potato Low Input	-9.6	-10.9	-7.8	-10.9	-12.2	-12.8	-11.5	-14.8	-8.4	-7.6	-7.6	-15.2	-13.7
Mustard High Input	-9.4	-11.1	-7.8	-11.1	-12.0	-12.8	-11.1	-15.3	-7.9	-6.1	-7.6	-15.7	-13.8
Mustard Low Input	-10.2	-10.3	-8.5	-10.3	-12.1	-13.8	-10.3	-14.0	-8.5	-5.0	-8.2	-16.1	-14.0
Lentil High Input	-8.3	-13.0	-9.9	-13.0	-14.3	-14.4	-13.6	-16.9	-10.6	-10.2	-9.6	-17.3	-15.9
Lentil Low Input	-7.6	-13.2	-9.7	-13.2	-13.5	-14.6	-13.2	-17.0	-10.9	-10.4	-10.4	-17.4	-16.1
Local Boro Low Input	2.0	2.4	2.8	2.7	2.4	2.0	2.3	2.0	2.8	3.1	2.7	1.7	2.0
HYV Boro (Quick) High Input	1.8	2.4	2.9	2.4	2.2	2.2	2.6	1.9	2.8	3.2	2.8	1.8	2.0
HYV Boro (Late) High Input	1.8	2.3	2.7	2.3	2.1	2.1	2.1	1.7	2.5	2.9	2.7	1.6	1.8
Local B.Aus Low Input	-4.6	-5.2	-4.9	-4.8	-4.8	-4.9	-4.8	-4.9	-4.9	-4.9	-4.5	-4.9	-4.9
Local T. Aus Low Input	-4.5	-4.5	-4.9	-4.8	-4.8	-4.2	-4.7	-4.2	-4.9	-4.9	-4.4	-4.9	-4.2
HYV T. Aus High Input	-4.7	-4.7	-4.8	-4.9	-5.1	-4.8	-5.1	-4.8	-4.8	-4.8	-4.8	-4.8	-5.0
Jute High Input	-4.9	-4.9	-5.0	-5.2	-4.9	-5.0	-4.8	-4.9	-5.3	-4.9	-5.2	-5.0	-5.3
Jute Low Input	-4.9	-4.9	-4.6	-5.2	-5.2	-4.6	-5.2	-4.6	-4.6	-4.6	-4.8	-5.3	-4.6
Local T. Aman Low Input	1.7	2.8	2.8	2.2	2.2	2.2	2.2	1.6	2.8	3.4	2.8	1.7	2.2
HYV T. Aman High Input	2.0	2.7	3.2	2.6	2.4	2.4	2.6	1.9	2.9	3.1	3.1	2.0	2.2

Sites

Crop & Input Level	14	15	16	17	18	19	20	21	22	23	24	25	26
Wheat High Input	-7.8	-10.5	-17.4	-7.8	-18.4	-9.6	-13.5	-17.7	-7.5	-8.2	-13.2	-7.7	-7.8
Wheat Low Input	-7.4	-10.7	-18.0	-7.4	-17.8	-9.2	-13.9	-17.8	-7.4	-8.7	-13.3	-7.3	-8.2
White Potato High Input	-7.7	-10.4	-24.1	-7.7	-18.4	-9.6	-13.4	-17.7	-7.7	-8.1	-13.2	-7.8	-7.9
White Potato Low Input	-7.7	-10.5	-17.5	-7.7	-18.5	-9.6	-13.2	-17.9	-7.7	-7.9	-13.3	-7.6	-8.0
Mustard High Input	-7.8	-10.5	-17.8	-7.0	-19.0	-9.4	-13.9	-17.4	-7.8	-8.7	-13.2	-7.6	-7.5
Mustard Low Input	-8.3	-10.5	-16.7	-6.8	-17.0	-10.2	-12.5	-17.0	-6.8	-6.9	-14.3	-6.7	-6.6
Lentil High Input	-9.8	-12.1	-19.6	-9.9	-20.6	-11.7	-15.4	-20.1	-9.8	-10.1	-14.8	-9.7	-10.1
Lentil Low Input	-9.6	-12.4	-19.3	-9.7	-20.7	-12.0	-16.1	-20.2	-9.6	-10.9	-16.1	-9.5	-10.3
Local Boro Low Input	2.8	2.5	1.7	2.8	1.4	2.7	2.1	1.4	3.1	2.8	2.1	3.1	3.0
HYV Boro (Quick) High Input	2.2	2.5	1.6	2.9	1.6	2.6	2.0	1.6	3.0	2.9	2.0	3.0	2.9
HYV Boro (Late) High Input	2.2	2.4	1.3	2.6	1.3	2.5	1.8	1.3	2.7	2.6	1.8	2.7	2.8
Local B.Aus Low Input	-4.9	-4.5	-5.0	-4.9	-4.3	-4.9	-4.6	-4.8	-4.3	-5.1	-4.6	-4.5	-4.8
Local T. Aus Low Input	-4.2	-5.0	-4.9	-4.9	-4.2	-4.9	-4.5	-4.7	-4.8	-4.4	-4.5	-5.1	-4.8
HYV T. Aus High Input	-4.8	-4.8	-4.9	-4.8	-4.9	-4.8	-4.7	-4.9	-5.0	-4.8	-4.7	-4.8	4.5
Jute High Input	-4.9	-5.1	-5.0	-4.9	-5.0	-5.0	-4.9	-5.2	-5.3	-4.8	-4.9	-4.8	-4.9
Jute Low Input	-4.6	-4.7	-4.7	-5.3	-4.6	-5.3	-4.9	-4.4	-5.3	-5.6	-4.9	-4.8	-4.5
Local T. Aman Low Input	2.3	2.3	1.7	2.3	1.7	2.8	1.7	1.1	2.8	2.8	2.3	2.8	3.3
HYV T. Aman High Input	2.7	2.5	1.8	2.5	1.6	2.9	2.2	1.6	3.1	3.2	2.3	3.1	3.0

Table A6.4 Average Percentage Change in Crop Productivity at Each Site

Crop & Input Level	Yield Before (t/ha)	Yield After (t/ha)	Average % Change*
Wheat High Input	3.37	3.00	-11.2
Wheat Low Input	1.71	1.52	-11.2
White Potato High Input	4.32	3.83	-11.5
White Potato Low Input	1.64	1.46	-11.2
Mustard High Input	1.25	1.12	-11.1
Mustard Low Input	0.58	0.52	-10.8
Lentil High Input	1.76	1.54	-13.1
Lentil Low Input	0.90	0.79	-13.2
Local Boro Low Input	2.92	2.99	2.4
HYV Boro (Quick) High Input	5.00	5.11	2.4
HYV Boro (Late) High Input	5.57	5.69	2.2
Local B.Aus Low Input	1.61	1.53	-4.8
Local T. Aus Low Input	1.42	1.35	-4.6
HYV T. Aus High Input	4.72	4.51	-4.5
Jute High Input	2.59	2.46	-5.0
Jute Low Input	1.30	1.23	-4.9
Local T. Aman Low Input	1.79	1.83	2.3
HYV T. Aman High Input	4.50	4.62	2.5

* Based upon mean of percentage changes for each site in Table 6.3.

Table A6.5 Thermal Suitability Class Areas Before & After the Climate Change Scenario

In this table, the total land area of Bangladesh is taken as 140,000 km². This figure includes 12,500 km² corresponding to the missing area of map 10 (see Section 7.4.1) subsequently omitted from the soil suitability survey areas, in Tables A6.8 and A6.9.

Crop	Class	Area Before	Area After	Change
Wheat				
	S1	19.2%	1.7%	-17.5%
	S2	66.8%	54.3%	-12.5%
	S3	14.0%	44.0%	30.0%
Potato				
	S1	86.0%	56.0%	-30.0%
	S2	7.1%	30.0%	22.9%
	S3	6.9%	14.0%	7.1%
Mustard				
	S1	100%	100%	-
Lentil				
	S1	56.0%	19.2%	-36.8%
	S2	44.0%	80.8%	36.8%
Local Boro				
	S1	72.7%	90.5%	17.8%
	S2	27.3%	9.5%	-17.8%
HYV Boro Early	S1	44.0%	80.8%	36.8%
	S2	56.0%	19.2%	-36.8%
HYV Boro Late	S1	44.0%	80.9%	36.8%
	S2	56.0%	19.1%	-36.8%
B. Aus Paddy	S1	100%	100%	-
Local T Aus Paddy	S1	100%	100%	-

Cont...

Crop	Class	Area Before	Area After	Change
HYV T. Aus				
	S1	100%	100%	-
Jute (*Cap.*)				
	S1	100%	100%	-
Jute (*Olit.*)				
	S1	100%	100%	-
Local T. Aman				
	S1	100%	100%	-
HYV T. Aman Paddy	S1	100%	100%	-
HYV T. Aman Paddy after	S1	80.8%	98.3%	17.5%
HYV/l. T. Aus	S2	19.2%	1.7%	-17.5%

Figure A6.1 Thermal Suitability Map from the GIS - Before the Climate Change Scenario for Wheat

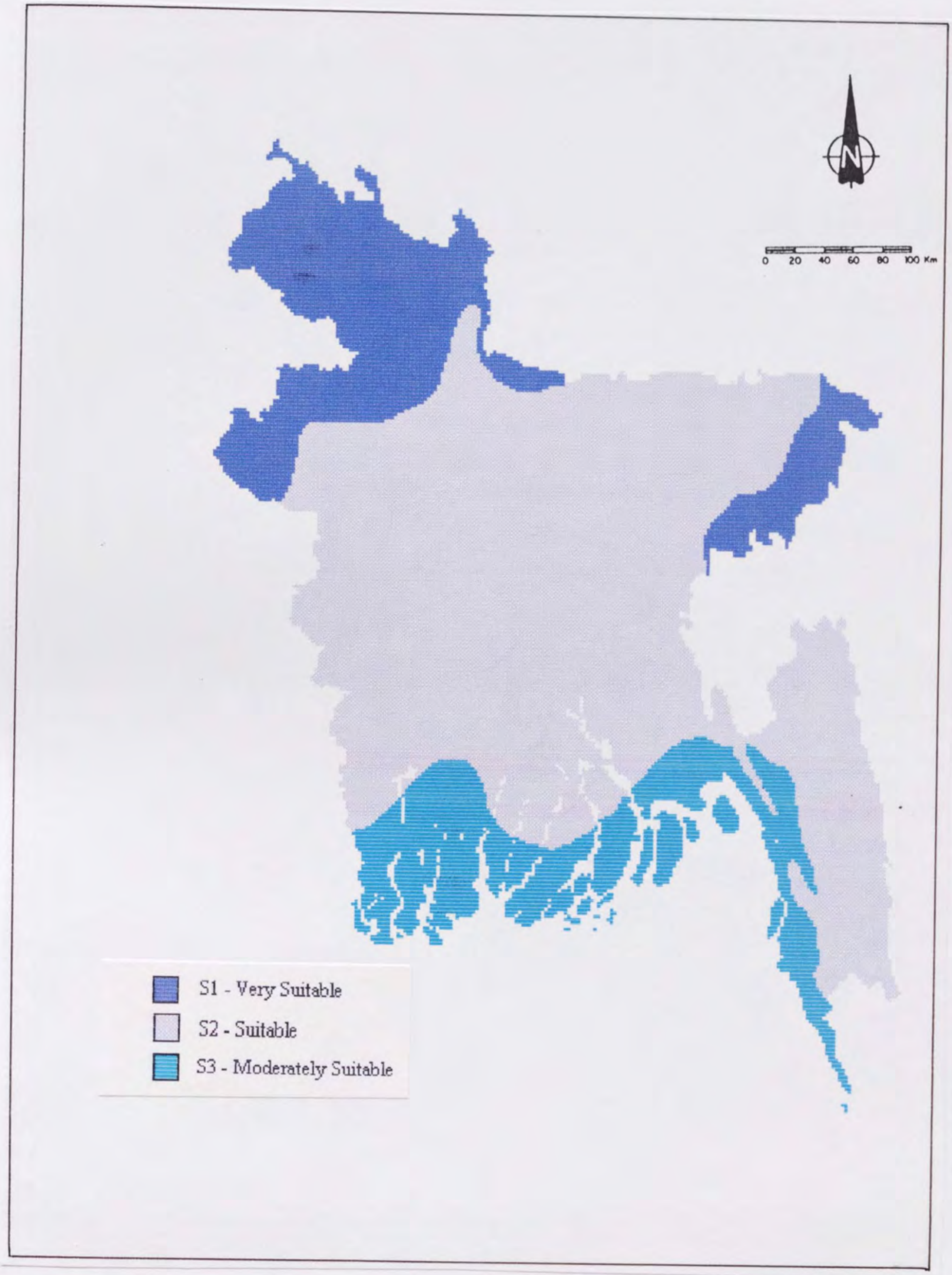

Figure A6.2 Thermal Suitability Map from the GIS - After the Climate Change Scenario for Wheat

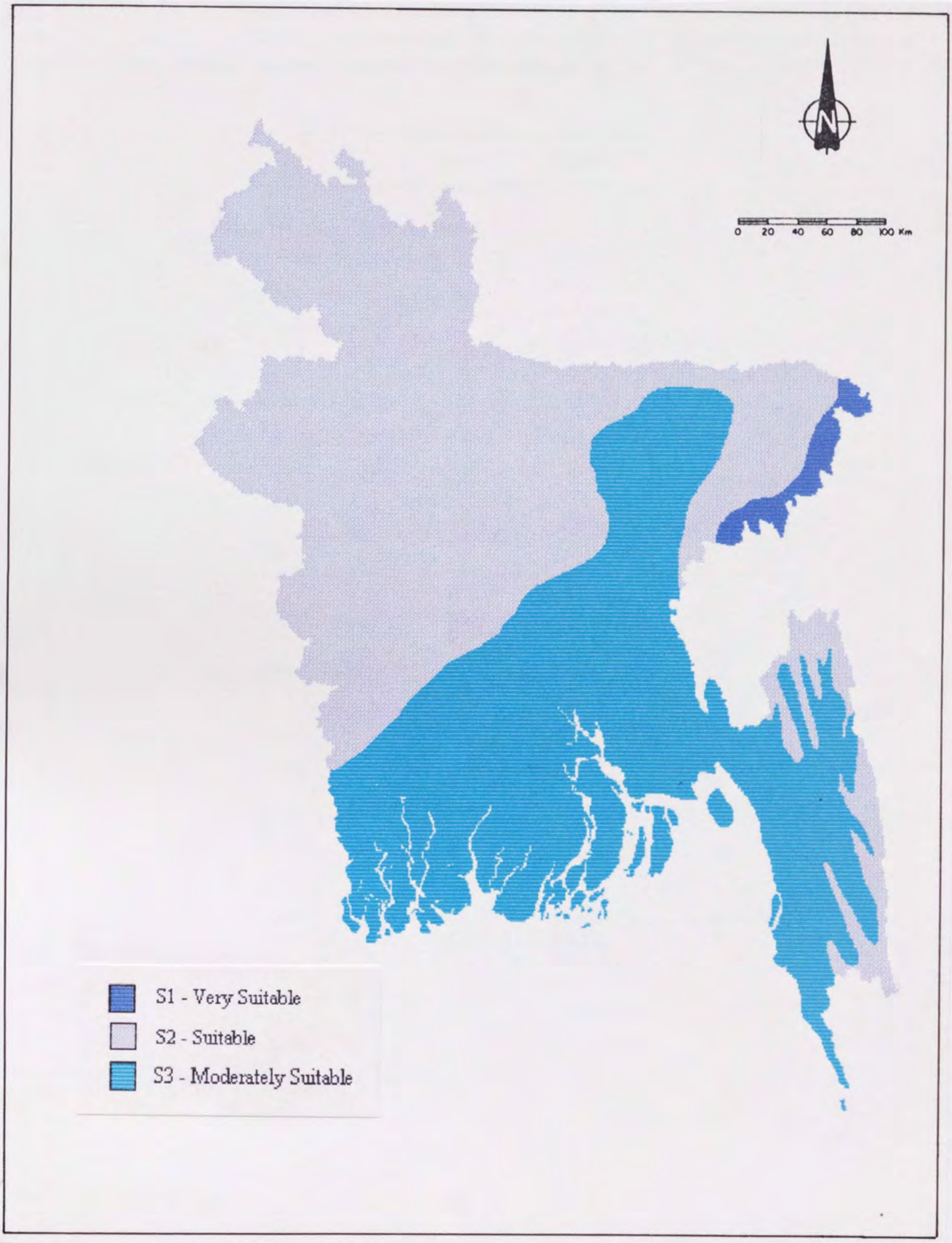

Table A6.6 Growing Period Suitability Class Areas

In this table the total land area is taken as 140,000 km². This figure includes 12,000 km² corresponding to the missing area of map 10 (see Section 7.4.1) subsequently omitted from the soil suitability survey areas, in Tables A6.8 and A6.9.

Crop	Class	% Area
Wheat		
	S2	67.0%
	S3	33.0%
Potato		
	S3	11.5%
	S4	84.7%
	NS	3.8%
Mustard		
	S1	14.0%
	S2	53.4%
	S3	32.6%
Lentil		
	S2	63.5%
	S3	36.5%
Local Boro		
	NS	100%
HYV Boro (Early)	NS	100%
HYV Boro (Late)	NS	100%
B. Aus Paddy	S2	62.9%
	S3	37.1%
Local T Aus Paddy	S2	44.9%
	S3	55.1%

Cont...

Crop	Class	% Area
HYV T. Aus		
	S2	35.0%
	S3	58.4%
	S4	6.6%
Jute (*Cap.*)		
	S2	53.5%
	S3	46.5%
Jute (*Olit.*)		
	S2	53.5%
	S3	46.5%
Local T. Aman		
	S2	51.2%
	S3	48.8%
HYV T. Aman Paddy	S2	51.2%
	S3	48.8%
HYV T. Aman Paddy after HYV/l. T. Aus	S3	26.0%
	S4	1.8%
	NS	72.2%

Figure A6.3 Growing Period Suitability Map from the GIS

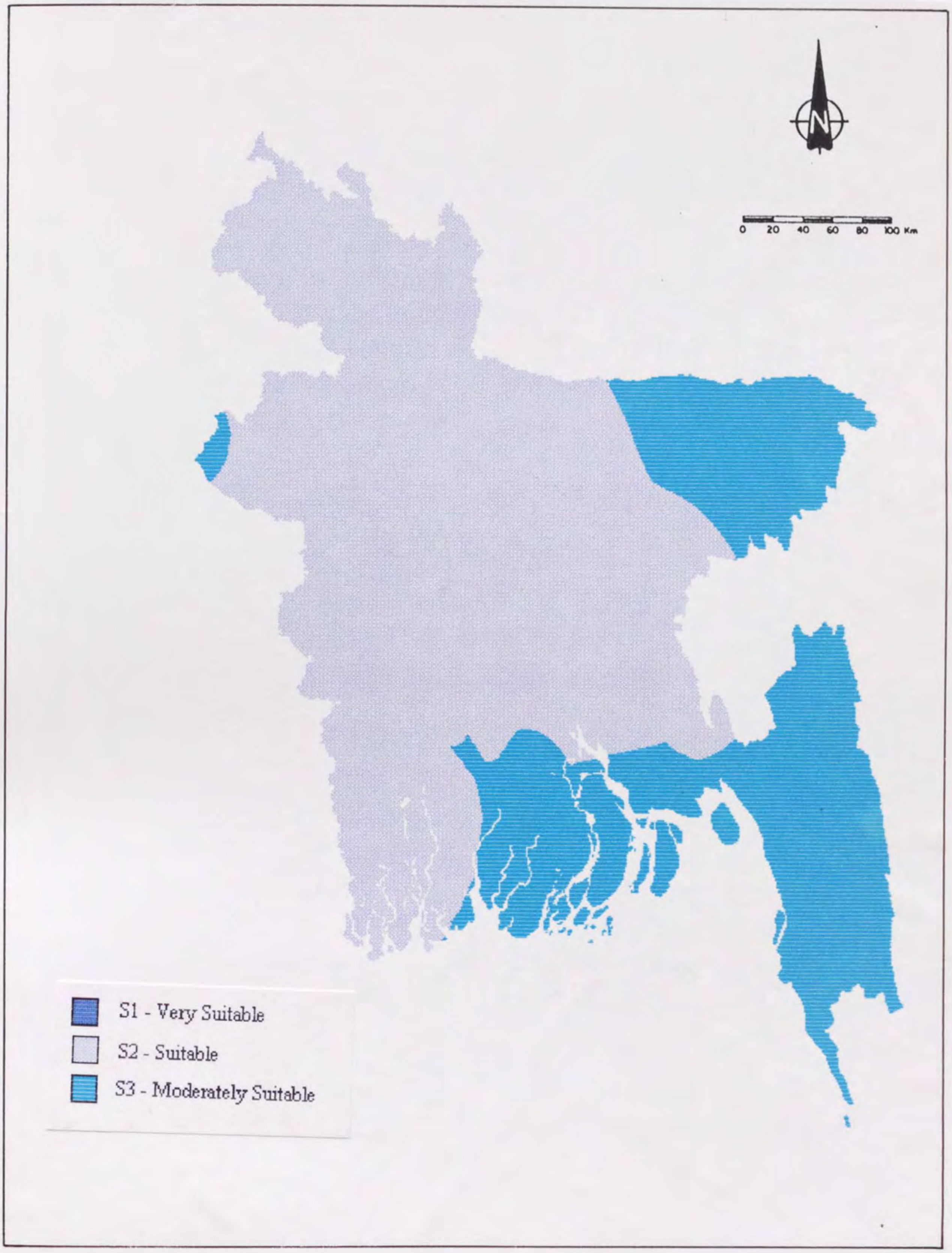

Table A6.7 Agro-climatic Suitability Class Areas Before & After the Climate Change Scenario

Crop	Class	Before	After	% Change
Wheat				
	S	15.7%	0.0%	-15.7%
	MS	49.4%	46.3%	-3.1%
	ms	34.9%	53.7%	18.8%
Potato				
	MS	11.5%	7.6%	-3.9%
	ms	77.8%	74.6%	-3.2%
	NS	10.7%	17.8%	7.1%
Mustard	VS	14.0%	14.0%	-
	S	53.4%	53.4%	-
	MS	32.6%	32.6%	-
Lentil	S	41.3%	12.9%	-28.4%
	MS	37.1%	56.8%	19.8%
	ms	21.7%	30.2%	8.6%
Local Boro	NS	100%	100%	-
HYV Boro Early	NS	100%	100%	-
HYV Boro Late	NS	100%	100%	-
B. Aus Paddy	S	62.9%	62.9%	-
	MS	37.1%	37.1%	-
Local T Aus Paddy	S	44.9%	44.9%	-
	MS	55.1%	55.1%	-

Cont...

Crop	Class	Before	After	% Change
HYV T. Aus	S	35.0%	35.0%	-
	MS	58.4%	58.4%	-
	ms	6.6%	6.6%	-
Jute (*Cap.*)	S	53.5%	53.5%	-
	MS	46.5%	46.5%	-
Jute (*Olit.*)	S	53.5%	53.5%	-
	MS	46.5%	46.5%	-
Local T. Aman	S	51.2%	51.2%	-
	MS	48.8%	48.8%	-
HYV T. Aman Paddy	S	51.2%	51.2%	-
	MS	48.8%	48.8%	-
HYV T. Aman Paddy after HYV/L T. Aus	MS	22.7%	24.4%	1.7%
	ms	5.1%	3.4%	-1.7%
	NS	72.2%	72.2%	0.0%

Figure A 6.4 Agro-climatic Suitability Map for Wheat from the GIS - Before the Climate Change Scenario

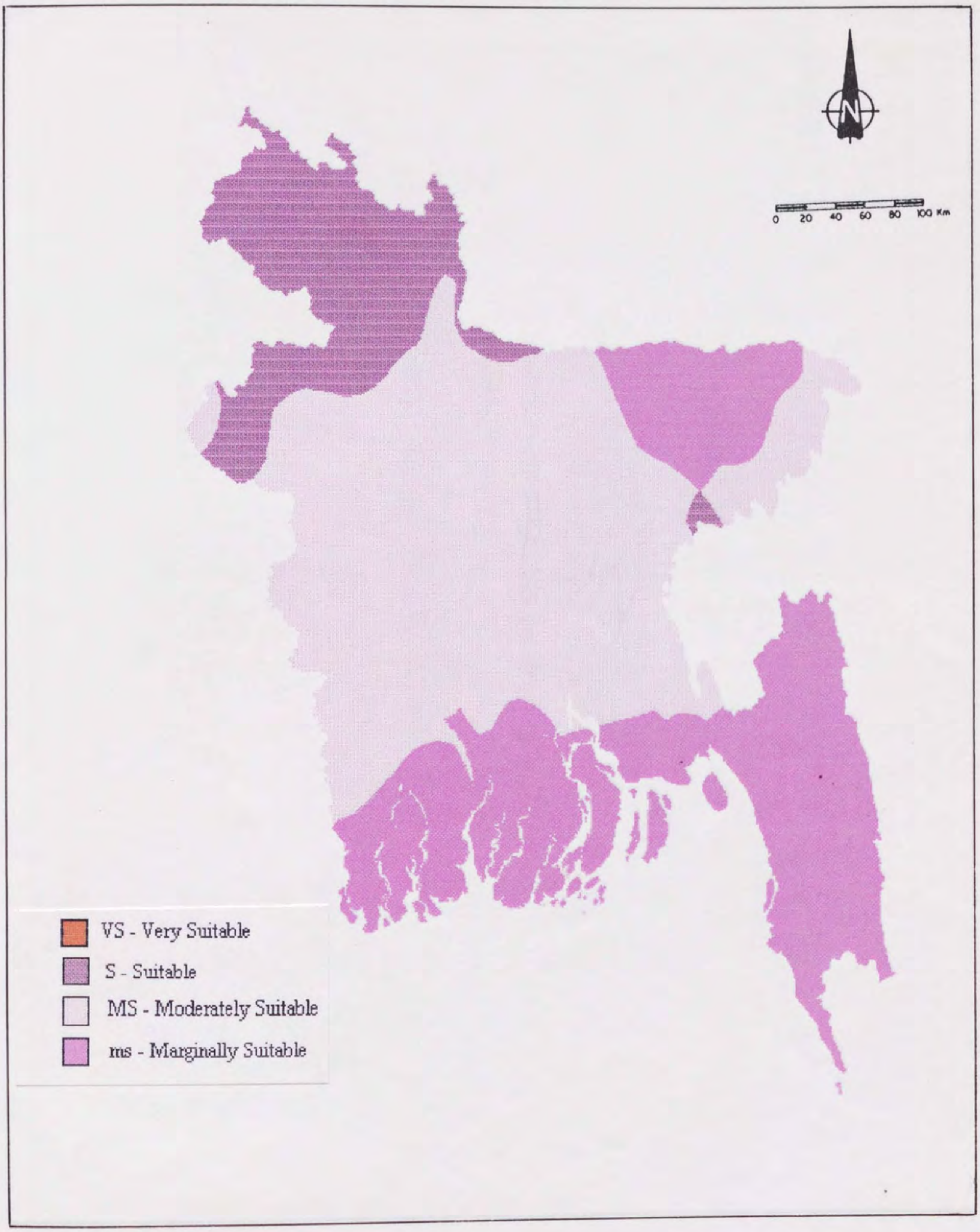

Figure A 6.5 Agro-climatic Suitability Map for Wheat from the GIS - <u>After</u> the Climate Change Scenario

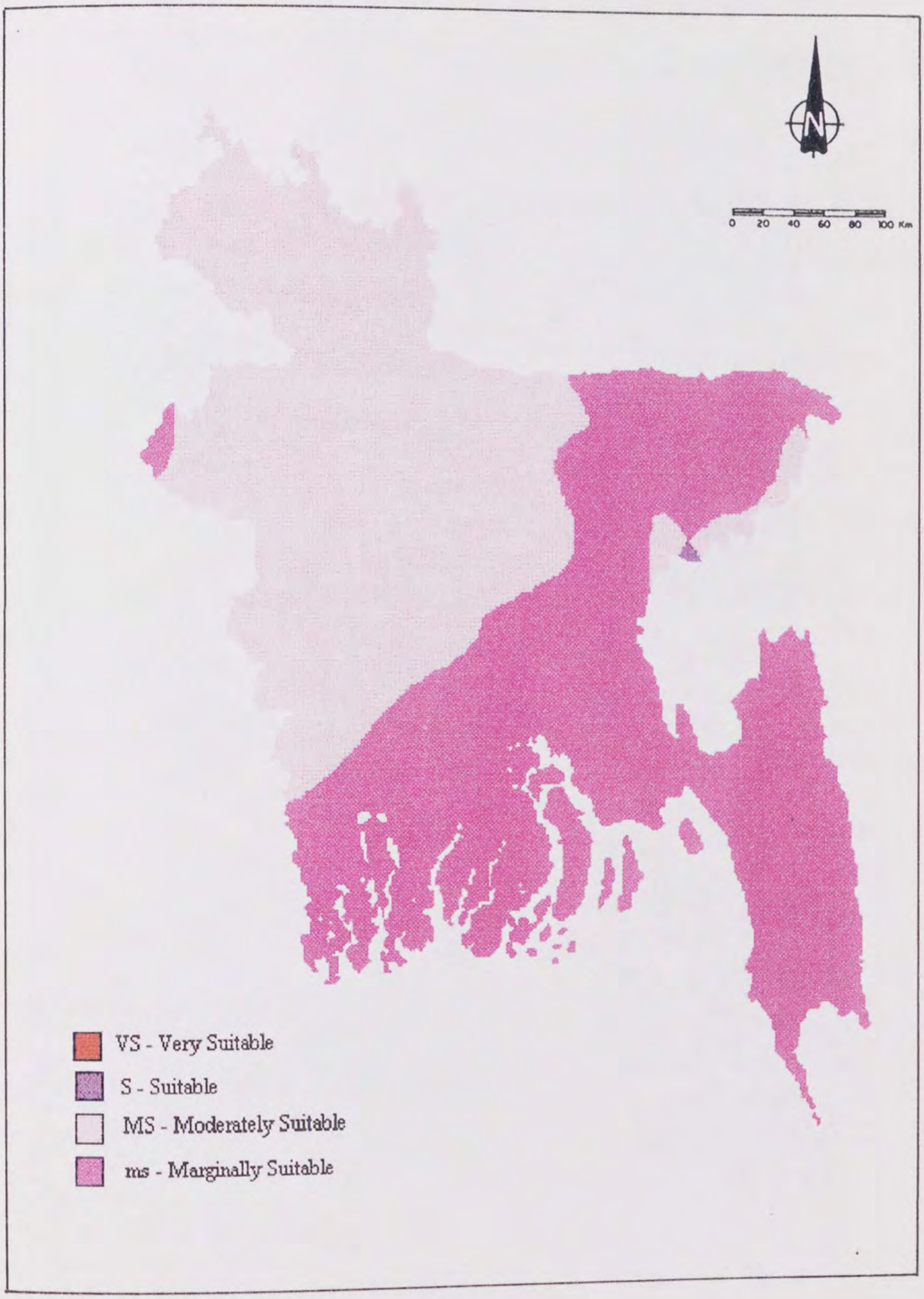

Table A 6.8 Soil Suitability Class Areas ('000' km²) Before & After the Climate Change Scenario

Region		NE				SE				SW				NW		
		Area	Area			Area	Area			Area	Area			Area	Area	
Crop		Before	After	Change		Before	After	Change		Before	After	Change		Before	After	Change
Wheat																
	S1	5.69	5.35	-0.99%	**S1**	1.57	1.57	0.00%	**S1**	5.89	5.46	-1.19%	**S1**	5.96	5.86	-0.29%
	S2	7.12	6.67	-1.30%	**S2**	1.34	1.20	-0.61%	**S2**	3.22	3.03	-0.53%	**S2**	14.95	14.41	-1.63%
	S3	10.57	8.79	-5.09%	**S3**	4.46	3.87	-2.55%	**S3**	8.22	7.82	-1.07%	**S3**	7.60	6.27	-4.01%
	S4	2.70	3.34	1.85%	**S4**	0.80	1.40	2.62%	**S4**	9.64	6.04	-9.78%	**S4**	2.51	3.38	2.60%
	NS	8.56	10.49	5.53%	**NS**	14.80	14.92	0.54%	**NS**	9.65	14.28	12.57%	**NS**	1.70	2.81	3.33%
	no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
	urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
	Total	34.80	34.80		*Total*	23.12	23.12		*Total*	36.82	36.82		*Total*	33.40	33.40	
Potato																
	S1	0.75	0.75	0.00%	**S1**	0.88	0.88	0.00%	**S1**	1.81	1.81	0.00%	**S1**	1.15	1.15	0.00%
	S2	6.34	5.27	-3.08%	**S2**	0.88	0.75	-0.57%	**S2**	4.31	3.87	-1.19%	**S2**	8.99	8.85	-0.42%
	S3	9.31	9.40	0.25%	**S3**	1.37	1.50	0.53%	**S3**	3.47	3.53	0.16%	**S3**	12.18	11.80	-1.12%
	S4	6.50	6.23	-0.79%	**S4**	4.45	3.73	-3.12%	**S4**	7.43	7.51	0.21%	**S4**	6.48	6.27	-0.63%
	NS	11.74	13.00	3.62%	**NS**	15.39	16.12	3.16%	**NS**	19.61	19.91	0.82%	**NS**	3.93	4.65	2.17%
	no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
	urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
	Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%

Cont..

Region		NE				SE				SW				NW		
Crop		Area Before	Area After	Change		Area Before	Area After	Change		Area Before	Area After	Change		Area Before	Area After	Change
Mustard																
	S1	6.13	5.73	-1.15%	**S1**	1.57	1.57	0.00%	**S1**	6.23	6.23	0.00%	**S1**	9.77	9.77	0.00%
	S2	9.13	9.16	0.10%	**S2**	4.32	3.92	-1.74%	**S2**	5.42	5.24	-0.49%	**S2**	13.86	13.75	-0.34%
	S3	9.93	9.65	-0.80%	**S3**	2.03	2.41	1.65%	**S3**	11.26	11.05	-0.58%	**S3**	7.12	5.81	-3.92%
	S4	0.34	0.99	1.85%	**S4**	0.33	0.29	-0.20%	**S4**	2.93	3.33	1.07%	**S4**	0.07	1.49	4.26%
	NS	9.11	9.11	0.00%	**NS**	14.71	14.78	0.29%	**NS**	10.77	10.77	0.00%	**NS**	1.90	1.90	0.00%
	no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
	urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
	Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%
Lentil																
	S1	5.69	5.35	-0.99%	**S1**	1.57	1.57	0.00%	**S1**	5.89	5.46	-1.19%	**S1**	5.96	5.86	-0.29%
	S2	7.12	6.67	-1.30%	**S2**	1.34	1.20	-0.61%	**S2**	3.22	3.03	-0.53%	**S2**	14.95	14.41	-1.63%
	S3	10.57	8.79	-5.09%	**S3**	4.34	3.75	-2.55%	**S3**	8.20	7.80	-1.07%	**S3**	6.34	5.81	-1.59%
	S4	2.70	3.34	1.85%	**S4**	0.86	1.47	2.62%	**S4**	8.90	5.29	-9.78%	**S4**	3.20	3.84	1.92%
	NS	8.56	10.49	5.53%	**NS**	14.86	14.98	0.54%	**NS**	10.41	15.04	12.57%	**NS**	2.28	2.81	1.59%
	no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
	urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
	Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%

Cont...

Region / Crop		NE Area Before	NE Area After	NE Change		SE Area Before	SE Area After	SE Change		SW Area Before	SW Area After	SW Change		NW Area Before	NW Area After	NW Change
Local Boro Paddy																
	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%
	S2	0.00	0.00	0.00%	S2	0.00	0.00	0.00%	S2	0.57	0.57	0.00%	S2	0.00	0.00	0.00%
	S3	0.64	0.64	0.00%	S3	0.00	0.00	0.00%	S3	0.16	0.16	0.00%	S3	0.00	0.00	0.00%
	S4	0.71	0.71	0.00%	S4	0.21	0.21	0.00%	S4	0.83	0.83	0.00%	S4	0.00	0.00	0.00%
	NS	33.29	33.29	0.00%	NS	22.76	22.76	0.00%	NS	35.05	35.05	0.00%	NS	32.72	32.72	0.00%
	no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
	urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
	Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%
HYV Boro Early																
	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%
	S2	0.00	0.00	0.00%	S2	0.00	0.00	0.00%	S2	0.57	0.57	0.00%	S2	0.00	0.00	0.00%
	S3	0.48	0.48	0.00%	S3	0.00	0.00	0.00%	S3	0.16	0.16	0.00%	S3	0.00	0.00	0.00%
	S4	0.86	0.86	0.00%	S4	0.21	0.21	0.00%	S4	0.67	0.67	0.00%	S4	0.00	0.00	0.00%
	NS	33.29	33.29	0.00%	NS	22.76	22.76	0.00%	NS	35.21	35.21	0.00%	NS	32.72	32.72	0.00%
	no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
	urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
	Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%

Cont...

Region / Crop		NE Area Before	NE Area After	NE Change		SE Area Before	SE Area After	SE Change		SW Area Before	SW Area After	SW Change		NW Area Before	NW Area After	NW Change
HYV Boro Late																
	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%
	S2	0.00	0.00	0.00%	S2	0.00	0.00	0.00%	S2	0.57	0.00	-1.55%	S2	0.00	0.00	0.00%
	S3	0.00	0.00	0.00%	S3	0.00	0.00	0.00%	S3	0.00	0.57	1.55%	S3	0.00	0.00	0.00%
	S4	0.00	0.00	0.00%	S4	0.00	0.00	0.00%	S4	0.42	0.00	-1.14%	S4	0.00	0.00	0.00%
	NS	34.64	34.64	0.00%	NS	22.97	22.97	0.00%	NS	35.63	36.05	1.14%	NS	32.72	32.72	0.00%
	no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
	urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
	Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%
B Aus Paddy																
	S1	6.13	5.73	-1.15%	S1	1.57	1.57	0.00%	S1	6.23	6.23	0.00%	S1	9.77	9.77	0.00%
	S2	9.13	9.16	0.10%	S2	4.32	3.92	-1.75%	S2	5.42	5.24	-0.48%	S2	13.86	13.75	-0.34%
	S3	9.93	9.65	-0.80%	S3	2.03	2.41	1.66%	S3	11.26	11.05	-0.59%	S3	7.12	5.81	-3.92%
	S4	0.34	0.99	1.85%	S4	0.33	0.29	-0.20%	S4	2.93	3.33	1.07%	S4	0.07	1.49	4.26%
	NS	9.11	9.11	0.00%	NS	14.71	14.78	0.29%	NS	10.77	10.77	0.00%	NS	1.90	1.90	0.00%
	no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
	urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
	Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%

Cont...

Region	NE				SE				SW				NW			
Crop	Area Before	Area After	Change		Area Before	Area After	Change		Area Before	Area After	Change		Area Before	Area After	Change	
Local T Aus Paddy																
S1	2.85	1.25	-4.58%	S1	0.58	0.10	-2.10%	S1	2.20	0.00	-5.95%	S1	11.98	7.56	-13.24%	
S2	10.54	9.78	-2.19%	S2	3.19	1.93	-5.47%	S2	7.59	5.91	-4.58%	S2	11.13	11.03	-0.32%	
S3	1.78	3.95	6.23%	S3	2.13	3.22	4.73%	S3	12.33	12.35	0.04%	S3	3.31	6.73	10.23%	
S4	1.10	1.25	0.42%	S4	0.60	0.79	0.83%	S4	1.21	4.46	8.82%	S4	0.72	1.74	3.05%	
NS	18.37	18.42	0.12%	NS	16.46	16.93	2.01%	NS	13.29	13.91	1.67%	NS	5.57	5.67	0.28%	
no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%	
urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%	
Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%	
HYV T Aus Paddy																
S1	2.49	0.17	-6.67%	S1	0.00	0.00	0.00%	S1	1.69	0.00	-4.59%	S1	10.97	5.56	-16.20%	
S2	1.38	3.01	4.69%	S2	1.57	0.00	-6.80%	S2	4.33	3.46	-2.37%	S2	4.10	7.27	9.49%	
S3	9.55	2.14	-21.30%	S3	1.85	2.55	3.00%	S3	2.84	4.37	4.14%	S3	5.54	5.32	-0.64%	
S4	2.60	9.24	19.10%	S4	2.00	2.40	1.74%	S4	9.67	1.22	-22.94%	S4	4.99	3.18	-5.40%	
NS	18.62	20.08	4.18%	NS	17.55	18.02	2.06%	NS	18.09	27.57	25.76%	NS	7.13	11.39	12.75%	
no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%	
urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%	
Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%	

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Region		NE				SE				SW				NW		
Crop		Area Before	Area After	Change		Area Before	Area After	Change		Area Before	Area After	Change		Area Before	Area After	Change
Jute (*Capsularis*)																
	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%
	S2	2.56	1.65	-2.60%	S2	0.80	0.16	-2.74%	S2	6.53	2.00	-12.33%	S2	10.60	7.85	-8.25%
	S3	5.83	3.91	-5.52%	S3	1.67	1.06	-2.63%	S3	0.94	5.26	11.73%	S3	6.85	5.61	-3.71%
	S4	5.25	4.15	-3.16%	S4	2.39	2.98	2.55%	S4	1.97	1.01	-2.60%	S4	7.15	8.49	3.99%
	NS	21.01	24.93	11.28%	NS	18.11	18.77	2.82%	NS	27.18	28.36	3.20%	NS	8.12	10.78	7.97%
	no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
	urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
	Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%
Jute (*Olitorius*)																
	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%	S1	0.00	0.00	0.00%
	S2	2.56	1.65	-2.60%	S2	0.80	0.16	-2.74%	S2	6.78	2.00	-13.01%	S2	10.57	7.63	-8.79%
	S3	3.64	2.77	-2.50%	S3	1.28	1.06	-0.95%	S3	0.69	5.26	12.41%	S3	4.03	5.53	4.48%
	S4	3.32	4.09	2.21%	S4	1.53	1.99	2.00%	S4	0.79	0.76	-0.09%	S4	6.90	4.57	-6.98%
	NS	25.11	26.12	2.89%	NS	19.36	19.75	1.69%	NS	28.36	28.61	0.69%	NS	11.22	14.99	11.29%
	no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
	urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
	Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%

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Region / Crop	NE Area Before	NE Area After	NE Change		SE Area Before	SE Area After	SE Change		SW Area Before	SW Area After	SW Change		NW Area Before	NW Area After	NW Change
Local T Aman Paddy															
S1	2.85	1.25	-4.58%	S1	0.58	0.10	-2.10%	S1	2.20	0.00	-5.96%	S1	11.98	7.56	-13.24%
S2	10.54	9.78	-2.19%	S2	3.19	1.93	-5.47%	S2	7.59	5.91	-4.57%	S2	11.13	11.03	-0.32%
S3	1.78	3.95	6.23%	S3	2.13	3.22	4.73%	S3	12.33	12.35	0.04%	S3	3.31	6.73	10.23%
S4	1.10	1.25	0.42%	S4	0.60	0.79	0.83%	S4	1.21	4.46	8.82%	S4	0.72	1.74	3.05%
NS	18.37	18.42	0.12%	NS	16.46	16.93	2.01%	NS	13.29	13.91	1.67%	NS	5.57	5.67	0.28%
no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%
HYV Aman Paddy															
S1	2.50	1.25	-3.57%	S1	0.49	0.00	-2.10%	S1	2.20	0.00	-5.96%	S1	11.06	7.52	-10.59%
S2	2.34	9.78	21.36%	S2	1.33	0.00	-5.77%	S2	4.53	5.27	2.01%	S2	4.01	7.19	9.53%
S3	8.58	3.95	-13.31%	S3	2.84	2.62	-0.99%	S3	2.14	2.70	1.53%	S3	5.54	3.44	-6.29%
S4	2.64	1.25	-4.01%	S4	0.76	2.37	7.00%	S4	12.25	0.99	-30.58%	S4	4.81	3.18	-4.86%
NS	18.58	18.42	-0.47%	NS	17.55	17.98	1.86%	NS	15.51	27.66	33.00%	NS	7.31	11.39	12.21%
no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%

Cont...

Region / Crop		NE Area Before	NE Area After	Change		SE Area Before	SE Area After	Change		SW Area Before	SW Area After	Change		NW Area Before	NW Area After	Change
Local T Aman Paddy																
	S1	2.85	1.25	-4.58%	S1	0.58	0.10	-2.10%	S1	2.20	0.00	-5.96%	S1	11.98	7.56	-13.24%
	S2	10.54	9.78	-2.19%	S2	3.19	1.93	-5.47%	S2	7.59	5.91	-4.57%	S2	11.13	11.03	-0.32%
	S3	1.78	3.95	6.23%	S3	2.13	3.22	4.73%	S3	12.33	12.35	0.04%	S3	3.31	6.73	10.23%
	S4	1.10	1.25	0.42%	S4	0.60	0.79	0.83%	S4	1.21	4.46	8.82%	S4	0.72	1.74	3.05%
	NS	18.37	18.42	0.12%	NS	16.46	16.93	2.01%	NS	13.29	13.91	1.67%	NS	5.57	5.67	0.28%
	no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
	urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
	Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%
HYV Aman Paddy after HYV/L T Aus																
	S1	1.16	0.08	-3.11%	S1	0.49	0.00	-2.10%	S1	0.51	0.00	-1.38%	S1	11.06	7.52	-10.59%
	S2	3.19	3.10	-0.25%	S2	1.21	0.00	-5.23%	S2	6.01	3.53	-6.72%	S2	4.01	7.19	9.53%
	S3	9.12	1.78	-21.10%	S3	2.94	1.68	-5.44%	S3	2.35	4.44	5.68%	S3	5.54	3.44	-6.29%
	S4	2.64	9.65	20.15%	S4	0.78	3.17	10.30%	S4	12.25	0.99	-30.58%	S4	4.81	3.18	-4.86%
	NS	18.53	20.03	4.31%	NS	17.55	18.12	2.47%	NS	15.51	27.66	33.00%	NS	7.31	11.39	12.21%
	no data	0.04	0.04	0.00%	no data	0.00	0.00	0.00%	no data	0.03	0.03	0.00%	no data	0.49	0.49	0.00%
	urban	0.12	0.12	0.00%	urban	0.14	0.14	0.00%	urban	0.17	0.17	0.00%	urban	0.19	0.19	0.00%
	Total	34.80	34.80	0.00%	*Total*	23.12	23.12	0.00%	*Total*	36.82	36.82	0.00%	*Total*	33.40	33.40	0.00%

Table A 6.9 Countrywide Soil Suitability Class Areas ('000' km²) Before & After the Climate Change Scenario

The total land area is taken as 128,000 km², which excludes 12,000 km² omitted due to lack of data (see section 7.4.1).

Crop	Class	Before	After	Change
Wheat	S1	19.12	18.24	-0.68%
	S2	26.64	25.31	-1.04%
	S3	30.85	26.75	-3.20%
	S4	15.65	14.17	-1.16%
	NS	34.71	42.49	6.08%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%
Potato	S1	4.59	4.59	0.00%
	S2	20.52	18.74	-1.39%
	S3	26.33	26.23	-0.08%
	S4	24.86	23.73	-0.88%
	NS	50.66	53.68	2.35%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%
Mustard	S1	23.71	23.31	-0.31%
	S2	32.73	32.06	-0.52%
	S3	30.34	28.92	-1.11%
	S4	3.68	6.09	1.89%
	NS	36.50	36.57	0.05%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%
Lentil	S1	19.12	18.24	-0.68%
	S2	26.63	25.30	-1.04%
	S3	29.44	26.15	-2.56%
	S4	15.66	13.95	-1.33%
	NS	36.11	43.31	5.61%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%

Cont...

Crop	Class	Before	After	Change
Local Boro Paddy	S1	0.00	0.00	0.00%
	S2	0.57	0.57	0.00%
	S3	0.80	0.80	0.00%
	S4	1.76	1.76	0.00%
	NS	123.83	123.83	0.00%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%
HYV Boro Early	S1	0.00	0.00	0.00%
	S2	0.57	0.57	0.00%
	S3	0.64	0.64	0.00%
	S4	1.75	1.75	0.00%
	NS	123.99	123.99	0.00%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%
HYV Boro Late	S1	0.00	0.00	0.00%
	S2	0.57	0.00	-0.45%
	S3	0.00	0.57	0.45%
	S4	0.42	0.00	-0.33%
	NS	125.97	126.39	0.33%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%
B Aus Paddy	S1	23.71	23.31	-0.31%
	S2	32.73	32.06	-0.52%
	S3	30.34	28.92	-1.11%
	S4	3.68	6.09	1.89%
	NS	36.50	36.57	0.05%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%
Local T Aus Paddy	S1	17.61	8.91	-6.79%
	S2	32.46	28.64	-2.98%
	S3	19.56	26.25	5.23%
	S4	3.64	8.24	3.59%
	NS	53.70	54.92	0.95%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%

Cont...

Crop	Class	Before	After	Change
HYV T Aus Paddy	S1	15.15	5.73	-7.35%
	S2	11.38	13.74	1.84%
	S3	19.78	14.38	-4.22%
	S4	19.26	16.05	-2.50%
	NS	61.39	77.06	12.23%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%
Jute (*Cap.*)	S1	0.00	0.00	0.00%
	S2	20.49	11.66	-6.89%
	S3	15.29	15.84	0.43%
	S4	16.75	16.62	-0.11%
	NS	74.42	82.84	6.57%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%
	Total	128.14	128.14	
Jute (*Olit.*)	S1	0.00	0.00	0.00%
	S2	20.71	11.45	-7.23%
	S3	9.65	14.63	3.88%
	S4	12.54	11.41	-0.88%
	NS	84.06	89.47	4.23%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%
Local T Aman Paddy	S1	17.61	8.91	-6.79%
	S2	32.46	28.64	-2.97%
	S3	19.56	26.25	5.22%
	S4	3.64	8.24	3.59%
	NS	53.70	54.92	0.95%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%
HYV Aman Paddy	S1	16.23	8.77	-5.82%
	S2	12.22	22.24	7.82%
	S3	19.10	12.71	-4.99%
	S4	20.45	7.79	-9.88%
	NS	58.96	75.45	12.87%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%
HYV Aman Paddy after HYV/Local T Aus	S1	13.21	7.59	-4.38%
	S2	14.41	13.83	-0.46%
	S3	19.95	11.34	-6.72%
	S4	20.48	16.99	-2.72%
	NS	58.91	77.21	14.28%
	no data	0.55	0.55	0.00%
	urban	0.62	0.62	0.00%

Table A6.10 Land Suitability Class Areas ('000' km²) Before & After the Climate Change Scenario

Region		NE				SE				SW				NW		
Crop		Area Before	Area After	Change		Area Before	Area After	Change		Area Before	Area After	Change		Area Before	Area After	Change
Wheat	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%
	S2	0.13	0.00	-0.4%	**S2**	0.00	0.00	0.0%	**S2**	0.00	0.00	0.0%	**S2**	5.03	0.00	-15.1%
	S3	5.66	2.32	-9.6%	**S3**	0.62	0.00	-2.7%	**S3**	4.40	3.50	-2.5%	**S3**	12.00	5.85	-18.4%
	S4	15.87	13.84	-5.8%	**S4**	2.69	2.77	0.4%	**S4**	9.39	7.94	-4.0%	**S4**	11.70	20.39	26.1%
	NS	12.96	18.47	15.8%	**NS**	19.52	20.06	2.3%	**NS**	22.15	24.49	6.5%	**NS**	3.94	6.44	7.5%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98	0.0%	*Total*	36.11	36.11	0.0%	*Total*	33.34	33.34	0.0%
Potato	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%
	S2	0.00	0.00	0.0%	**S2**	0.00	0.00	0.0%	**S2**	0.00	0.00	0.0%	**S2**	0.00	0.00	0.0%
	S3	0.29	0.29	0.0%	**S3**	0.00	0.00	0.0%	**S3**	0.00	0.00	0.0%	**S3**	0.00	0.00	0.0%
	S4	7.26	6.93	-1.0%	**S4**	1.30	0.82	-2.1%	**S4**	5.88	5.20	-1.9%	**S4**	9.76	9.62	-0.4%
	NS	27.07	27.41	1.0%	**NS**	21.53	22.02	2.1%	**NS**	30.06	30.74	1.9%	**NS**	22.92	23.06	0.4%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	
Mustard	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.06	0.06	0.2%	**S1**	5.45	5.45	0.0%
	S2	5.63	5.47	-0.5%	**S2**	0.65	0.65	0.0%	**S2**	4.70	4.70	12.8%	**S2**	14.62	14.50	-0.3%
	S3	8.21	7.78	-1.2%	**S3**	1.45	1.42	-0.2%	**S3**	5.74	5.64	2.6%	**S3**	5.40	5.39	0.0%
	S4	11.61	11.59	-0.1%	**S4**	5.71	5.73	0.1%	**S4**	14.89	14.99	25.6%	**S4**	5.31	5.43	0.4%
	NS	9.18	9.78	1.7%	**NS**	15.01	15.04	0.1%	**NS**	10.55	10.55	-12.0%	**NS**	1.90	1.90	0.0%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	-29.2%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.5%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	

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Region / Crop		NE Area Before	NE Area After	NE Change		SE Area Before	SE Area After	SE Change		SW Area Before	SW Area After	SW Change		NW Area Before	NW Area After	NW Change
Lentil	S1	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%
	S2	2.19	0.13	-5.9%	**S2**	0.00	0.00	0.0%	**S2**	3.50	0.00	-9.7%	**S2**	5.62	4.69	-2.8%
	S3	7.76	5.32	-7.0%	**S3**	0.65	0.65	0.0%	**S3**	2.88	4.42	4.2%	**S3**	11.87	9.17	-8.1%
	S4	13.39	13.92	1.5%	**S4**	2.70	2.59	-0.5%	**S4**	10.21	8.36	-5.1%	**S4**	12.31	12.93	1.9%
	NS	11.28	15.25	11.4%	**NS**	19.48	19.59	0.5%	**NS**	19.34	23.15	10.6%	**NS**	2.89	5.88	9.0%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	
B. Aus Paddy	S1	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%
	S2	5.16	5.00	-0.5%	**S2**	0.65	0.65	0.0%	**S2**	3.74	3.74	0.0%	**S2**	7.53	7.53	0.0%
	S3	8.55	8.13	-1.2%	**S3**	1.45	1.42	-0.2%	**S3**	6.02	5.92	-0.3%	**S3**	15.18	15.06	-0.3%
	S4	11.58	11.70	0.4%	**S4**	5.71	5.73	0.1%	**S4**	14.97	15.06	0.3%	**S4**	8.07	8.18	0.3%
	NS	9.34	9.80	1.3%	**NS**	15.01	15.04	0.1%	**NS**	11.21	11.21	0.0%	**NS**	1.90	1.90	0.0%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	
Local T. Aus Paddy	S1	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%
	S2	1.32	0.71	-1.8%	**S2**	0.00	0.00	0.0%	**S2**	0.88	0.00	-2.4%	**S2**	5.44	2.51	-8.8%
	S3	6.24	5.13	-3.2%	**S3**	1.09	0.33	-3.3%	**S3**	3.98	2.70	-3.6%	**S3**	13.11	12.02	-3.3%
	S4	8.48	10.10	4.7%	**S4**	4.80	5.01	0.9%	**S4**	17.16	12.25	-13.6%	**S4**	8.22	11.55	10.0%
	NS	18.58	18.68	0.3%	**NS**	16.94	17.49	2.4%	**NS**	13.91	20.98	19.6%	**NS**	5.90	6.60	2.1%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	

Cont...

Region		NE				SE				SW				NW		
Crop		Area Before	Area After	Change		Area Before	Area After	Change		Area Before	Area After	Change		Area Before	Area After	Change
HYV T.	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%
Aus	**S2**	1.23	0.17	-3.0%	**S2**	0.00	0.00	0.0%	**S2**	0.45	0.00	-1.3%	**S2**	1.75	0.43	-4.0%
Paddy	**S3**	2.17	1.42	-2.2%	**S3**	0.19	0.00	-0.8%	**S3**	2.58	1.15	-3.9%	**S3**	6.85	3.88	-8.9%
	S4	11.29	7.97	-9.5%	**S4**	3.40	2.90	-2.2%	**S4**	7.96	6.17	-5.0%	**S4**	14.18	14.23	0.2%
	NS	19.94	25.06	14.7%	**NS**	19.25	19.93	3.0%	**NS**	24.95	28.61	10.2%	**NS**	9.90	14.14	12.7%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	
Jute	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%
(Cap.)	**S2**	0.00	0.00	0.0%	**S2**	0.00	0.00	0.0%	**S2**	0.00	0.00	0.0%	**S2**	0.00	0.00	0.0%
	S3	2.12	1.48	-1.8%	**S3**	0.42	0.16	-1.1%	**S3**	0.92	0.00	-2.5%	**S3**	5.31	3.83	-4.5%
	S4	8.86	7.15	-4.9%	**S4**	3.17	2.17	-4.4%	**S4**	8.27	7.86	-1.1%	**S4**	16.39	16.65	0.8%
	NS	23.64	26.00	6.8%	**NS**	19.24	20.50	5.5%	**NS**	26.75	28.07	3.7%	**NS**	10.97	12.20	3.7%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	
Jute	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%
(Olit.)	**S2**	0.00	0.00	0.0%	**S2**	0.00	0.00	0.0%	**S2**	0.00	0.00	0.0%	**S2**	0.00	0.00	0.0%
	S3	2.12	1.48	-1.8%	**S3**	0.42	0.16	-1.1%	**S3**	1.17	0.00	-3.2%	**S3**	5.31	3.83	-4.5%
	S4	7.00	4.69	-6.6%	**S4**	2.54	1.83	-3.1%	**S4**	6.87	7.68	2.2%	**S4**	14.91	13.37	-4.6%
	NS	25.51	28.45	8.5%	**NS**	19.87	20.84	4.2%	**NS**	27.90	28.25	1.0%	**NS**	12.45	15.49	9.1%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	

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Region		NE				SE				SW				NW		
Crop		Area Before	Area After	Change		Area Before	Area After	Change		Area Before	Area After	Change		Area Before	Area After	Change
Local T.	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%
Aman	**S2**	0.89	0.45	-1.3%	**S2**	0.00	0.00	0.0%	**S2**	1.62	0.00	-4.5%	**S2**	5.26	2.49	-8.3%
Paddy	**S3**	5.83	4.39	-4.1%	**S3**	1.09	0.33	-3.3%	**S3**	5.64	5.08	-1.5%	**S3**	11.97	10.33	-4.9%
	S4	9.32	11.02	4.9%	**S4**	4.80	5.12	1.4%	**S4**	15.14	15.86	2.0%	**S4**	9.52	13.22	11.1%
	NS	18.59	18.77	0.5%	**NS**	16.94	17.38	1.9%	**NS**	13.53	14.99	4.0%	**NS**	5.93	6.64	2.1%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	
HYV	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%
Aman	**S2**	0.83	0.45	-1.1%	**S2**	0.00	0.00	0.0%	**S2**	1.62	0.00	-4.5%	**S2**	3.78	2.49	-3.9%
Paddy	**S3**	2.29	1.66	-1.8%	**S3**	0.67	0.00	-2.9%	**S3**	4.29	4.96	1.8%	**S3**	9.52	8.43	-3.2%
	S4	11.63	6.81	-13.9%	**S4**	4.03	2.97	-4.6%	**S4**	10.54	3.48	-19.5%	**S4**	9.47	8.48	-3.0%
	NS	19.87	25.70	16.8%	**NS**	18.13	19.86	7.5%	**NS**	19.48	27.50	22.2%	**NS**	9.92	13.28	10.1%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	
HYV	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%	**S1**	0.00	0.00	0.0%				
Aman	**S2**	0.00	0.00	0.0%	**S2**	0.00	0.00	0.0%	**S2**	0.00	0.00	0.0%				
Paddy	**S3**	0.80	0.00	-2.3%	**S3**	0.00	0.00	0.0%	**S3**	0.30	0.00	-0.8%				
after	**S4**	5.67	2.35	-9.5%	**S4**	2.65	0.58	-9.0%	**S4**	1.23	1.04	-0.5%				
HYV/T	**NS**	28.15	32.27	11.8%	**NS**	20.18	22.25	9.0%	**NS**	34.41	34.90	1.4%	**NS**	32.68	32.68	0.0%
Aus	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	

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Region / Crop		NE Area Before	NE Area After	NE Change		SE Area Before	SE Area After	SE Change		SW Area Before	SW Area After	SW Change		NW Area Before	NW Area After	NW Change
Local Boro Paddy	NS	34.62	34.62	0.0%	NS	22.83	22.83	0.0%	NS	35.93	35.93	0.0%	NS	32.68	32.68	0.0%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	
HYV Boro Early	NS	34.62	34.62	0.0%	NS	22.83	22.83	0.0%	NS	35.93	35.93	0.0%	NS	32.68	32.68	0.0%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	
HYV Boro Late	NS	34.62	34.62	0.0%	NS	22.83	22.83	0.0%	NS	35.93	35.93	0.0%	NS	32.68	32.68	0.0%
	no data	0.04	0.04	0.0%	no data	0.00	0.00	0.0%	no data	0.00	0.00	0.0%	no data	0.47	0.47	0.0%
	urban	0.12	0.12	0.0%	urban	0.14	0.14	0.0%	urban	0.17	0.17	0.0%	urban	0.19	0.19	0.0%
	Total	34.78	34.78		*Total*	22.98	22.98		*Total*	36.11	36.11		*Total*	33.34	33.34	

Figure A 6.6 Land Suitability Map for Wheat from the GIS - Before the Climate Change Scenario

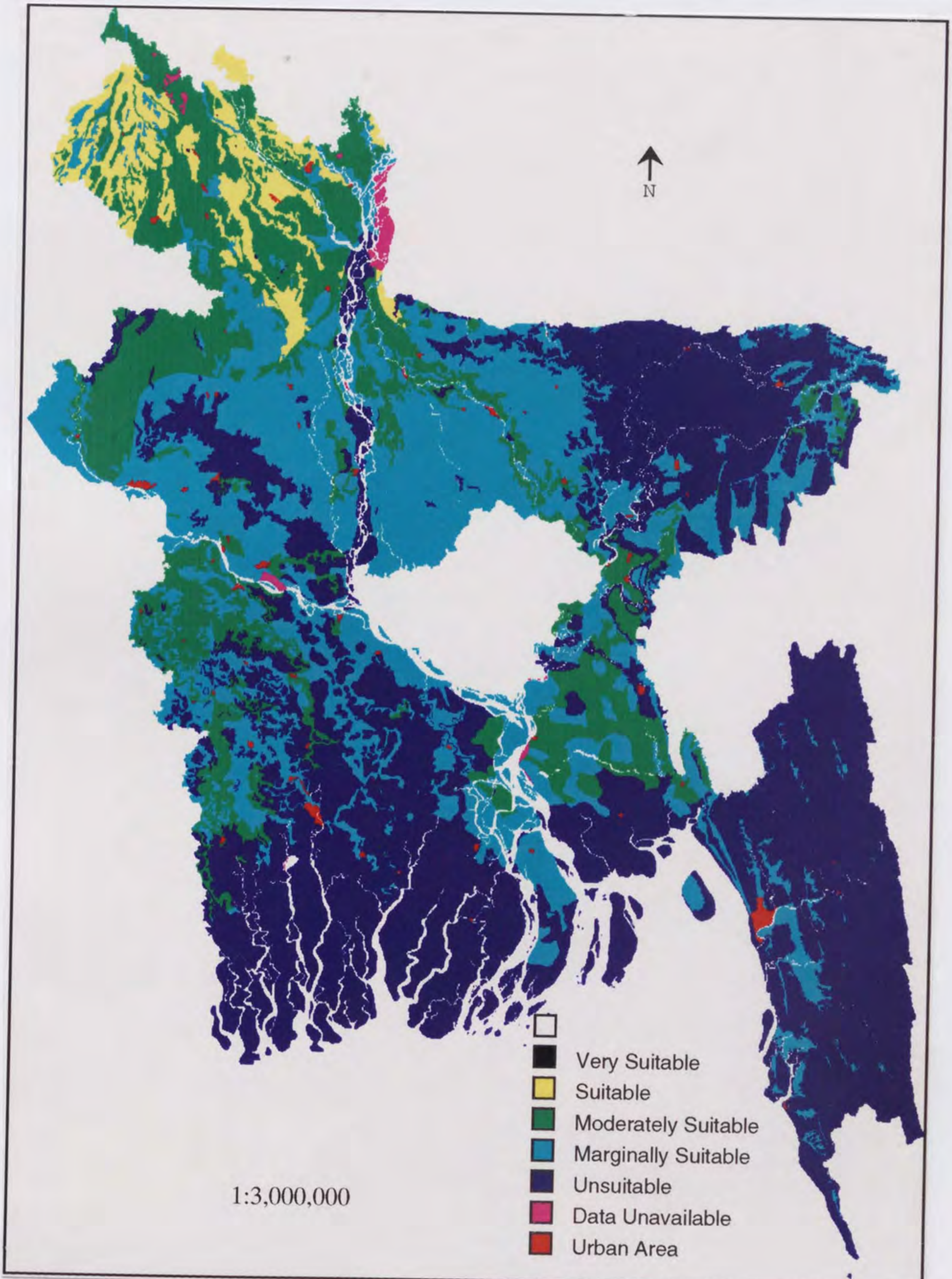

Figure A 6.7 Land Suitability Map for Wheat from the GIS - After the Climate Change Scenario

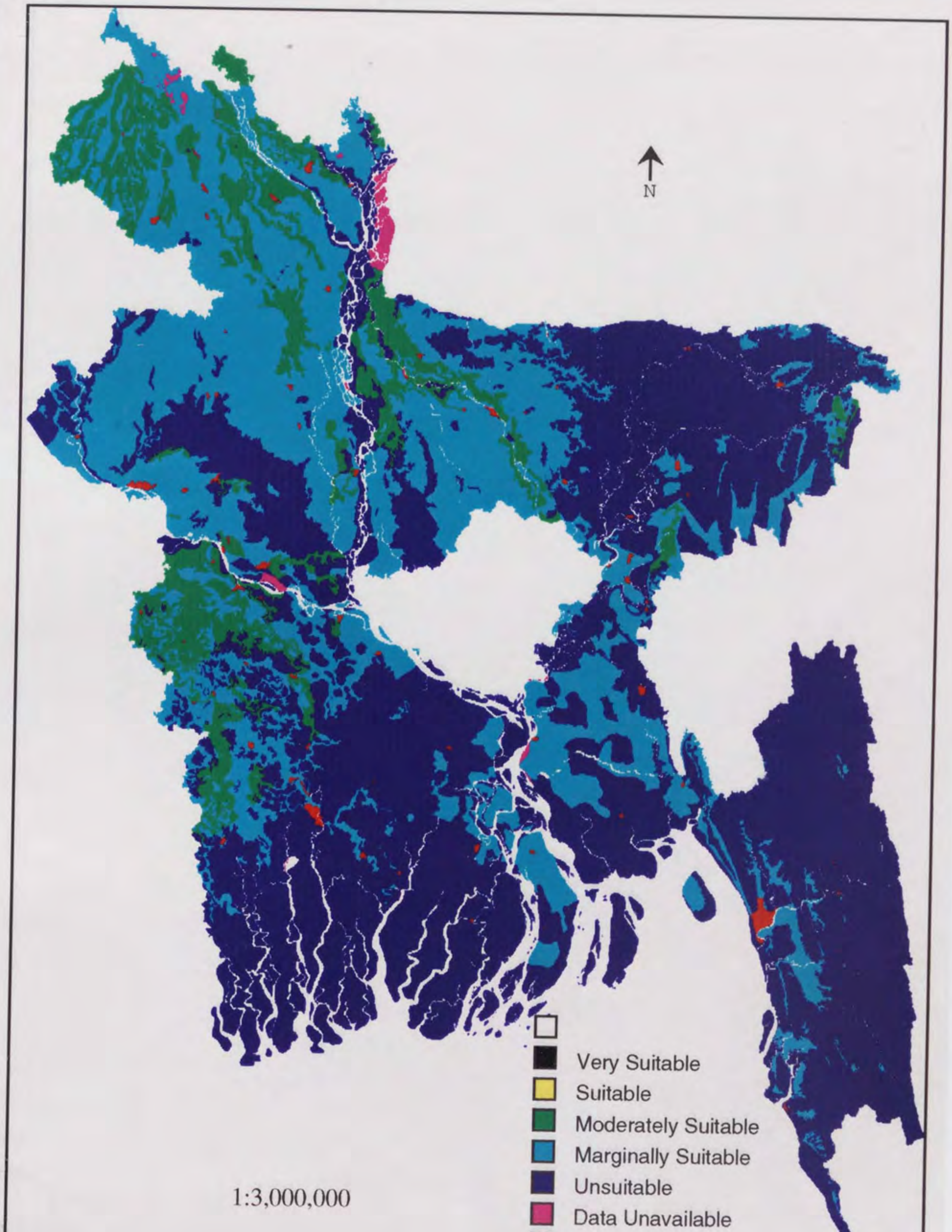

Table A6.11 Countrywide Land Suitability Class Areas Before & After the Climate Change Scenario

In the following table the land area is taken as 128,000 km².

Crop	Class	Before	After	Change
Wheat	VS	0.0%	0.0%	0.0%
	S	4.1%	0.0%	-4.1%
	MS	17.8%	9.2%	-8.6%
	ms	31.2%	35.3%	4.2%
	Total Suitable Area	*53.1%*	*44.5%*	
	NS	46.1%	54.6%	8.5%
	ND	0.4%	0.4%	0.0%
	urban	0.5%	0.5%	0.0%
Potato	VS	0.0%	0.0%	0.0%
	S	0.0%	0.0%	0.0%
	MS	0.2%	0.2%	0.0%
	ms	19.0%	17.7%	-1.3%
	Total Suitable Area	*19.3%*	*18.0%*	
	NS	79.9%	81.1%	1.3%
	ND	0.4%	0.4%	0.0%
	urban	0.5%	0.5%	0.0%
Mustard	VS	4.3%	4.3%	0.0%
	S	20.1%	19.9%	-0.2%
	MS	16.4%	15.9%	-0.4%
	ms	29.5%	29.7%	0.2%
	Total Suitable Area	*70.3%*	*69.8%*	
	NS	28.8%	29.3%	0.5%
	ND	0.4%	0.4%	0.0%
	urban	0.5%	0.5%	0.0%
Lentil	VS	0.0%	0.0%	0.0%
	S	8.9%	3.8%	-5.1%
	MS	18.2%	15.4%	-2.8%
	ms	30.4%	29.7%	-0.6%
	Total Suitable Area	*57.5%*	*48.9%*	
	NS	41.7%	50.2%	8.6%
	ND	0.4%	0.4%	0.0%
	urban	0.5%	0.5%	0.0%

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Crop	Class	Before	After	Change
Local B. Aus Paddy	VS	0.0%	0.0%	0.0%
	S	13.4%	13.3%	-0.1%
	MS	24.5%	24.0%	-0.5%
	ms	31.7%	32.0%	0.3%
	Total Suitable Area	*69.7%*	*69.3%*	
	NS	29.4%	29.8%	0.4%
	ND	0.4%	0.4%	0.0%
	urban	0.5%	0.5%	0.0%
Local Boro Paddy	*Unsuitable*	100%		
HYV Boro Early	*Unsuitable*	100%		
HYV Boro Late	*Unsuitable*	100%		
Local T. Aus Paddy	VS	0.0%	0.0%	0.0%
	S	6.0%	2.5%	-3.5%
	MS	19.2%	15.9%	-3.3%
	ms	30.4%	30.6%	0.2%
	Total Suitable Area	*55.6%*	*49.0%*	
	NS	43.5%	50.1%	6.6%
	ND	0.4%	0.4%	0.0%
	urban	0.5%	0.5%	0.0%
HYV T. Aus Paddy	VS	0.0%	0.0%	0.0%
	S	2.7%	0.5%	-2.2%
	MS	9.3%	5.1%	-4.2%
	ms	28.9%	24.6%	-4.4%
	Total Suitable Area	*40.9%*	*30.1%*	
	NS	58.2%	69.0%	10.8%
	ND	0.4%	0.4%	0.0%
	urban	0.5%	0.5%	0.0%
Jute *(Cap.)*	VS	0.0%	0.0%	0.0%
	S	0.0%	0.0%	0.0%
	MS	6.9%	4.3%	-2.6%
	ms	28.9%	26.6%	-2.3%
	Total Suitable Area	*35.7%*	*30.9%*	
	NS	63.4%	68.2%	4.8%
	ND	0.4%	0.4%	0.0%
	urban	0.5%	0.5%	0.0%

Cont...

Crop	Class	Before	After	Change
Jute	VS	0.0%	0.0%	0.0%
(Olit.)	S	0.0%	0.0%	0.0%
	MS	7.1%	4.3%	-2.8%
	ms	24.6%	21.7%	-3.0%
Total Suitable Area		*31.7%*	*26.0%*	
	NS	67.4%	73.1%	5.7%
	ND	0.4%	0.4%	0.0%
	urban	0.5%	0.5%	0.0%
Local T. Aman	VS	0.0%	0.0%	0.0%
Paddy	S	6.2%	2.3%	-3.9%
	MS	19.2%	15.8%	-3.4%
	ms	30.5%	35.6%	5.1%
Total Suitable Area		*55.9%*	*53.7%*	
	NS	43.2%	45.4%	2.2%
	ND	0.4%	0.4%	0.0%
	urban	0.5%	0.5%	0.0%
HYV Aman	VS	0.0%	0.0%	0.0%
Paddy	S	4.9%	2.3%	-2.6%
	MS	13.2%	11.8%	-1.4%
	ms	28.0%	17.1%	-10.9%
Total Suitable Area		*46.1%*	*31.2%*	
	NS	53.0%	67.9%	14.9%
	ND	0.4%	0.4%	0.0%
	urban	0.5%	0.5%	0.0%
HYV Aman	VS	0.0%	0.0%	0.0%
Paddy after	S	0.0%	0.0%	0.0%
HYV/T Aus	MS	0.9%	0.0%	-0.9%
	ms	7.5%	3.1%	-4.4%
Total Suitable Area		*8.4%*	*3.1%*	
	NS	90.7%	96.0%	5.2%
	ND	0.4%	0.4%	0.0%
	urban	0.5%	0.5%	0.0%

Table A6.12 Total Yield Output in '000' Tonnes For Each Region Before & After the Climate Change Scenario, For Each Input Level

Crop		High Input			Low Input			Change
		Before	After	Difference	Before	After	Difference	
Wheat								
	NW	3,502	2,026	-1,476	1,773	1,030	-743	-42%
	NE	1,887	1,147	-740	953	584	-370	-39%
	SW	259	157	-103	132	80	-52	-39%
	SE	1,219	891	-327	618	453	-165	-27%
	Total	*6,868*	*4,221*	*-2,646*	*3,476*	*2,146*	*-1,330*	
White Potato								
	NW	861	778	-83	328	296	-32	-10%
	NE	683	590	-94	260	225	-36	-14%
	SW	503	395	-108	192	150	-41	-21%
	SE	110	60	-50	42	23	-19	-46%
	Total	*2,157*	*1,822*	*-335*	*821*	*694*	*-127*	
Mustard								
	NW	2,101	1,926	-175	965	890	-75	-8%
	NE	1,144	1,002	-142	528	464	-64	-12%
	SW	1,015	896	-118	468	414	-54	-12%
	SE	260	224	-36	120	104	-17	-14%
	Total	*4,521*	*4,049*	*-472*	*2,081*	*1,871*	*-210*	
Lentil								
	NW	1,929	1,484	-446	988	760	-229	-23%
	NE	1,279	789	-490	655	404	-250	-38%
	SW	929	525	-404	476	268	-208	-44%
	SE	137	113	-25	70	58	-12	-17%
	Total	*4,276*	*2,911*	*-1,365*	*2,189*	*1,490*	*-699*	
Jute *(Cap.)*								
	NW	1,413	1,207	-206	706	603	-102	-15%
	NE	688	504	-184	344	252	-92	-27%
	SW	513	380	-133	257	190	-66	-26%
	SE	210	124	-86	105	62	-43	-41%
	Total	*2,825*	*2,215*	*-609*	*1,411*	*1,108*	*-304*	

Note: The percentage change is the same for both the high and low scenario, the figures have only been produced once therefore.

Cont...

Crop		High Input			Low Input			Change
		Before	After	Difference	Before	After	Difference	
Jute (*Olit.*)								
	NW	1,335	1,043	-292	667	521	-146	-22%
	NE	589	381	-209	295	190	-104	-35%
	SW	469	372	-97	234	186	-48	-21%
	SE	177	107	-70	89	54	-35	-40%
	Total	*2,571*	*1,902*	*-668*	*1,285*	*951*	*-334*	
HYV T. Aus								
	NW	3,146	2,104	-1,041				-33%
	NE	1,845	1,032	-813				-44%
	SW	1,344	750	-594				-44%
	SE	359	263	-96				-27%
	Total	*6,693*	*4,149*	*-2,544*				
HYV T. Aman								
	NW	3,560	3,019	-541				-15%
	NE	1,683	1,057	-625				-37%
	SW	2,147	1,227	-920				-43%
	SE	489	276	-213				-44%
	Total	*7,878*	*5,579*	*-2,299*				
HYV T. Aman after HYV/L. T. Aus	NW	Unsuitable	Unsuitable					0%
	NE	656	216	-439				-67%
	SW	165	96	-69				-42%
	SE	241	55	-186				-77%
	Total	*1,061*	*367*	*-695*				
Local T. Aman								
	NW				1,992	1,513	-479	-24%
	NE				847	776	-71	-8%
	SW				1,116	949	-167	-15%
	SE				252	213	-40	-16%
	Total				*4,207*	*3,451*	*-756*	
Local B. Aus								
	NW				1,972	1,875	-97	-5%
	NE				1,439	1,333	-106	-7%
	SW				1,205	1,145	-60	-5%
	SE				342	323	-19	-5%
	Total				4,957	4,675	-282	

Cont...

Crop	High Input		Low Input		Change	
	Before	After	Before	After	Difference	
Local T. Aus						
NW			1,447	1,171	-277	-19%
NE			715	615	-100	-14%
SW			768	466	-302	-39%
SE			199	154	-45	-22%
Total			*3,129*	*2,405*	*-724*	
Local Boro Low Input	*Unsuitable*					
HYV Boro (Quick) High Input	*Unsuitable*					
HYV Boro (Late) High Input	*Unsuitable*					

Table A6.13 Final Countrywide Percentage Reduction in Yield For Each Crop

Crop	Actual Reduction in Yield (million tonnes)	% Change
HYV T. Aman	0.70	65
Wheat	2.65 (high) 1.33 (low)	38
HYV T. Aus	2.54	38
Lentil	1.34 (high) 0.67 (low)	32
HYV T. Aman	2.30	29
Jute (*Olit.*)	0.67 (high) 0.33 (low)	26
Local T. Aus	0.72	23
Jute (*Cap.*)	0.61 (high) 0.30 (low)	22
Local T. Aman	0.76	18
White Potato	0.34 (high) 0.13 (low)	16
Mustard	0.47 (high) 0.21 (low)	10
Local B.Aus	0.28	6
Local Boro	*Unsuitable*	
HYV Boro (Quick)	*Unsuitable*	
HYV Boro (Late)	*Unsuitable*	

Table A6.14 Total Number of Calories Available for Individual Crops Before & After the Climate Change Scenario

Crop	Calories (x exp13) Before	After
Wheat	5.67874	4.98438
Potato	1.53058	1.99599
Local B. Aus	97.2739	75.3807
Local T. Aus	54.7778	43.4752
HYV T. Aus	33.3356	17.8384
Local T. Aman	25.472	8.83935
HYV T. Aman	16.7495	16.9969
HYV T. Aman after HYV/L. T. Aus	2.73515	1.24853

Table A6.15 Total Number of Calories Theoretically Available for Optimised Crops in Each Season

		Maximum Calories (x exp 13)		Supporting Capacity (millions)	
Season	**Optimised Crops**	**Before**	**After**	**Before**	**After**
Rabi	Wheat *or* Potato	6.07397	5.51977	73	66
Kharif	Local B. Aus *or* Local T. Aus or HYV T Aus *or* Local T. Aman or HYV T. Aman	111.738	90.5445	1,346	1,091
3 Crop Rotation	Local T. Aus *or* HYV T. Aus and HYV T. Aman	66.9182	46.8067	806	549

Figure A6.8 Optimisation of Calories per Cell for Wheat & Potatoes After the Climate Scenario

Figure A6.9 Soil Suitability of Wheat Before the Climate Change Scenario

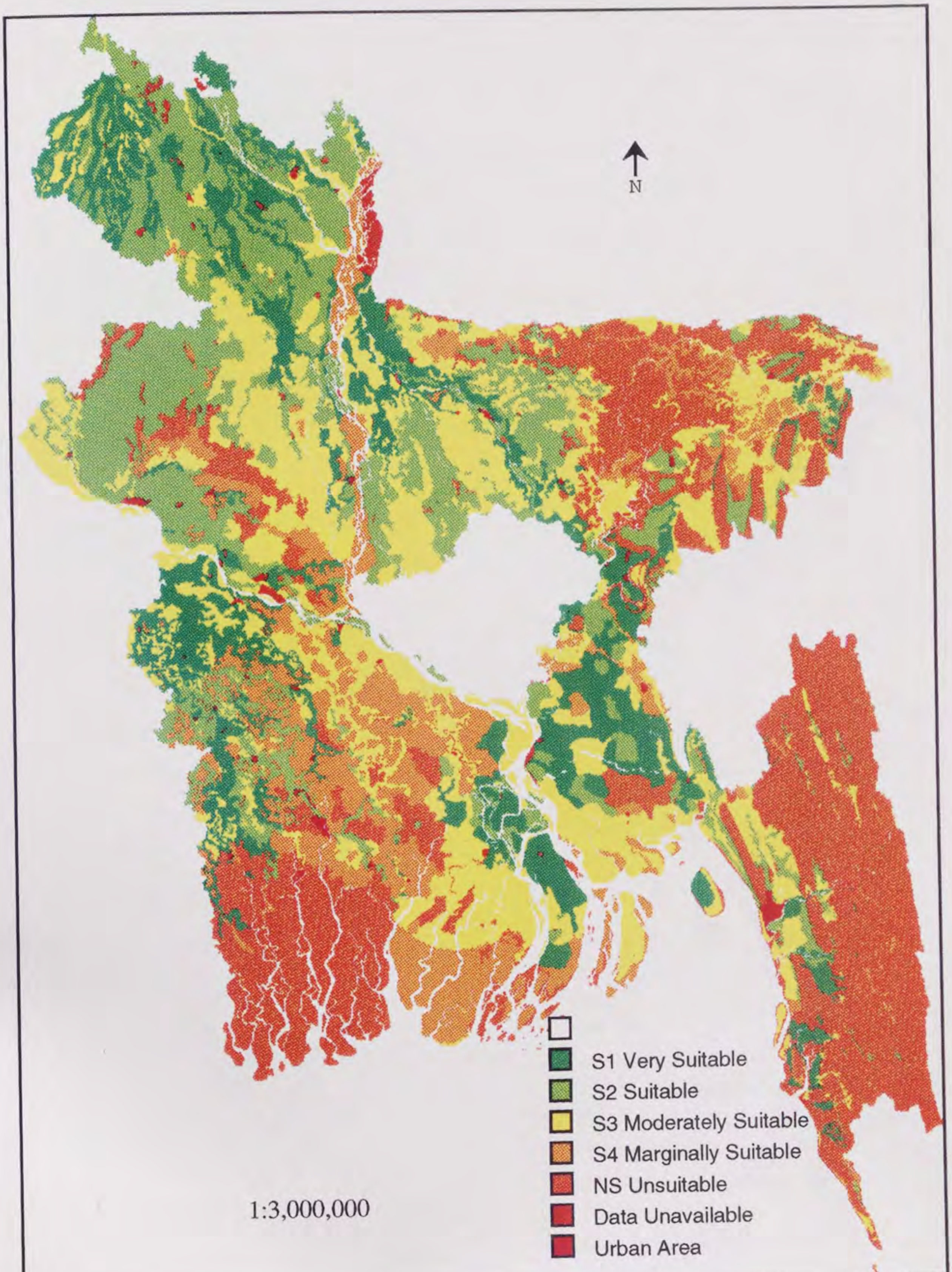

Figure A6.10 Soil Suitability of Wheat After the Climate Change Scenario