Chapter 2

Agriculture and forestry

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1 Introduction

1.1 Objectives and approach

The purpose of this chapter is fourfold: first, to identify those systems, sectors and regions of agriculture and forestry that are most sensitive to anticipated changes of climate;[1] second, to summarise the present knowledge about the potential socioeconomic impact of changes of climate on world agriculture and forestry; third, to consider the adjustments in agriculture and forestry that are most likely to occur (even if no policy responses were implemented);[2] finally, to establish research priorities for future assessments of impact.

This chapter gathers together many different types of information. It is a synthesis of all available published material, as well as unpublished government and non-government reports. It also draws on summaries of expert judgment concerning impacts in many regions that resulted from contact made with more than 100 scientists in 50 different countries.

1.2 Assumptions

1.2.1 Climatic scenarios

The scenarios used in the estimates of global warming effects on agriculture and forestry were based on both General Circulation Model (GCM) simulations at 2 x CO_2 climate and palaeoclimatic reconstructions. The GCM scenarios are described in detail in Working Group I Report. The analog scenarios used in Soviet studies at mid-latitude Northern Hemisphere agriculture impacts are based on climate reconstructions of three past warm epochs as discussed in Chapter 1.

Where reference is made to an equivalent doubling of atmospheric CO_2, this is taken to be 460 ppm in about the year 2030 (which is the current best estimate, Working Group I). This represents a ca 60% increase over pre-industrial levels because CO_2 comprises about 60% of estimated greenhouse gas (GHG) forcing.

1.2.2 Assumptions concerning technology and management

Since the effects of changes in climate will be felt progressively over time, though not necessarily in linear increments, it is necessary to assess these against an exposure unit that is itself changing (irrespective of climate change). The nature of this 'moving target' is difficult to describe with accuracy, primarily because of the relatively long time scales involved (eg 50-100 years). Changes in technology and management may, over that length of time, alter some aspects of agriculture and commercial forestry beyond recognition.

A common approach to this problem is, first, to estimate impacts as they might occur in the future, assuming technology and management as it is now; for example, assuming the extent of irrigation and fertiliser application to be as at present. Subsequent assessments then allow for possible developments in technology and management, identifying those adjustments necessary either to obviate major negative effects or to exploit positive ones. This distinction between 'impact experiments' and 'adjustment experiments' has been made in a number of previous impact assessments (see Parry and Carter, 1988).

In the present report, and unless otherwise stated, data on estimated impacts relate to changes in productive *potential* against a baseline of present-day base technology and management. However, likely *(actual)* effects on production must be measured against a realistic future reference base. In order to characterise this baseline certain assumptions must be made about changes in food and timber demand (on the basis of changes in population and per capita income), in use of inputs (particularly amount of fertiliser), in extent of the farmed and forested area and in many other aspects of agriculture and forestry which are likely to alter in the future even if climate did not change. These assumptions are consistent with UN and World Bank projections.

2 Potential impacts on agriculture and land use

2.1 Introduction

Owing to the many remaining uncertainties about possible future changes of climate (particularly changes in regional precipitation patterns and the rate of climate change over time) *no forecast can be*

1 Note impacts on fisheries are considered in Chapter 6 of IPCC Working Group II

2 Note technical adjustments which can reasonably be presumed to occur as a result of changes of climate are considered in this report Policy responses at the national and international level are evaluated in the report of the IPCC Working Group

made in this report concerning any specific impact on agriculture. It is possible, however, to identify what types of impacts might occur under a number of possible changes of climate and thus, by inference, what types of climate change could constitute a significant risk or benefit for agriculture. Four approaches can be adopted to achieve this end: (i) the identification *a prion* of the types of climate change most critical for agriculture; (ii) the identification of regions most at risk from such changes of climate; (Hi) the consideration of types of impact likely to result from climatic change; and, (iv) the evaluation of adjustments that are likely to occur in agriculture in response to such impacts or to the perception of their risk of occurrence. These four approaches will be followed, in turn, in this report.

2.2 Critical types of climatic change

The potentially most important changes of climate for agriculture, upon which there is some agreement by GCMs, include changes in climatic extremes, warming in the high latitudes, poleward advance of monsoon rainfall, and reduced soil water availability (particularly in mid latitudes in midsummer, and at low latitudes).

2.2.1 Climatic extremes

It is not clear whether temporal variances in temperature or precipitation will occur as a result of climatic change. However, even if variances remain the same as under the present climate, an increase in monthly or annual average temperatures will result in the increased frequency of occurrences of days with temperatures above particular thresholds. Changes in the frequency of distribution of precipitation is not as certain, but the combination of elevated temperatures and drought constitutes the greatest risk to agriculture in many regions from global climatic change.

2.2.2 Warming in high latitudes

There is relatively strong agreement among GCM predictions that warming will be greater at higher latitudes. This will reduce temperature constraints on high-latitude poleward agriculture, increase the competition for land here, and result in the northward retreat of the southern margin of the boreal forest (these possible effects are discussed in detail in Section 3.4.1). Warming at low latitudes, although less pronounced, is also likely to have a significant effect on agriculture.

2.2.3 Poleward advance of monsoon rainfall

In a warmer world the intertropical convergence zones (ITCZs) would be likely to advance further poleward as a result of an enhanced ocean-continent pressure gradient (itself the result of more warming of the land surface in the pre-monsoon season). If this were to occur - and it should be emphasised that this conclusion is based on GCM equilibrium experiments, and that the transient response could be different - then total rainfall could increase in some regions of monsoonal Africa, monsoonal Asia and Australia, though there is currently little agreement between GCMs on which regions these might be. Rainfall could also be more intense in its occurrence, so flooding and erosion could increase.

2.2.4 Reduced soil water availability

Probably the most important consequences for agriculture would stem from higher potential évapotranspiration, primarily due to the higher temperatures of the air and the land surface. Even in the tropics, where temperature increases are expected to be smaller than elsewhere, the increased rate of loss of moisture from plants and soil would be considerable. It may be somewhat reduced by greater humidity and increased cloudiness during the rainy seasons, but could be pronounced in the dry seasons.

At present we cannot be certain about the regional pattern of soil water changes that may occur. There are, however, regions in the world where the GCM predictions are in some agreement regarding such changes. The following is a summary of those regions where current 2 x CO_2 experiments by three GCMs (GISS, GFDL and NCAR) all project decreases in soil water (Kellogg and Zhao, 1988; Zhao and Kellogg, 1988; Schlesinger and Mitchell, 1985). It should be emphasised that coincidence of results for these regions is not statistically significant and that the evidence available at present is extremely weak. Moreover, the significance of decreases in soil water will vary considerably from region to region according to whether they occur during the growing or non-growing season.

i) Decreases of soil water in December, January and February

Africa: Horn of Africa[1], southern Africa[1], western West Africa[2]
Asia: western Arabian Peninsula, Southeast Asia

1 Note it should be emphasised that recent (and, in some cases, unpublished) GCM experiments do not produce drying in these regions

2 Note changes over western West Africa are small

Australasia: eastern Australia
North America: southern United States
South America: northern Argentina

ii) Decreases in soil water in June, July and August:

Africa: Maghreb, West Africa, Horn of Africa[1]
Europe: parts of Western Europe
Asia: north and central China, (including Mongolia); Soviet central Asia and parts of Siberia
North America: southwestern United States, and central America
South America: eastern Brazil
Australasia: western Australia

The regions identified above are those where soil water may decrease in an equilibrium climate for doubled equivalent CO_2. But different latitudes could approach equilibrium at different rates of change in temperature and rainfall because they include different amounts of land, which warms up faster than ocean. Thus the time-evolving patterns of soil water change could vary significantly from the equilibrium simulation. Moreover, the effects of climatic changes on agriculture are likely to be greater during periods of rapid change, before equilibrium is reached and before farming systems have had time to adapt to their altered environment. Despite these important caveats, we may conclude that there may be some regions where significant reductions in agricultural potential occur due to decreases in crop water availability. There is at present, however, little agreement as to which regions these will be.

2.3 Present-day vulnerability to climate

In addition to the unequal regional pattern of critical types of climatic change, there are important inequalities in the distribution of present-day vulnerability to climate. Since climate is the major factor limiting potential productivity at the global level, changes of climate are likely to have substantial effects on such limits. Insufficient temperature and rainfall are the main climatic limits which operate largely through the curtailment of the growing period. Overall, 63% of the land area of developing countries is climatically suited to rain-fed agriculture, but this endowment varies considerably between regions (FAO, 1984). It amounts to as much as 85% in South America, 84% in Southeast Asia, but is limited to 64% in Central America and 53% in Africa. The severest climatic limitations to rain-fed agriculture are to be found in Southwest Asia where 17% is too mountainous and cool, and 65% is too dry, leaving only 18% as potentially productive (FAO, 1984).

These climatic limits to agriculture, in combination with soil constraints (particularly shallowness, poor drainage and salinity) mean that the potential base for rain-fed agriculture is quite limited in certain regions. Any further curtailment of potential owing to changes of climate could severely strain the ability of many developing countries to feed their population.

Certain regions stand out as particularly vulnerable as a result of climatic and soil constraints on then-land base and their population requirements where, even with high levels of inputs, land resources cannot meet the needs of local populations. These occupy as much as 22% of the global land area and contain 11% of the population. Areas under greatest pressure, where there is a high degree of imbalance between population and land potential, are the cool and cold tropics (eg the Andean region, the Maghreb, the mountain regions of Southwest Asia), the Indian subcontinent, and parts of mainland and insular Southeast Asia.

2.4 Regions of risk

One means of identifying regions most at risk from climate change is to combine the two preceding analyses, noting those regions which (i) are regions where preliminary projections indicate decreases in soil water under equilibrium 2 x CO_2 climates and also which (ii) are regions identified as critically vulnerable in terms of their resource ability to support existing population. These regions at risk are:

Africa: Maghreb, West Africa, Horn of Africa, southern Africa
Asia: western Arabia, southeast Asia
North America: Mexico and Central America
South America: parts of eastern Brazil

2.5 Critical vulnerabilities in food trade

An additional set of regions that deserves particular attention includes the food-exporting countries, which are the source of most of the world's traded cereals. Here, substantially adverse or beneficial changes of climate could markedly affect the amount of traded food and its price. A key role in the world food system is played by a few food-exporting countries, with only 21 out of 172 countries in the world currently being net exporters of cereals. In 1987, 77% of all traded cereals derived from only three countries.

The major food-producing countries, because of their key role as holders of large food stocks, are doubly important to the world food system. In 1988-

89 the US, Canada and European Community held almost one-third of the world's stock of wheat and coarse grain (mainly maize, sorghum and barley). The US held 17% of wheat and 47% of maize.

In addition, it should be noted how sensitive world food security remains to variations in weather. To illustrate, in 1987-88 world wheat and coarse grain stocks stood at 353 million tonnes (mt), but fell to 248 mt in 1988-89 and are estimated to be 249 mt in July 1989 (International Wheat Council, 1989). Most of this fall is attributable to reductions in stock in North America due to the 1988 heatwave and drought in the Great Plains and Corn Belt. Closing stocks of wheat in the US fell from 49 mt in 1986-87, to 34 mt in 1987-88 and to 17 mt in 1988-89. Thus factors affecting stocks in North America also affect world food stocks and prices.

These 'breadbasket' countries are critical to the world food system, being regions where relatively small percentage changes in production due to changes of climate could have severe impacts on the quantity, price and type of food products bought and sold on the world food market.

The following list summarises those regions and countries which are both net food exporters and for which there is some agreement between GCMs regarding reductions in soil water under 2 x CO_2 climates:

Europe: parts of Western Europe
North America: southern US
South America: northern Argentina
Australasia: western Australia.

2.6 Potential effects on agriculture and land use

2.6.1 Types of effect

Three types of effect of climatic change on agriculture are considered in this report: (i) the physiological ('direct') effect of elevated levels of atmospheric CO_2 on crop plants and weeds, (ii) the effect of changes in parameters of climate (eg temperature, precipitation and solar radiation) on plants and animals, and (iii) the effects of climate-related rises in sea-level on land use (considered in section 2.8)

2.6.2 'Direct' effects of elevated CO_2 and other greenhouse gases

Considerable basic physiological information is now available from a large number of studies showing that increases in ambient CO_2 have diverse and profound effects on plant growth. These effects of elevated CO_2 can be experimentally demonstrated with concentration increases in the upper end of the range expected to occur by the middle of next century. The major effects are on photosynthesis and respiration and thereby on growth (the accumulation of dry matter), and there are additional effects of increased CO_2 on development, yield quality and stomatal aperture and water use (see Gifford, 1988; Morison, 1989).

i) Photosynthesis, respiration and growth

In general, as photosynthesis is the net accumulation of carbohydrates formed by the uptake of CO_2, increased CO_2 results in increased photosynthesis. A doubling of CO_2 increases the instantaneous photosynthetic rate by 30% to 100%, depending on the other environmental conditions (Pearcy and Bjorkman, 1983). The balance between the photosynthetic gain and loss of carbohydrate from plants by respiration is the resultant growth. Unfortunately, the response of respiration to CO_2 has been little studied and there are suggestions that respiration could be lower rather than higher owing to a changed carbohydrate status (Bunce, 1989). This process may underlie some of the unexpectedly high responses of growth to increased CO_2 that have been observed. Within single species there are differences in responsiveness between different varieties and genotypes, differences that offer the possibility of breeding for optimum advantage with increased CO_2. In order to take full advantage of such opportunities these varieties and genotypes must be identified now.

In the overwhelming majority of cases the effect of CO_2 on productivity has been shown to be beneficial - if all other factors are maintained constant - and a 10-50% increase in dry matter accumulation can occur in most species with a doubling of ambient CO_2 concentration. In a summary of 770 studies the mean mature yield increase for C3 crops (see below) was 26% but the extremes ranged from a decrease of 20% to an increase of 200% (Kimball, 1983). For temperate cereals the mean increase observed in grain yield was 36%. The large range in effect of CO_2 can, to some extent, be attributed to species differences, however few realistic studies under comparable conditions have been made.

Part of the variation in results can also be attributed to interaction with other environmental conditions, which is clearly of importance as increased CO_2 will occur in combination with changes in temperature, rainfall etc. A doubling of CO_2, for example, in addition to increasing net photosynthesis in C3 plants at a fixed temperature, also increases the optimum temperature for photosynthesis by about

4°-6°C (Acock and Allen, 1985; Osmond et al., 1980; Jones, 1986). This may appear to be of considerable advantage in warmer climates, but the optimum range of temperature for photosynthesis also narrows. In present conditions temperature has relatively little effect over a broad range for most plants growing in the habitats to which they are currently adapted. Under elevated levels of CO_2, photosynthesis and, by inference, growth rate, may therefore become more variable as temperature conditions vary.

The interactions with other environmental conditions are critical in determining the net effect of increased CO_2. In particular, it has been demonstrated that in adverse conditions (eg nutrient limitation, water shortage, salinity, cool temperatures and air pollution) the relative effect of increased CO_2 is larger than under optimal conditions (Morison, 1988; Warrick et al., 1986). Indeed, increased CO_2 could improve growth sufficiently to make saline and polluted environments more productive though, as with all of these interactions, insufficient data exist to produce quantitative predictions. Another environmental interaction for which few, if any, studies have been completed is the combined effect on agriculture of acidic depositions and GHG-induced changes.

ii) C3 and C4 plants

Two groups of plants differ in their fundamental carbon fixation biochemistry - the C3 and C4 groups. It is widely accepted that the response of growth to elevated CO_2 in C3 plants (eg wheat, rice, barley, root crops, legumes) is larger than that of C4 plants (eg maize, sorghum, millets, sugarcane). It has been estimated that the average effect of doubled CO_2 concentration on wheat grain yield is an increase of 35% (from eight studies, Cure, 1985) while that on maize has not been adequately quantified (Cure, 1985). Most crops grown in cool, temperate or moist habitats are C3 plants, as are all trees. The C3 group therefore accounts for most of the world's plant biomass.

Although C4 crops account for only about one-fifth of the world's food production they are a particularly important source of world food in the tropical regions. Maize alone accounts for 14% of world food. Moreover, many pasture and forage grasses worldwide are C4 including important prairie grasses in the US and in the subtropics and tropics (Edwards and Walker, 1983).

In addition, 14 of the world's most troublesome 17 terrestrial weed species are C4 plants in C3 crops (Morison, 1989). The difference in response to CO_2 may make such weeds intrinsically less competitive, but the final outcome will depend on the relative response of crop and weed to climatic changes as well. C3 weeds in C4 crops may increase as a problem.

Changes in relative crop performance may force changes in areas sown, for example increasing areas of soybean and reducing areas of maize. This may accelerate the existing trend in the third world countries to replace C4 crops with C3 as a response to the promise of high-yielding varieties of wheat, rice and barley. For example, in the last 20 years in India there has been a reduction in the production of C4 crops from 40% to only 23% of the total cereal production. Conversely, it may counteract the current poleward expansion in the temperate zone of grain maize which would otherwise follow increases in global temperature. Similarly, it may reverse the current trend away from perennial rye-grass (C3) towards silage maize as the major forage product in temperate zones (Jones, 1986). Another probable area of impact will be on sugar production, reducing further the value of the sugar-cane crop (C4) in tropical countries relative to the success of sugar beet in the temperate zone.

A third biochemical group of plants that is locally important in the arid zone are those with CAM metabolism (Crassulacean Acid Metabolism), which includes many plants in the cactus family, the *Crassulaceae* and desert succulents. The species in this group of major commercial importance are sisal and pineapple. These plants will show little or no response to increased CO_2, thus eroding their competitive advantage over common C3 weeds and reducing yields relative to C3 crops.

Hi) Plant development

Some developmental processes such as flowering have also been shown to be affected by elevated CO_2 in both positive and negative directions, although this has not yet been widely studied (Morison, 1989). If the developmental process is affected then the progress of the crop through the different stages of the life cycle is altered, thus potentially shortening or lengthening the required growing period. In temperate zones this may mean decreases or increases in yield, respectively, but in seasonally arid areas any lengthening of the required growing season is generally associated with increased drought risk. Since many of the advances in cropping in such areas have been due to the introduction of shorter duration varieties, the developmental response of the crops of these areas urgently needs to be examined. As with the other processes affected by CO_2, genetic variation in responsiveness is evident and could prove amenable for selection by traditional and modern breeding methods.

iv) Yield quality

The amount of information available on the effect of increased CO_2 on quality is very small compared to that on dry matter production. Some changes in composition of crop tissue have been noted, though much remains to be done. Generally, there is a rise in the total non-structural carbohydrate content (starch and sugars) with increase in CO_2 concentration (Bazzaz et al., 1985; Strain, 1985). This is particularly the case at low temperatures. For fruits, grains and vegetables this change in carbohydrate status may affect palatability, nutritional value and taste, as well as storage qualities.

Nitrogen content of leaf, stems and fruits is generally reduced by high CO_2. This has been clearly demonstrated in species as diverse as white oak, soybean, *Echinochloa* (a C4 grass), wheat, cotton, lettuce and cucumber. This implies reduced protein levels and reduced nutritional value for livestock, pests and disease organisms and humans. Over the last 40 years there has been a 1-to-l relationship between nitrogen applied to wheat crops in the UK and the nitrogen taken off in the grain and straw (Austin, 1988). With increased CO_2 the same yield may be produced with less nitrogen fertiliser application. However, the bread-making quality of the grain may be diminished unless there are changed management and varieties to counteract this effect.

Further, in the very few experimental studies carried out, pest herbivory was altered under conditions of high CO_2: more leaves were eaten but individuals were smaller with probable reductions in population growth. Changing the carbon to nitrogen and carbon to phosphorus ratio of plant material also has consequences on the decomposition processes in agricultural and forest soils, leading to reductions in decomposition rates and decreases in ecosystem productivity (Dahlman et al., 1985).

v) *Stomatal aperture and water use*

Increases in atmospheric CO_2 reduce the water requirements of plants by reducing transpiration (per unit leaf area) through reductions in stomatal aperture. A doubling of CO_2 causes partial stomatal closure in both C3 and C4 plants (approximately a 40% decrease in aperture, Morison, 1987). In many experiments this results in reductions of transpiration of about 23% to 46% (averages compiled by Cure and Acock, 1986; Kimball and Idso, 1983). However, there is considerable uncertainty over the magnitude of this effect in natural conditions. Many calculations of evaporation have relied on the Penman-Monteith model for evaporation which includes meteorological and vegetation variables in a sound mechanistic framework. However, its use in predictions is limited as the variables are not independent of each other. At the level of single leaves the evaporation rate affects the leaf temperature, which affects the net radiation, to an extent dependent on the degree of 'coupling' of leaf to the air around it (Morison, 1985 and 1989). There is additional feedback in whole canopies between the humidity in the canopy and the evaporation rate from the plant and the soil surface (Morison, 1989; McNaughton and Jarvis, 1983; Goudriaan, 1989). Further, at the regional scale, the temperature and humidity conditions in the mixed planetary boundary layer are also dependent on the heat and vapour transfer from the vegetation surface. The extent of these feedbacks varies with the microclimatic and vegetation conditions so that predictions of changes in evaporation rates with changed climate and increased CO_2 vary considerably both in magnitude and sign. In addition, increased growth results in greater leaf area so the total water use per plant in high CO_2 may be similar to that in present concentrations (Gifford, 1988), although for complete vegetation stands the changes in leaf area index may change the whole pattern of energy exchange at the surface. The net effect is likely to be small for short, dense, extensive crops and more important in sparse and tall vegetation in semi-arid areas.

vi) Effect on biological nitrogen fixations

Increased levels of CO_2 can enhance nitrogen fixation by leguminous species, through increased rates of photosynthesis. Many C4 species harbour nitrogen-fixing bacteria such as *Axospirullum* and *Azatobactor* in their rhizosphere which contribute to nitrogen fixation and support growth at low nitrogen contents of the soil. The direct effects of CO_2 on nitrogen fixation could be advantageous in grass and legume pastures. However, increased temperature can reduce nitrogen fixation and also increase the energy cost of nitrogen fixation. At what temperature the beneficial effects of CO_2 would be counteracted is difficult to predict, but the existing strains of *Rhizobium* which are adaptable at low temperature may require replacement for deriving the potential benefits of enhance CO_2. This would also apply to many tree species which fix nitrogen through rhizobial and non-rhizobial symbiosis. However, limiting water conditions could impair these effects. More research in this important area is needed.

vii) Effects of increases in other greenhouse gases

The other GHG contributing to the greenhouse effect are methane (CH_4), nitrous oxide (N_20), tropospheric ozone (0_3) and halocarbons (CFCs). Carbon monoxide is also involved as it exerts strong control over the chemistry of the troposphere and lower stratosphere and affects the concentration of the GHG.

Methane and nitrous oxide are both products of agricultural systems, the former from anaerobic respiration in rice paddies and animal rumens, and the latter from denitrification (oxidation) of soil nitrate by bacterial respiration. However, there is no evidence that atmospheric concentrations of these gases will lead to direct effects on animals or plants. Other pollutant oxides of nitrogen (NO and $N0_2$ occur at lower concentrations and can cause crop damage at concentrations in the ppb range such as typically arise from local sources of fossil fuel combustion.

Carbon monoxide does not affect plants, and a major sink for carbon monoxide produced by fossil fuel burning is soil uptake and microbial oxidation. In humans and presumably in other mammals used in agriculture the concentrations at which health is affected start at 10-50 ppm, whereas atmospheric concentrations are in the range of 100 ppb, ie 100-500 times lower (Wellburn, 1988).

Halocarbons have no direct effects on plants or animals at atmospheric concentrations.

Ozone is a potent inhibitor of plant growth and has effects on animal health. The US Health Standard requires that an hourly mean of 120 ppb should not be exceeded more than once a year. In practice during photochemical smog episodes in industrial areas, concentrations exceed these levels frequently, for several days at a time. However, these are local episodes related to strong local sources of pollutants and are not global means. Surface monitoring stations suggest annual average background concentrations of 15-30 ppb (Penkett, 1988) in the troposphere. A large amount of experimental evidence has shown that filtering air of normal pollutant concentrations of 0_3 can enhance crop growth. For example, removal of mean seasonal concentrations of 80 ppb in the southeast US can enhance crop yield by 10-50% (Heck et al., 1982). Any further increases in troposphere 0_3 will there-fore add to this damage.

2.6.3 Effects of changes in climate

i) Introduction

This section discusses those effects on agriculture that may occur as a result of GHG-induced changes of climate. Consideration is given, in turn, to (i) effects on agroclimate, (ii) effects on pests and diseases, (iii) effects on other aspects of the agricultural environment such as soils, (iv) effects on crop yields and livestock and (v) effects on agricultural production.

ii) Effects on agroclimate

Shifts of thermal limits to cropping Increases in temperature can be expected to lengthen the growing season in areas where agricultural potential is currently limited by insufficient warmth, resulting in a poleward shift of thermal limits of agriculture. The consequent extension of potential will be most pronounced in the northern hemisphere because of the greater extent here of temperate agriculture at higher latitudes.

An indication of the extent of shift is given by the relocation of critical levels of effective temperature sums (accumulated temperatures) for cropping in northern regions. Taking 1300 day-degrees (above a base of 5°C as the southern limit of the boreal zone, and thus as a proxy northern limit of arable agriculture, this limit shifts about 500-1000 km northwards under the 2 x $C0_2$ equilibrium climate simulated by the GISS GCM (Kauppi and Posch, 1988).

There may, however, be important regional variations in our ability to exploit this shift. The greater potential for exploitation of northern soils in Siberia than on the Canadian Shield, may mean relatively greater increases in potential in northern Asia than in northern North America (Jager, 1988).

A number of estimations have been made concerning the northward shift in productive potential in mid-latitude northern hemisphere countries. These relate to changes in the climatic limits for specific crops under a variety of climatic scenarios, and are therefore not readily compatible (Newman, 1980; Biasing and Solomon, 1983; Williams and Oakes, 1978; Parry and Carter, 1988; Parry et al., 1989). They suggest, however, that a 1°C increase in mean annual temperature would tend to advance the thermal limit of cereal cropping in the mid-latitude northern hemisphere by about 150-200 km; and to raise the altitudinal limit to arable agriculture by about 150-200 m.

While warming may extend the margin of potential cropping and grazing in mid-latitude regions, it may reduce yield potential in the core areas of current production, because higher temperatures encourage more rapid maturation of plants and shorten the period of grain filling.

An important additional affect of warming, especially in temperate and mid-latitudes, is likely to be the reduction of winter chilling (vernalisation). Many temperate crops require a period of low temperatures in winter to either initiate or accelerate the flowering process. Low vernalisation results in low flower bud initiation and, ultimately, reduced yields. A 1°C warming would reduce effective winter chilling by between 10% and 30%, thus contributing to poleward shift of temperate crops (Salinger, 1989).

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 crop calendar which is finely tuned to present climatic conditions. (Kaida and Surareks, 1984; Yoshino, 1984).

Shifts of moisture limits to agriculture There is much less certainty about GHG-induced changes in rainfall than there is about temperature - not only concerning the magnitude of change, but also its spatial pattern and its distribution through the year. For this reason it is difficult to identify possible rainfall-induced shifts in the climatic limits to agriculture. This is particularly so because relatively small changes in the seasonal distribution of rainfall can have disproportionately large effects on the viability of agriculture in tropical areas, largely through changes in growing period when moisture is sufficient and thus through the timing of critical episodes such as planting etc. However, regions where changes in average rainfall may have the most pronounced effect have been outlined in Section 2 (above).

Regions affected by drought, heat stress and other extremes Probably most important for agriculture, but about which least is known, are the possible changes in measures of climatic variability, such as the magnitude and frequency of drought, storms, heatwaves and severe frosts. Some modelling evidence suggests that hurricane intensities will increase with climatic warming (Emanuel, 1987). This has important implications for agriculture in low latitudes, particularly in coastal regions.

Since crop yields often exhibit a non-linear response to heat or cold stress, changes in the probability of extreme temperature events can be significant (Mearns et al., 1984; Parry, 1976). In addition, even assuming no change in the standard deviation of temperature maxima and minima, we should note that the frequency of hot and cold days can be markedly altered by changes in mean monthly temperature. To illustrate, under the GISS 2 x CO_2 scenario the number of days in which temperatures would fall below freezing would decrease from 39 to 20 in Atlanta, Georgia (US), while the number of days above 90°F would increase from 17 to 53 (EPA, 1989). The frequency and extent of area over which losses of agricultural output could result from heat stress, particularly in tropical regions, is therefore likely to increase significantly. Unfortunately, no studies have yet been made of this. The apparently small increases in mean annual temperatures in tropical regions (ca I° to 2°C under a 2 x CO_2 climate) could sufficiently increase heat stress on temperate crops such as wheat that these are no longer suited to such areas. Important wheat-producing areas such as Northern India could be affected in this way.

There is a distinct possibility that, as a result of high rates of evapotranspiration, some regions in the tropics and subtropics could be characterised by a higher frequency of drought, or a similar frequency of more intense drought than at present. Current uncertainties about how regional patterns of rainfall will alter, mean that no useful prediction of this can at present be made. However, it is clear in some regions that relatively small decreases in water availability can readily produce drought conditions. In India, for example, lower-than-average rainfall in 1987 reduced food grains production from 152 mt to 134 mt, lowering food buffer stocks from 23 to 9 mt. Changes in the risk and intensity of drought, especially in currently drought-prone regions, represent potentially the most serious impact of climatic change on agriculture both at the global and the regional level.

Hi) Effects on the distribution of agricultural pests and diseases

Studies suggest that temperature increases may extend the geographic range of some insect pests currently limited by temperature (EPA, 1989; Hill and Dymock, 1989). As with crops, such effects would be greatest at higher latitudes. The number of generations per year produced by multivoltine pests (such as the European red mite and two-spotted mite in New Zealand) would increase, with earlier establishment of pest populations in the growing season and increased abundance during more susceptible stages of growth (Salinger, personal communication, 1989b). An important unknown, however, is the effect that changes in precipitation amount and air humidity may have on the insect pests themselves and on their predators, parasites and diseases. Climatic change may significantly influence interspecific interactions between pests and their predators and parasites.

Under a 2 x CO_2 climate there would be an increase in the over-wintering range and population density of a number of important agricultural pests in the US, such as the potato leafhopper which is a serious pest of soybeans and other crops (EPA, 1989). Assuming planting dates did not change, warmer temperatures would lead to invasions earlier in the growing season and probably lead to greater damage to crops. In the US Grain Belt increased damage to soy-beans is also expected due to earlier infestation by the corn earworm.

Examination of the effect of climatic warming on the distribution of livestock diseases suggests that those at present limited to tropical countries, such as Rift Valley fever and African swine fever, may spread, causing serious economic losses (EPA, 1989). The geographic distribution and activities of other diseases already important in the US may also expand. The horn fly, which currently causes losses of $730.3 million in the US beef and dairy cattle industries might extend its range under a warmer climate leading to reduced gain in beef cattle and a significant reduction in milk production (Drummond, 1987; EPA, 1989). In the 1960s and 1970s a combination of the increased resistance of ticks to insecticides and the high costs of dipping threatened the profitability of the Australian beef industry. Prolonged summer rainfall and an extended developmental season, or conversely prolonged dryness leading to increased nutritional stress in the host, are likely to cause heavy infestations (Sutherest, 1987). If such climatic conditions were to prevail in the future it is likely that ticks could become an increasing problem.

'New* or migrant pests may become established as climatic conditions become more favourable for them. In New Zealand there is the possibility of incipient swarming of locusts now developing in the Northland (Messenger, 1988) which may be an indication of climatic changes (Hill and Dymock, 1989). Indeed favourable climatic conditions in 1986-88 led to locust swarms reaching new limits in southern Europe (Pedgley, 1989).

In temperate regions, where insect pests and diseases are not generally serious at present, damage is likely to increase under warmer conditions. In Iceland, for example, potato blight currently does little damage to potato crops, unlike in warmer regions, being limited by the low summer temperatures. However, under a 2 x CO_2 climate that may be 4°C warmer than at present, crop losses to disease may increase to 15% (Bergthorsson et al., 1988).

Most agricultural diseases have greater potential to reach severe levels under warmer conditions. Fungal and bacterial pathogens are also likely to increase in severity in areas where precipitation increases (Beresford and Fullerton, 1989). Under warmer and more humid conditions cereals would be more prone to diseases such as Septoria. Also, increases in population levels of disease vectors may well lead to increased epidemics of the diseases they carry. An example would be increases in infestations of the Bird Cherry aphid *(Rhopalosiphum padi)* or Grain aphid *(Sitobian avenae)* leading to increased incidence of Barley Yellow Dwarf virus in cereals.

iv) Indirect effects on agriculture through effects on other environmental processes

There are numerous other paths by which changes in climate can have an indirect but important effect on agriculture, largely through concurrent effects on other physical systems.

Probably the most important, but about which we currently know little, is the effect on water resources for irrigation, particularly through changes in snow fall, spring snowmelt and groundwater recharge. In mid-latitude, mid-continental areas there are indications that reduced amounts of rainfall and snow fall could significantly reduce rates of groundwater recharge thus increasing rates of groundwater depletion. This could be the case, for example, with the Ogallala aquifer in the central US (EPA, 1989). In tropical regions, particularly areas of monsoon rainfall, increased intensity of rainfall could result in more runoff, but no increase in percolation or less available water in spite of increases in total rainfall amount. A similar effect could occur in some currently maritime mid-latitude regions, such as northwest Europe, where higher temperatures may result in a larger proportion of the total rainfall occurring from convective thunderstorms, with consequent increased intensity of rainfall, increased runoff and reduced percolation (Beran and Arnell, 1989).

Changes in the intensity of rainfall may affect rates of soil erosion and desertification. In addition, higher rates of évapotranspiration could, in some regions, lead to more frequent spells during which topsoils are dry and therefore prone to erosion by wind. In Saskatchewan, for example, the frequency of moderate and extreme droughts is estimated to increase threefold under the GISS 2 x CO_2 scenario, with significant changes in the potential for wind erosion (Williams et al., 1988).

In major parts of the world where rain-fed agriculture is practised, the premium on soils with a large available water capacity may increase, because of the expected change to higher ET rates and greater variability in rainfall. This emphasises the need for sound land husbandry practices incorporating effective soil conservation.

A third, and more long-term, consequence of changes in rainfall may be changes in soil fertility resulting from changes in soil base status. In regions where rainfall increases, there may be an increased tendency for soil leaching and consequent reductions of fertility. For example, it has been estimated that soil fertility in the Leningrad region of the USSR could fall by more than 20% by the year 2035 as a result of rainfall increases and in spite of assumed trended increases in fertiliser application (Pitovranov et al., 1988a).

v) *Potential effects on crop yields and livestock productivity*

The following is a summary of current estimations, both published and unpublished, of the potential effects of climate change on crop and livestock productivity for different regions of the world. It should be emphasised that such potential effects are those estimated assuming present-day management and technology. They are not the estimated actual effects, which depend on how farmers and governments respond to the altered potential through changes in management and technology.

Unless otherwise stated the following estimates are for climates described by 2 x CO_2 GCM experiments. Also, unless otherwise stated, they are based on quantitative results from experiments with crop response models, not qualitative estimations derived from expert judgment.

North America

US: warming of 3.8° to 6.3°C, with soil moisture reduced by 10% (which is consistent with the GISS and GFDL 2 x CO_2 climate) is estimated to decrease potential yields of maize allowing for the limited beneficial fertilising effect of enhanced CO_2 on this C4 plant, by about 4-17% in California, 16 to 25% on the Great Plains (assuming irrigation), and by 5-14% in the southeast (also assuming irrigation) (EPA, 1989). In the Great Lakes region there could be a small increase in potential yields, depending on available moisture. Potential wheat yields decrease in the southern and central Great Plains, even with the beneficial direct effects of enhanced CO_2. Some northward shift of productive potential is evident. On average, over the region, dryland wheat yields decrease by 2-3%, and irrigated yields increase by 5 to 15% (EPA, 1989). Dryland soybean yields show a wide range of decreases from -3% in the Great Lakes region to between -24% to -72% in the southeast. Irrigation could offset much of these potential losses.

Canada: a warming of 3°-4°C, accompanied by reduced soil moisture consistent with the GISS 2 x CO_2 climate, is estimated to decrease yields of spring wheat nationally by about 19%, with regional variations from ca 18% in Saskatchewan, to ca 10% in Manitoba, to a small increase near the current northern limit of production (Williams et al.,1988; Smit, 1989). An expansion of wheat into the Peace River District might be possible, though elsewhere soils and terrain would continue to limit agriculture. Winter wheat would probably be better able to withstand an increased frequency of spring and early summer drought and might expand its area at the expense of spring varieties (though its yield is also expected to decline by about 4%). Yields of grain corn, barley, soybeans and hay are expected to decline in all but the northern part of Ontario (Smit, 1989). There would also be a decrease in yields of potatoes and forage crops in most regions of Canada.

Central and South America

Mexico and Central America: a warming of 3.3° to 5.4°C (consistent with 2 X CO_2 GCM projections) combined with either increases or decreases in rainfall (-23% to +3% depending on GCM) are likely to produce warmer, drier conditions and reductions in soil moisture of 10-20%. This could result in decreases in yields of maize and other rain-fed crops (of 5% to 25%), and, combined with heat stress and irrigation water scarcity, decreases in yields of major irrigated crops such as wheat (-Liverman, personal communication, 1990). If there were increases in rainfall, particularly rainfall intensity, this could lead to enhanced rates of soil erosion and consequent long-term loss of productive potential (Ramirez, personal communication, 1989).

Brazil: in the most vulnerable region of Brazil, the northeast, much depends on whether increases in precipitation are sufficient to compensate for increased potential évapotranspiration due to higher temperatures. An insufficient increase in rainfall is likely to lead to a serious decline in yield potential. For example, short-term rainfall decreases in the El

Nino years 1982-83 reduced total agricultural production in northeast Brazil by almost a quarter (Magalhaes, et el., 1988).

More precipitation in the centre-west would probably increase productivity in soybeans and, in the south, of wheat. A reduction in the frequency of frosts would decrease the risks in citrus and coffee production in the south (Magalhaes, personal communication, 1989).

Argentina, Chile and north Andean region: according to 2 x CO_2 GCM experiments, rainfall is projected to increase in currently moist areas and decrease in the semi-arid areas in the rain shadow of the Andes.

Increases of 2°-4°C would increase évapotranspiration by at least 10%, possibly leading to a drying of the Pampas. Cattle raising might become less productive (Salinger, 1989a). In the more maritime climate of Chile, increased winter precipitation could counter the small increases in évapotranspiration more than in Argentina. Grass production and cattle raising would probably stand to gain most in the centre and south. At high levels in the Andes, where cultivation limits are constrained by winter minimum temperatures, a 1°C warming would raise limits by ca 200 m (3800 m to 4000 m in central Ecuador) (Bravo et al., 1988). Increases in rainfall would probably lead to decreases in yields of barley but increases in those of potatoes.

Europe

Northern Europe: agriculture in Fennoscandia stands to gain from global warming more than perhaps any other region of the world. For example, in Finland, where the equilibrium 2 x CO_2 climate is projected to be ca 4°C warmer and also wetter than at present, yields of adapted cultivars of spring wheat are estimated to increase by about 10% in the south, up to 20% in central Finland, and more near the current northern limit of wheat. Yields of barley and oats are raised by 9-18%, depending on the region in Finland (Kettunen et al., 1988). In Iceland the carrying capacity of improved grassland for sheep is estimated to increase by about two-and-a-half times, and on unimproved rangeland by more than a half (Bergthorsson et al., 1988).

Northwest Europe: in the more maritime areas of this region (eg Ireland, UK, northern France, Netherlands, Belgium, Denmark) yields of indeterminate crops such as grass and potatoes would tend to increase under higher growing season temperatures, assuming sufficient increases in precipitation to counter higher rates of évapotranspiration. To illustrate, under a warming of ca 3°-4°C, grass yields in the Netherlands may increase by about 10% (Klijn et al., 1987) and potato yields in the UK by 50-75% (Squire and Unsworth, 1988). In addition, some crops which are now barely profitable to grow because of inadequate summer warmth (such as grain maize in the southern UK) may extend their profitable range several hundred kilometres further north (Parry et al., 1989). The yields of determinate crops such as wheat would, however, decrease with increasing temperatures - though in C3 crops these would be partly compensated by the direct effect of enhanced CO_2. In the UK it is estimated that the beneficial direct effect of doubled ambient atmospheric CO_2 on yields of winter wheat would be completely offset by the adverse effect of a mean annual temperature increase greater than 4.5°C (Squire and Unsworth, 1988).

Southern Europe: in the Mediterranean region quite substantial decreases in productive potential could occur if the GCMs are correct in predicting decreases in soil moisture in the summer, and possibly also in the winter months. Under a warming of 4°C and with annual rainfall reduced by >10% (the BMO 2 x CO_2 climate), biomass potential in Italy and Greece is projected to decrease by 5% and 36% respectively (Santer, 1985). In general there is a quite striking contrast between the increases in biomass potential in northern Europe and decreases in southern Europe that are implied by current GCM projections of GHG-induced changes in temperature and rainfall. This suggests an important northward shift of the balance of agricultural potential in the European Community.

Alpine Europe: in the European Alps a 1°C warming can be expected to raise climatic limits to cultivation by ca 150 m, (Balteanu et al., 1987) and a 4°C warming of the order projected for a doubling of atmospheric CO_2, would probably raise climatic zones in the Alps by 450-650 m, which would then be similar to the levels of those today in the Pyrenees which lie 300 km south of the Alps (Balteanu et al., 1987).

USSR and mid latitudes, Northern Hemisphere: Previous studies using the 2 x CO_2 GISS scenario assessed impacts on winter wheat, maize, rye, barley, oats, potatoes and green vegetables (Pitovranov et al., 1988a; Pitovranov et al., 1988b), but the most detailed current assessment is based on palaeoclimatic analogs.

The impact on potential crop productivity of three palaeoclimatic scenarios (Holocene Optimum, Eemian Interglacial, and Pliocene Optimum) was gauged including estimates of the direct effect of increased CO_2 concentration (Koval et al., 1983;

Mendzhulin et al., 1987; Mendzhulin, personal communication, 1989). The results of these studies for the mid latitudes of the Northern Hemisphere indicate that with 1°C of warming (ca 2000) there would be regional differences in moisture conditions, leading to a decrease in potential productivity in the drier parts of the mid-latitudes. This decrease in potential productivity may well be within the current limits of agricultural adaptation to climate variations. The Eemian and Pliocene palaeoanalog studies indicate improved moisture conditions which together with the beneficial effects of CO_2 enhancement were estimated to result in increased potential productivity of C3 crops.

A further set of calculations was made based on an empirical analysis of historical yield data to estimate the year-to-year variability of wheat yields for the three palaeoanalogs (Mendzhulin et al., 1985,1987), This study showed that in the Holocene analog (through the early part of the next century) a small increase in yield variability may occur in a number of mid-latitude regions. With global warming of 1°C yield variability for less favourable North American grain regions was estimated to be equivalent to the present-day yield variability of the most favourable grain region of the USSR (the Krasnodar region). With further warming corresponding to the Eemian Interglacial (+2°C by 2030) and subsequently the Pliocene Optimum (+3° to 4°C by late in the 21st century) the year-to-year yield variability was estimated to decrease in all mid-latitude grain regions of the Northern Hemisphere.

A regional study by Abashina and Sirotenko (1986) and Sirotenko et al. (1984 and in press) for each administrative unit of the European USSR used a dynamic model of productivity for various crops (Sirotenko, 1981). These studies considered the changes in surface biomass and the yield of some C3 grain crops for several levels of soil fertility for the Holocene and Eemian scenarios. For warming up to 1°C (up to 2000) there were regional variations in agroclimatic potential: a decrease of 5-10% was estimated for the steppe and forest-steppe zones of the USSR and an increase of up to 8% was found for the non-chernozem zone. With further warming, agroclimatic potential was estimated to increase by 5-10% in all but two regions of the European USSR for a warming of 1°C (after 2000) and by 10-20% with warming of 2°C (ca 2030).

Middle East

Few estimations of possible impacts have been completed for this region. Projected changes include an increase in temperature of ca 3.5°C and possible decreases in rainfall (of perhaps 0.5 mm per day, although this is very uncertain). Evidence from experiments in Israel indicate that under these changes of climate wheat yields would be reduced by up to 40% (Van Diepen et al., 1987).

Smaller increases in temperature (eg of 1°C) are estimated to decrease barley yield by ca 5% and any corresponding reduction in rainfall could result in decreases in excess of 20% without additional irrigation (evidence for Cyprus from Pashiardis and Michaelides, 1989).

Africa

Maghreb: assuming an increase in annual temperature of 1.5°C, évapotranspiration would increase by more than 10%, leading (without) any change in rainfall) to a decrease in river flow of more than 10% (Salinger et al., 1989a). The likelihood is that the irrigable area will contract, requiring a shift from arable farming to cattle ranching.

West Africa and northeast Africa: a northward shift of the ITCZ, which is implied by GHG warming, is expected to increase summer precipitation (Working Group I Report).

However, evaporation also increases, so that there are both increases and decreases of crop-water availability over the region, and it is at present uncertain how these differences will be geographically distributed. Where precipitation exceeds évapotranspiration this could reduce current constraints on agriculture by increasing crop-water availability. It could also be expected, however, to encourage the northward extension of locusts and other pests (Boko, 1988).

Where increases in precipitation were insufficient to compensate for increases in évapotranspiration under high temperatures, this would reduce crop-water availability. Although no specific impact assessments have yet been completed for this region, studies of analogous individual dry years in Benin and Nigeria such as those of 1973 and 1978, imply substantial reductions in agricultural output (Boko, 1988; Oguntoyinbo, personal communication, 1989).

Any decreases in rainfall or its concentration into a shorter rainy period could reduce yields of maize and the carrying capacity of rangeland for cattle. Erosion and flooding could become more troublesome in mountain regions such as in Ethiopia (Haile, 1989)

East Africa and southern Africa: estimated increases in temperature for an equivalent doubling of atmospheric CO_2 are around 1.5°C to 3.5°C for this region, depending on latitude. This would lead to rates of évapotranspiration being increased by ca 5%

to 15% (Schulze, personal communication, 1989). Much depends on changes in precipitation, which would profoundly affect maize yields and grass growth (and thus carrying capacity) of rangelands. In Kenya, the driest 10% of years occurring at present lead to reductions of maize yield by ca 30% to 70% and of forage yield by 15-60% (Akong'a et al., 1988). Any changes in the frequency of such years would clearly substantially affect the average output of agriculture in the region. Improved knowledge of possible GHG-induced changes in the probability distribution of rainfall in this and other semi-arid regions is thus a matter demanding a high priority in future research.

Asia

China: there are indications that global warming would lead to a weaker winter but stronger summer monsoon. Rainfall receipt could thus increase in already rainy areas, and would extend further westward and northward than at present. If this were to occur then the risk of flooding in southern China, which is already serious in wet years, might be significantly increased. Under a 1°C warming and with precipitation increases of 100 mm yields of rice, maize and wheat are estimated to increase by about 10% overall nationally, though there may be modest decreases in the north and east (Zhang, 1989).

Without increases in available moisture, however, maize yields in the eastern and central regions decrease on average by 3% per 1°C increase (Terjung et al., 1984).

India: in Northern India a temperature increase of 0.5°C is estimated to reduce wheat yields by about 10% (Sinha, personal communication, 1989). Similar increases in central India would probably lead to larger percentage reductions from a lower base yield. However, given sufficient increases in rainfall, rice yields may increase perhaps ca 7% with +2.5°C and +0.75 mm rainfall per day (Van Diepen et al., 1987). The fertilising effect of CO_2 could enhance this increase to over 20%. Sorghum yields in central southern India are estimated to decrease in response to higher temperatures during the rainy season, owing to premature development and reduced grain filling (Jodha et al., 1988). During the post rainy season, however, when moisture is currently in short supply, increases in temperatures may lead to increases in yield because the period of moisture stress would be reduced by a shortened growing period.

SE Asia: intensification of the SE Asia monsoon would tend to lead to increased summer but reduced winter rainfall. Preliminary indications are that with rainfall changes of +5% (summer) and -11.4% (winter) (which equate to a GISS 2 x CO_2 climate), irrigation requirements in northern Thailand would decrease by ca 3% in summer and increase by ca 30% in winter (Panturat and Eddy, 1989). Resulting potential rice yields would decrease by 1-7%, although the direct CO_2 effect could enable increases of 4-13%. Increases in temperature expected under an equilibrium 2 x CO_2 climate are +0.3° to +0.5°, which could lead to reduced rice and maize yields (due to more rapid crop growth) and to an increase in losses to pests (Nguyen Huu Ninh, personal communication, 1989). Experiments in the Philippines indicate that increased summer rainfall, with small increases in temperature combined with the effect of elevated CO_2 could raise rice yields by up to 30% (Van Diepen et al., 1987).

Japan: under a warming of 3°-3.5°C and a 5% increase in annual precipitation (the GISS 2 x CO_2 climate), rice yields are expected to increase in the north (Hokkaido) by ca 5%, and in the north-central region (Tohoku) by ca 2%, if appropriate technological adjustments are made (Yoshino et al., 1988). The average increase for the country overall is ca 2-5%. Cultivation limits for rice would rise about 500 m and advance ca 100 km north in Hokkaido. Yields of maize and soybeans are both estimated to increase by about 4%. Sugarcane yields in the most southern part of Japan could decrease if rainfall was reduced. The northern economic limit of citrus fruits would shift from southern Japan to northern Honshu Island (Yoshino, personal communication, 1989). Net primary productivity of natural vegetation is expected to increase by ca 15% in the north, ca 7% in the centre and south of Japan (Yoshino et al., 1988).

Oceania

New Zealand: grassland production is estimated to increase by 6%, 9% and 18% under a 1°, 2° and 3°C warming. There may be a decrease in the area under wheat, barley and oats and an increase in the area under maize and vegetables (though a decrease of the latter in North Island - Salinger et al., 1989b). Maize yields would increase, as would those of potatoes and other vegetables (except in North Island). The area under pipfruit would shift further southwards in South Island; berry fruit would shift south to South Island. Kiwi fruit yields may increase 15-20%, but the major growing areas may also shift south, as would viticulture.

Australia: there are indications that GHG forcing will lead to increases in summer rainfall where there is at present a summer rainfall maximum, and more uncertainly to decreases in winter rainfall where there is at present a winter rainfall maximum (Pittock, 1989). Under a 40% increase in summer rainfall and 20% decrease in winter rainfall, and with increases in mean annual temperature of 1°C at 10°S, 2°C at 20°S, 3°C at 30°S and 4°C at 40°S, net primary productivity increases by about 30% at 10-20°S, 25% at 20-30°S and 10-15% at 30-40°S (Pittock and Nix, 1986). There would be increases in wheat yields in the eastern wheatbelt, but a decrease in Western Australia (Pittock, personal communication, 1989). Present marginal areas of wheat production, particularly in southwestern Western Australia, northwestern Victoria and western South Australia could decrease. Experimental work suggests that spring wheat yields could increase by about 20% and 27% under a 2°C and 3°C warming respectively, provided there was sufficient water for full irrigation. Dryland wheat yields would decrease unless there occurred a substantial increase in rainfall (Gifford, 1988). The area under maize and sorghum may increase at the expense of wheat, barley and oats, particularly in northern New South Wales. There would be an increase in yields of sugarcane and tropical fruits, with a tendency for a southward shift of these from Queensland into northern New South Wales (Pittock, personal communication, 1989; Linforth, personal communication, 1989). However, yields of temperate fruits (apples, pears etc) would decline and areas of production would be pushed into southern Victoria and Tasmania (Pittock, personal communication, 1989). Increased grass growth would allow greater cattle production, but problems of heat stress in sheep would increase. Cattle might therefore increase their range at the expense of sheep (Pittock, personal communication, 1989). Potential benefits from increased grass growth will unfortunately more than likely be offset by the poor nutritive value of tropical as compared with temperate species. This, together with (a) loss of the Mediterranean-type climatic zones of Victoria and Western Australia, which are the prime lamb and wool producing areas, and (b) increased heat stress of both sheep and cattle, means that livestock productivity will very probably decrease.

Pacific Islands: the most important impacts on agriculture in this region stem from rises in sea-level. In Fiji, for example, islands such as Moala and Vatulele would lose 8.8% and 6.2% respectively of the land area with a 1.5 m rise in sea-level (though this is not currently estimated to occur before 2100). As a consequence, there could be a decrease in the productive potential for subsistence crops, such as yams, and for commercial crops, particularly those such as copra for which production is concentrated on the coastal fringe (Nunn, 1988; New Zealand Intelligence Assessments Committee, 1988). Any increases in frequency of tropical storms could have a detrimental effect on copra production.

vi) Higher order effects on economy and society

The various effects that climatic changes could have on crop yields and the carrying capacity of grassland can, through a web of reinforcing and countervailing circumstances, have a number of higher order effects on (for example) farm incomes, rural employment, national food production, national food security and exports. The latter, in turn, may influence the pattern of international food trade and food prices. This section summarises the range of possible higher order effects and illustrates these by reference to results from recent impact assessments. It does not purport to be a comprehensive statement of such effects, which are bound to be specific to the local economic and political environment, to the technical and management characteristics of particular farming types, and to the rates and magnitudes of climatic change - all of which will vary from region to region. Moreover, the few studies thus far completed are limited to the developed countries and it is important to emphasise that the magnitude of these higher order effects will depend greatly on the technical adjustments and policy responses to climatic changes. The data presented below are therefore simply illustrative of the type of possible effects rather than of their specific nature.

Effects on production costs Some changes in costs of inputs can be expected to flow directly from altered management requirements. In the US, for example, irrigation requirements have been estimated to increase by 20-25% in the southern Great Plains and Corn Belt under a warming of 4.5°C and with precipitation reduced by about 12.5% (95 mm), at a time when groundwater depiction is likely to accelerate as a result of reduced recharge rates from snowmelt in the Rocky Mts (EPA, 1989). The costs of operations to reduce pest damage may also alter (EPA, 1989).

In centrally planned economies, where production targets tend to be fixed and where inputs are often adjusted to counter climate-related variations of yield, it is possible to estimate the extent to which production costs may alter in relation to altered yield potential. In the Central (Moscow) Region of the USSR, for example, a 1°C temperature increase may reduce production costs of winter wheat and corn by 22% and 6%, respectively, while increasing production costs of cool-summer crops such as barley, oats and potatoes (Parry and Carter, 1988; Pitovranov et al., 1988a).

Other, possibly more significant, cost increases may derive from changes in prices of agricultural inputs due to changes in government policy, particularly those policies that may be designed to mitigate the greenhouse effect (for instance, by increasing energy and fertiliser prices). These indirect effects are considered in Working Group III Report.

Effects on net returns, profitability and farm incomes These will depend, among other things, on changes in costs of inputs and the prices of outputs (and no adequate estimation of these is currently feasible). Recent regional impact assessments have considered price responses only within a national, rather than international, context (cf EPA, 1989).

Assuming, unrealistically, that prices and input costs remain constant, then changes in farm profitability and incomes are estimated to alter in sympathy with changes in yield potential. To illustrate, in Saskatchewan (Canada) where spring wheat yields are estimated to decrease by 18% under a warming of 3°-4°C with reduced soil moisture and where yields of other cereals and oilseed are assumed to decline by the same proportion, farm incomes are projected to decline by 7% and farm expenditures on goods from other sectors by ca 0.5% (Williams et al., 1988). In contrast, in southern Finland, increased yield potential is estimated to raise net returns to barley cultivation by about three-quarters (Kettunen et al., 1988). It should be emphasised, however, that these assessments take no account of changes in the worldwide supply, demand and price of agricultural products.

Effects on rural employment, society and settlement Very little attention has been given to these, and such current estimates as exist are based on present-day statistical relationships with farm income, which are likely to change in the future. For example, in Saskatchewan, the reduced farm incomes described above are projected to lead to reductions of 0.8% and 0.5% in agricultural and provincial employment respectively (Williams et al., 1988).

Effects on regional and national production These are strongly dependent on the many adjustments in agricultural technology and management that undoubtedly will occur in response to any climate change. So numerous and varied are these adjustments likely to be, however, that it is extraordinarily difficult to evaluate their ultimate effect on aggregate production. In this part of the report we consider the effects on production that are likely to stem directly from changes in yield, unmodified by altered technology and management. Adjustments in technology and management will be discussed later (Section 2.7). Unless otherwise stated the following estimates are for impacts under GCM 2 x CO_2 scenarios of altered climate.

The large regional differences in estimated altered production in the US typifies the complexity of the issue: the largest reductions under a range of possible 2 x CO_2 climates are projected for sorghum (-20%), maize (-13%) and rice (-11%) (EPA, 1989). Overall, production is estimated to be sufficient for domestic needs, but the potential for export is reduced. In Canada, production is estimated to decrease in Alberta and Saskatchewan, but perhaps increase in Manitoba and Ontario (Smit, 1987; Arthur, 1988). In northern Europe cereal production might increase in the order of 15%, and livestock production would be greater as a result of the higher carrying capacities of pasture (Bergthorsson et al., 1988, Kettunen et al., 1988; Koster et al., 1987). In Western Europe, production may increase in the Low Countries, UK and Denmark (if available moisture levels are maintained), but decrease in France and FRG (if there is reduced available moisture resulting from higher temperatures) (Santer, 1985; Parry et al., 1989). In the Mediterranean region production may fall substantially if GCM projections of reduced rainfall prove to be correct (Santer, 1985). There is currently no agreement between GCMs as to how moisture levels may change in eastern Europe, but reductions in moisture would tend to reduce production (Farago, personal communication, 1989; Parry et al., 1987). In the USSR warming would enable production to be increased near the present northern limit of commercial winter wheat cultivation. Further south, in the current major producing regions of Ukraine and Kazakhstan, increases in moisture (which are most uncertain) would also enable output of winter wheat and maize to be increased (Pitovranov et al., 1988b; Nikonov et al., 1988; Mendhzulin, personal communication, 1989; Sirotenko, personal communication, 1989).

Our limited knowledge of the implications of climate change for overall production, together with great uncertainties about future regional patterns of comparative advantage, make hazardous any assessment concerning effects on patterns and quantities of exports. A few estimates have, however, been made. Exports of some crops in the US are projected to decline by up to 70% under the most adverse climatic changes simulated for a doubling of GHG (EPA, 1989). Exports of maize and wheat may increase for Canada, but decrease for barley (Land Evaluation Group, 1987). Sweden and Finland could probably export more cereals (Koster et al., 1987), as could Denmark, the Low Countries, UK and FRG (Santer, 1985). However, the countries around the Mediterranean might experience reduced possibilities for export as a result of reduced productive potential (Santer, 1985).

Implications for food supply and food security In high mid-latitude countries, where warming tends to reduce climatic constraints on agriculture, increases in productive potential would, if current price and policy incentives continue, be likely to lead to increases in surplus production.

In regions where productive potential is reduced, which is possible in the low mid latitudes and low latitudes as a result of decreased water availability, there could occur a reduction of levels of food security. The most vulnerable regions are probably Africa and South America. Smaller nations are likely to be affected more than large ones because of the smaller opportunity for risk pooling across climatic regions (Sinha et al., 1988). Overall, there is no compelling evidence that global food supplies will be radically diminished (Crosson, 1989), but of greater concern is the possibility that inherently vulnerable regions may have their already limited productive capacity further reduced by warming and drying. This is considered in greater detail in Section 2.4 of this report.

Effects on prices and trade Since the effects of changes in climate will occur on a global agricultural system that is, itself, constantly changing and since possible climate-induced changes in production in one region will almost certainly affect changes elsewhere.

At present it is merely possible to consider, in a very simple manner, the effect that future climatic change would have on present-day agriculture, if it were to occur *now* under present technology, management and trade structures. The following is a preliminary analysis based on estimates of generalised climate-induced changes in production, inferred from the changes in productive potential outlined above (Section 2.6.3 above).

It should be emphasised that these estimates do not, for two reasons, represent a forecast of impacts. First, they do not take into account the spontaneous adjustments that will occur within agriculture and which will markedly affect how production responds to climate change. Second, they are based on a most imperfect understanding of those changes in climate that may occur and of their effect on crop yields, soils, pests, diseases etc (Smit, 1989).

Under the estimate of changes in productive potential outlined in this report, prices of some mid-latitude crops such as maize and soybean could increase in the order of 10%, reflecting a small net decrease in the food production capability of the world. Rice production could, however, increase if available moisture increased in Southeast Asia. The average global increase in production costs due to climate could thus be small (perhaps a few per cent of world agricultural GDP). This accords with estimates that, worldwide, average agricultural production could increase by 10-20% (Schelling, 1983), result of the greenhouse effect.

Much depends, however, on how beneficial are the effects of increased CO_2 on crop yield. If productivity is substantially enhanced *and* more moisture is available in some major production areas, then world production of staple cereals could increase relative to demand with food prices reduced as a result. If, on the contrary, there is little beneficial direct CO_2 effect *and* climate changes are negative for agricultural potential in all or most of the major food-exporting areas, then the average costs of world agricultural production could increase significantly. These decreases or increases in production potential could result in decreases or increases in costs equivalent to perhaps over 10% of the value of world agriculture. It should be emphasised, however, that even larger changes in costs are likely to stem from non-climatic factors such as population, income and technology.

These estimations of the average effect of world production do not include the short-term impacts that might occur as a result of the increased risk of a concurrent downturn of production due to global warming. If, for example, higher temperatures and évapotranspiration rates led to a single concurrent drought in the major producing regions, the implications for world prices in the short term could be substantial. Figure 2.1 illustrates the change in commodity prices that could occur as a result of concurrent yield reductions of between 10% and 50% in the US, European Community and Canada. Assuming there were no other climatic effects on production elsewhere, agricultural prices would increase by about 10%, and by a third for a 50% fall. If there were concurrent yield decreases of 25% in Africa and Southeast Asia, agricultural prices would increase by a fifth and a half respectively (Kane et al, 1989).

While it is certain that regional agricultural changes will result from climatic change, it remains highly uncertain which specific region will actually experience yield gains or losses because (i) regional climate scenarios remain imprecise, (ii) capability of farmers to respond to climate change remains uncertain and may vary across regions and (iii) the tolerance of crops to the range of climate conditions under altered climate have not been fully assessed. Agricultural trade will play a significant role in determining the direction of regional impact because changing world agricultural prices will present opportunities and costs for producers and consumers of agricultural products. Thus, a nation's farm sector may benefit from improved yields and higher commodity prices while its population may be adversely affected by higher prices for food. These changes would be reversed if the world generally benefits from climate change and world commodity prices fall.

2.7 Likely adjustments in agriculture

2.7.1 Introduction

The foregoing analyses have assumed that technology and management in agriculture do not alter significantly in response to climate change, and thus do not alter the magnitude and nature of the impacts that may stem from that change. It is certain, however, that agriculture will adjust and although these adjustments will be constrained by economic and political factors, it is likely that they will have an important bearing on future impacts.

There are two broad types of adjustment that may occur. Those at the farm level that flow from decisions as a result of farmers' perception of altered conditions; and those at the regional, national and international levels that flow from changes in government policy. This report considers only those farm-level adjustments that are likely to occur in an intuitive and spontaneous manner as a result of perceived changes of climate, and do not require explicit changes in government policy. Consideration of the latter falls within the responsibilities of Working Group III.

Because of the very wide array of potential adjustments, which will vary according to type of climate change, type of farming, and many other factors, it is not profitable (even if sufficient information on likely changes of climate were available) to generalise at length about them. More specific discussion is needed at the regional case study level than is appropriate here. In this report we simply list and illustrate the various types of adjustment and their likely efficacy under different types of climate change.

Three broad types of adjustment may be expected: changes in land use, management and infrastructure.

2.7.2 Changes in land use

Three types of land use change may be considered: changes in farmed area, crop type and crop location.

i) Changes in farmed area

Where warming tends to reduce climatic constraints on agriculture, such as in high latitude and high altitude areas, an extension of the farmed area can be expected if other environmental factors and economic incentives permit. Expansion may be most marked in the USSR and northwest and northern Europe, where terrain and soils would permit further reclamation (Pitovranov et al., 1988a; Squire and Unsworth, 1988). It may be limited in much of Canada, with the exception of the Peace River region in northern Alberta and parts of Ontario (Arthur, 1988; Smit, 1987). There may also be potential for high latitude reclamation in some of the valleys of central Alaska, in northern Japan and in southern Argentina and New Zealand (Jager, 1988; Salinger et al., 1989).

Warming may also tend to induce an upward extension of the farmed area in upland regions. As indicated in Section 2.6.3 (above) a 1°C warming in the European Alps can be expected to raise climatic limits to cultivation by ca 150 m. Similar upward shifts are estimated to increase the farmed area significantly in high mid latitude mountain environments such as northern Japan and South Island New Zealand (Yoshino et al.,1988; Salinger et al.,1989). These shifts of the limit of the farmed area imply major impacts on the semi-natural environment and on extensive rangeland economies in mountain regions, such as Alpine pastures, which may come under pressure both from the upward advance of more intensive agriculture and from afforestation (Balteanu et al., 1987).

In regions where reduced moisture availability leads to decreased productive potential, particularly where current agriculture is only marginally productive, there may occur a significant decline in acreage under use. This may occur, for example, in parts of the eastern Mediterranean if projected decreases in rainfall are correct, and also possibly in western Australia (Santer, 1985; Pittock, personal communication, 1989). In the southeast US, increased heat stress and evaporation losses may reduce profitability to the point where commercial cropping becomes non-viable. For example, the cropped acreage in the southern Great Plains of the US is estimated to decline by between 5% and 23% under a warmer and drier 2 x CO_2 climate, but is partially compensated by increases in cultivated area in the Great Lakes region (EPA, 1989).

ii) Changes in crop type

Changes to crops with higher thermal requirements In regions where there are substantial increases in the warmth of the growing season (and where output is currently limited by temperature rather than by rainfall) it is logical that substitution by crops with higher thermal requirements, that would make fuller use of the extended and more intense growing season, should allow higher yields. Recent impact assessments have considered this as a predictable response in the US, UK, Japan and New Zealand (EPA, 1989; Rowntree et al., 1989; Yoshino et al., 1988; Salinger et al., 1989). To illustrate, yields of present-day quick-maturing rice varieties in northern Japan would probably increase by about 4% with the 35% increase in growing degree-days estimated under the GISS 2 x CO_2 scenario (Yoshino et al., 1988). However, the adoption of late-maturing rice (at present grown in central Japan) might increase yields by 26%.

Changes in annual crops can be made relatively swiftly, but a switch in perennials (such as from temperate to citrus tree crops) will require more time.

Change to more drought tolerant crops Where moisture rather than temperature is more generally the current climatic constraint on output, or where increases in temperature could well lead to higher rates of évapotranspiration and thus to reduced levels of available moisture, there may occur a switch to crops with lower moisture requirements. Once again the lack of information on likely changes in rainfall makes further speculation on this unprofitable, particularly at lower latitudes. However, there is some evidence that, at high mid-latitudes, a switch from spring to winter varieties of cereals would be one strategy for avoiding losses in more frequent dry spells in the early summer. This might be the case in Scandinavia and on the Canadian Prairies (Koster et al., 1987; Williams et al., 1988).

Hi) Changes in crop location

The switch of crops considered above implies changes in the allocation of land to given uses. In general, land uses which show a greater productivity per unit area than others are likely to increase their comparative advantage over competing uses; and given sufficient change in the pattern of comparative advantage, then decisions may follow which involve a change in use. The amount of land use change is likely to depend on how finely land uses in a given area are currently tuned to economics and climate, and much will depend on the changes in price that are largely determined by changes in potential in other areas. The response is therefore likely to be complex and extremely difficult to predict. As a much simplified illustration, consider the effect that a 1°C warming may have on land use in the area around Moscow, USSR. Yields of winter wheat and silage maize may increase because they are currently limited by temperature, but yields of temperate-zone crops such as barley and oats are reduced. Experiments suggest that the optimal reallocation of land under these circumstances would be a 30% and 5% increase in land under winter wheat and maize, and a 20-30% decrease in land under barley and oats (Parry and Carter, 1988; Pitovranov et al., 1988a).

The broad-scale changes in crop location imply a general poleward shift of present day agricultural zones. This is likely to be most pronounced in mid- and high- latitudes, partly because warming will be most marked here, but largely because it is in these regions that latitudinal zoning is most evident as a result of differences in available warmth for crop maturation.

In the UK, northern limits of sunflower production, which are at present located in the extreme south of the country, would shift about 300 km northwards for each degree ca rise in mean annual temperature (Parry et al., 1989). Broadly similar shifts are projected for southern Scandinavia where maize, soybeans, oilseeds and a wider range of fruits and vegetables would be viable (Koster et al., 1987). In southern Europe, higher temperatures imply a more northerly location of present limits of citrus, olives and vines (Imeson et al., 1987).

In central North America zones of farming types are estimated to shift ca 175 km northwards for each °C of warming, resulting in reduced intensity of use in the south, and increased intensity in the north where soils and terrain permit (EPA, 1989). In Canada up to 4m ha of currently unused northern soils may be suitable for cultivation in a warmer climate (Smit et al., 1989) A northward movement of production would suggest that a sizeable area of output currently located in the northern Great Plains of the US would relocate in the southern Canadian Prairies.

Similar southward shifts of land use have been suggested for the Southern Hemisphere, perhaps up to 6° of latitude (670 km) under a 2 x CO_2 climate (Salinger et al., 1989). It should be emphasised, however, that these broad-scale effects will be much affected at local levels by regional variations in soils etc, by the competitiveness of different crops and their environmental requirements and, most importantly, by regional patterns of rainfall, none of which can adequately be projected at the present.

2.7.3 Changes in management

It is reasonable to expect that a large number of changes in management, adopted over time as the effects of climate change are perceived, will modify these effects outlined above. As a unit exposed to impact, agriculture is thus a moving target, continually adjusting itself both to perceived non-climatic and climatic conditions. The following summary covers only those adjustments that are likely to occur without the stimulus of change in national or international government policy on agriculture. The latter are considered in Working Group III Report.

i) Changes in irrigation

There are likely to occur very substantial increases in the need for and the costs of irrigation, in order to substitute for moisture losses due to increased evapotranspiration. The most detailed estimates yet available are for the US, where irrigation requirements may increase by about 25% in the southern and 10% in the northern Great Plains under a 2 x CO_2 climate. Given the likely increased rate of groundwater depletion, this will probably lead to significantly higher costs of production, with consequent shifts to less water-demanding uses in the most affected areas (EPA, 1989).

Substantially increased irrigation needs are also projected for most of western and southern Europe (Imeson et al., 1987). Elsewhere, although data are not available, it is probable that effects will be similar where available water is reduced. Where there are substantial rainfall increases changes in management may be needed to tackle soil erosion, etc (see below).

Irrigation is practised mostly in arid or semi-arid regions where there is already a strain on available resources. Most of the irrigated land of the world is in Asia with a rapidly increasing population and not much latitude for increases in use of land and water resources. To counter the increased water demand due to climate change, tighter water management practices should lead to higher irrigation efficiency.

ii) Changes in fertiliser use

More use of fertilisers may be needed to maintain soil fertility where increases in leaching stem from increased rainfall, such as in New Zealand (Salinger et al., 1989). In other regions, warming may increase productive potential to the extent that current levels of output can be achieved with substantially lower amounts of fertilisers. In Iceland, for example, fertiliser use could possibly be halved under a 2 x CO_2 climate while maintaining present day output (Bergthorsson et al., 1988).

Much will depend on other factors, for example how far higher CO_2 will make nutrients more limiting, thus requiring more use of fertilisers, and how future changes in energy prices affect the cost of fertilisers.

iii) Control of pests and diseases

The costs of these are likely to alter substantially, although it is quite impossible to specify them with any degree of detail. Possibly most important for global cereal production may be the costs of controlling the spread of subtropical weed species into the current major cereal-producing regions (EPA, 1989).

iv) Soil drainage and the control of erosion

Adjustments in management are likely to be necessary in tropical regions, particularly those characterised by monsoon rainfall, where there is an overall increase, or at least increase in the intensity of rainfall. Recent assessments in the USSR have indicated that, over the longer term, reduced soil fertility, increased salinity and the costs of erosion control may more than offset the beneficial effects of a warmer climate, leading ultimately to reduced yields and higher production costs (Pitovranov et al., 1988a).

v) Changes in farm infrastructure

Regional shifts of farming types and altered irrigation requirements imply major changes in types of capital equipment, in farm layout and in agricultural support services (marketing, credit etc). In the US it has been estimated that these will be substantial (EPA, 1989). Because of the very large costs involved only small, incremental adjustments may occur without changes in government policies.

vi) Changes in crop and livestock husbandry

The adjustments summarised above imply a plethora of small, but important changes in farm husbandry. In particular there are likely to occur very many alterations to the timing of various farm operations such as of tillage (ploughing, sowing, harvesting etc), of fertilising and of pest and weed control (spraying etc), because the timing of these in the present farming calendar, though of course different for various parts of the world, is frequently affected by present climate. Particular aspects of husbandry are also likely to be affected, such as the density of planting, the use of fallowing and mulching and the extent of inter-cropping. These aspects are, today, frequently part of a package of strategies designed to mitigate the adverse effects (and exploit the beneficial effects) of present-day climate. Thus a change of climate implies a retuning of these strategies to harmonise with the new set of climatic conditions.

An illustration of this is the management of double cropping (of summer rice and winter barley) in Japan. At present the northern limit of double cropping is located at 37°N. Under the increased temperatures projected for an equivalent doubling of CO_2, double cropping would be viable 150 km further north, though, the response to this northward shift of potential would depend greatly on crop prices and input costs (Yoshino, personal communication, 1989).

An indication of the impact on animal production systems is given by preliminary work in Ireland. Here livestock production is currently dominated by the effects of high rainfall and wet soils (Brereton, 1989). A high proportion of grassland in Ireland is affected by high water tables. Total feed production might not be greatly affected but the low-cost grazing system would not be sustainable and there would be a shift to indoor feeding systems, with a consequent increase in the problem of waste disposal (Keane, personal communication, 1990).

2.7.4 Changes in policies of agricultural support

In most countries agriculture is currently affected in many different ways by a wide range of government policies that influences product prices, costs of farm inputs, marketing arrangements, the cost of credit and even the levels of production of specific commodities. Relatively minor alterations to these policies can have a marked and quite rapid effect on agriculture. In large countries, and in supranational organisations such as the European Community, a few decisions of policy can affect production over large areas. It is likely, then, that changes in government policy resulting from changes in climate would have a marked influence on how agriculture ultimately responds. These issues are discussed in Working Group III Report.

2.8 Effects of changes in sea-level

2.8.1 Scenarios

Sea-level change Global warming as a result of increased concentrations of GHG is likely to cause an acceleration of the slow sea-level rise already in progress. This expected acceleration will be the consequence of thermal expansion of oceanic surface layers and melting of glaciers and polar icecaps.

It is generally accepted that global sea-level has risen by 10-15 cm over the last century but it is not certain if this is entirely attributable to the greenhouse effect. Current estimates suggest a further rise of 10-30 cm by 2030 (Working Group I).

2.8.2 Vulnerability

Vulnerability studies frequently take an assumed sea-level rise as the major, and often only, factor. Impacts are assessed usually in terms of vulnerability to inundation and its probable consequences for land management and agriculture. Coastal regions of low elevation can be identified by reference to contoured maps and remote sensing sources. However, contour information is inadequate worldwide and remote sensing insufficiently accurate. Therefore to date a coastal lowland morphological categorisation has been used for broad global investigations (UNEP, 1989). Categories of high vulnerability include deltas, polders, areas subject to marine flood damage, areas with certain soil types (eg young fluviosols, gleysols), small islands and atolls, and wetlands including mangrove swamps and marshes (UNEP, 1989).

2.8.3 Vulnerable regions

The draft ISOS (Impact of Sea Level Rise on Society) Report (UNEP, 1989) provides a global inventory of high risk areas using information on terrestrial topography as the key determinant. Areas with more than 100 persons per km^2 were given priority consideration. Most countries in the world are vulnerable to some extent since fewer than 30 are entirely landlocked. Over 50 million people could be forced to relocate with the scale of sea-level change considered (+1.5 m). Inundation of important agricultural lands supporting such a population is implied unless protective measures are implemented. A master checklist of 27 vulnerable countries was compiled, omitting developed nations regarded capable of protective action. The 27 nations can be grouped regionally, scores indicating an ascending scale of vulnerability (1 to 10) based on the votes of experts who were asked to select what they considered to be the ten most vulnerable countries to sea-level rise. Four countries/ regions received no votes for the ten most vulnerable list, although they are still identified as being among the 27 most likely to experience serious impacts. The groups and scores are:

Asia Bangladesh (10), Burma (1), China (8), India (2), Indonesia (4), Malaysia (-), Pakistan (2), Philippines (2), Sri Lanka (1), Taiwan (1), Thailand (9), Vietnam (2)

South America Argentina (4), Brazil (7), Colombia (-), Ecuador (-), Surinam (1), Venezuela (2)

Africa Egypt (9), Kenya (1), Mozambique (2), Nigeria (2), Senegal (2), The Gambia (1)

Islands Caribbean (-), Maldives (1), Pacific Islands (1)

To these may be added major regions in developed countries:

Europe Southern North Sea coasts (eastern England, northern Belgium, Netherlands, northern Germany (FDR), western Denmark (7); eastern North Italian Plain (3); head of Gulf of Finland (mainly USSR) (1); western Black Sea coasts of USSR (1)

Asia Japan (Pacific coastlands of Honshu) (1)

North America Gulf Coast of Mexico (1), Louisiana (6), Florida and US East Coast States (1)

2.8.4 Direct impacts on agriculture

Direct impacts refer to the effects of inundation. Agricultural lands could be flooded permanently, some lost by increased marine erosion and some frequently inundated as a result of disrupted river and tidal regimes together with greater storm and high wave incidence. The nature of acceleration of sea-level change is crucial because many environments have so far kept pace with the slow rise (eg through coral, silt or peat accretion) but may not be able to do so in the near future.

The most significant impacts can be summarised by reference to the 27 countries designated vulnerable (2.8.3 above):

Asia Southeast Asia would be seriously affected because of the extreme vulnerability of several large deltaic regions with dense populations supported by paddy rice cultivation. For example Bangladesh would have 15% of land inundated with a 1.5 m rise, with another 6% below 3 m made vulnerable. Altogether 21.3% of agricultural production could be lost, mainly rice, sugarcane and jute (UNEP, 1989). Thailand and China are regarded as also being especially vulnerable to large farmland losses.

South America Losses through inundation would occur in the districts of the Pampas of Argentina bordering the Plate estuary with consequent reduced cereal (wheat/maize) and cattle production. Some sections of the Brazilian coastlands and the Amazon delta are vulnerable with losses of tropical agriculture (sugarcane, citrus fruits, oilpalm, cocoa etc). Coastal regions of Venezuela and Surinam would lose rice, banana and sugarcane lands.

Africa Assuming a 1.5 m sea-level rise, most losses would be in the large delta areas of The Gambia, Senegal, Nigeria, Mozambique and Egypt. Of these the Nile Delta/lower Nile Valley in Egypt is the most intensively cultivated so that 17% of national agricultural production and 20% of farmland could be lost with severe impacts on food supplies (especially of rice, wheat, vegetables) and non-food crops (eg cotton).

Islands Many coral atolls and small islands have very limited relief above present sea-level and so could have the greatest proportional losses of farmland in the world. As an example of an atoll group, the Maldive Islands in the Indian Ocean would have 50% of all land inundated with a 2 m rise (Delft Hydraulics Lab, 1986). An additional danger is that sea defences might not be effective owing to coral porosity and underground seawater flow. Even islands with higher terrain, such as Fiji, would lose much of their farmland, Vatulele losing 6.2% of agricultural land with a 1.5 m rise and 31% with a 3.5 m change. Moala would lose 8.8% and 15% of farmland respectively (Nunn, 1988).

Developed countries Not all developed countries have the resources for works to counteract inundation especially where rapid sea-level rises occur in regions of coastal downwarping. For example a i m downwarping has occurred over the last hundred years in the Mississippi Delta region of the US. Land is being lost here at a rate of 250 km^2 per year and 35% of the estimated national dryland loss from a 0.5 m sea-level rise would be in Louisiana (EPA., 1989). Consequent loss of subtropical agriculture in the US would be considerable.

The north and west of The Netherlands is reclaimed polder land with protective dykes and artificial drainage, representing some of the most intensively farmed land in the world. Defences constructed after the serious inundation of 1953 are designed to withstand a 10,000 year surge event, but even here a 1 m sea-level change would reduce that safety margin by an order of magnitude (Hekstra, 1986). The southern North Sea coastlands are also subject to crustal downwarping that would exaggerate any change.

2.8.5 Indirect impacts on agriculture

In many coastal regions indirect or secondary impacts of rising sea-level may have far-reaching significance for agriculture. Costs of protection of vulnerable farmland would escalate. In addition to improvement of coastal defences, the higher level of rivers approaching the sea would necessitate adjustment of dykes, sluices and pumping systems. This is especially so where the general land level is no longer rising because flood protection schemes prevent any further silt accumulation. In developed nations decisions have to be made concerning expenditure for protection of relatively low-value farmlands compared with urban land. Measures may be more essential for subsistence agriculture in a developing country. Modifications of land drainage systems would require further resources where they need to be adapted to rivers with higher levels and inhibited outflow.

Saltwater intrusion into surface water and groundwater could have deleterious effects. Deeper tidal penetration could increase the danger of flooding causing salinisation of farmlands and reducing the value of river water for irrigation. Aquifers could be recharged with sea water if abstraction occurs to below sea-level. Rising sea-levels could raise underground saltwater levels to reduce the depth of overlying fresh groundwater. In areas of low relief, such as atolls, freshwater reservoirs of less than 1 m depth could disappear in dry seasons, as water tables fall to saltwater levels, leaving no useful irrigation supply.

Threats of inundation could lead to relocation of farming and farming employment. If this is feasible there are obvious implications for land acquisition, land preparation, infrastructural changes and farming modifications. But relocations could be prohibitively large scale as in Bangladesh where some 20% of farmland and population could be affected by a 1 m sea-level rise (UNEP, 1989). Often relocation could be difficult as in Egypt where irrigation is feasible in the delta and flood plain areas only. Sometimes, relocation would be impossible, as in the Maldives where half the land would be lost as a result of a 1 m sea-level rise and the remaining half would he within a vulnerable 1 m of sea-level (Delft Hydraulic Lab, 1986). Out-migration of population would be the only solution for many small oceanic islands.

3 Potential impacts on managed forests and the forest sector

3.1 Introduction

The social, economic and environmental aspects of major forest ecosystems are significant, but often neglected, attributes of forest policies (Shea and Carlson, 1984). Forests and woodland cover roughly one-third of the land surface of the world, and therefore deserve serious consideration in assessments of socioeconomic implications of climatic changes. Monitoring, evaluation and feedback concerning the social, economic and environmental aspects of forestry need to be accounted for in planning forest-related programs. A comprehensive international effort is necessary to assess objectively the socioeconomic impacts, given the variety of languages, customs, social and political systems. International bodies such as FAO, WMO, UNEP, IUFRO and IUCN are examples of basic structures used to foster these global assessments. The prediction of changes and consequences fifty years or more into the future, with large elements of risk and uncertainty, is a challenging and necessary effort. The need to develop proactive, not reactive, strategies will be one of forestry's greatest challenges.

3.2 Managed and unmanaged forests

Although the distinction between 'unmanaged' and 'managed' forests is seldom clear (Warrick et al., 1986), this report considers managed forests to have some degree of planned or actual physical intervention and include the following levels of intervention:

- Extensive silviculture with attention to harvest design to promote natural regeneration, and subsequent protection.

- Basic silviculture with plantations established after harvesting, followed by more intensive protection.

- Intensive management with multiple inputs, including site preparation, planting, competition control, pre-commercial or commercial thinning and protection from insects and fire.

- Elite management regimes dedicated to short rotations using many of the above methods plus fertilisers to promote growth.

It is particularly difficult to determine how much of the world's forests are under each level of management. Therefore, this report incorporates all forests in which some harvest takes place, with particular emphasis on forests where there is some degree of management. The definition excludes protected forests, forest parks and wilderness areas.

In many forests around the world, stands on sites of superior productivity and with desired species type are managed more intensively, while other stands on sites of marginal productivity, or with non-commercial species composition, receive little or no physical intervention. Thus, within a managed forest, there can be found a mosaic of 'managed' and 'unmanaged' stands.

This report focuses on the effects of climatic changes induced by higher atmospheric concentrations of GHG such as CO_2, rather than on the direct effects of CO_2 enhancement (see Working Group I, Ecosystems, for a detailed discussion of the direct effects of CO_2 enhancement). It is accepted that important forest ecosystem effects, particularly enhanced photosynthetic rates and increased efficiency of water use, may result from increased concentrations of atmospheric CO_2 but there is no consensus on the effects on mature forest trees (Eamus and Jarvis, 1982; Jarvis, 1989). In particular, Jarvis (1989) concluded that short-term experimental results on young, pot-bound trees cannot be used to assess long-term responses of forest stands to direct CO_2 enrichment. Extrapolation to stand level effects is also not possible (Jarvis, 1989). Models for effects of climatic changes on forest stands have been constructed, however, and are being used to generate scenarios of potential forest responses to climatic changes.

3.3 World forest sector and managed forests

3.3.1 World forest sector

In 1980, forests covered about 31% of the land surface of the world (Table 2.1). Within the developed regions, the USSR and Japan have significantly higher than average areas under forest. As a group, Australia, Israel, South Africa and New Zealand are considerably below average with only 13% of their combined land areas forested. Likewise, within developing regions, the Near East and China are below average, whereas Latin America as a whole is much above average (Table 2.1). Regions with large shares of the world area of forests include North America (particularly Canada), the USSR (especially in Siberia), equatorial Africa and tropical Latin America.

3.3.2 Managed forests

Climatic changes will affect the managed forest resources of the global community to different degrees as a result of the existence of a variety of social systems and levels of political and economic development. The intensity of forest management does not necessarily parallel the level of national development. Frequently where high intensity of forest management prevails, exotic species are widely planted.

The amount of managed forest land varies widely between and within the developed and less developed countries (LDC). This suggests that impacts from climate change will affect people differently. In developed countries, the fear will be that living real fear that subsistence could be threatened. It is not possible from these data to conclude what proportion of the population relies on forests and to what degree, but there are similarities for all countries. All countries use fuelwood for heating and cooking to some extent. If the availability of wood is altered, the impacts will be most severe where alternative energy supplies are limited.

Trees also supply food for many people: date palms in tropical areas, nut pines and sugar maple in boreal and temperate areas. The forests may therefore be critical for survival, useful to augment diets or economically valuable.

Depending on the economy/environment combination, different species provide economic value to the population.

In the boreal countries, populations rely on the spruce/pine group, mostly of native origin. Temperate and tropical countries tend to rely to a greater degree on exotics such as radiata pine in New Zealand and Eucalyptus in Brazil.

Selected data from 13 nations representing all continents, Northern and Southern Hemispheres, and nations in various stages of development are illustrated in Table 2.2. The statistics in this table are based on different time periods and were collected under different methods and standards. Nevertheless, attempts have been made to base them on one currency and to relate total inventoried forest land to intensively managed forests. For example, intensively managed forests is high in New Zealand and Germany, but smaller in China and Canada.

3.4 Potential biophysical responses of forests to climate change

3.4.1 Forest protection

Many trees display a surprisingly large ability to acclimatise after long geographic transfers of seed such as occurs in provenance trials (Hall, 1989). However, each genetic unit has its ultimate limits and species are quite limited in this respect. Quantified characteristics are so far very few; some of these could be derived from the large number of seed source/provenance trials which have been established by forest research agencies over the last 80 years. This information is urgently needed for elaboration of realistic vegetation response models.

Mortality due to physical stresses is expected to increase as enhanced degrees of stand decline are experienced (Solomon, 1986; Solomon and West,1985; 1986; Auclair, 1987). If climate changes abruptly compared to the normal longevity of most tree species, many trees may not be able to survive the associated stress and consequently, competitive and pest/disease relationships could be altered. According to Smith and Tirpak (1988), climate induced declines may be seen as early as 30-60 years from now in the US Great Lakes States, 60-70 years

Table 2.1 Forest land in area in 1980. Hectare and per-caput data from Peck (1984)

Region	Total land area (million ha)	Forest land area (million ha)	Forest area proportion of total land in the region (%)	Forest area proportion of total world forests (%)	Forest land area per caput (ha/person)
World total	**13075**	**4094**	**31.3**	**100.0**	**0.9**
Developed regions	**5485**	**1829**	**33.3**	**44.7**	**1.6**
North America	1835	611	33.3	14.9	2.4
Western Europe	373	126	33.8	3.1	0.3
Eastern Europe	100	29	29.0	0.7	0.3
USSR	2227	920	41.3	22.5	3.5
Japan	37	25	67.6	0.6	0.2
Other*	913	118	12.9	2.9	2.3
Developing regions	**7591**	**2264**	**29.0**	**55.3**	**0.7**
Africa	2331	642	27.5	15.7	1.7
Near East	1192	98	8.2	2.4	0.5
China	931	116	12.5	2.8	0.1
Other Asia/Pacific	1028	356	34.6	8.7	0.3
Latin America	2020	1015	50.2	24.8	2.8
Other**	88	37	42.0	0.9	7.2

* Australia, Israel, New Zealand, South Africa

** Mainly Pacific Islands and Greenland

in the southeastern US and 30 years in the dry areas of central and western US.

Species native to cool temperate regions have been adapted to alternation ofseasons. After an active period, they become dormant and resistant to frost and drought. After a chilling period above 0°, ambient temperatures are the main driving force of dormancy release. If early winter is mild, trees may deharden and be damaged by frost in late winter. Paradoxically, a milder climate may increase the risk of frost damage. In general, the survival rhythm of trees may be broken, particularly in the far north where photoperiod is very long during the growing season.

Interactions between anthropogenic climatic changes and air pollution are particularly stressful to trees. As air pollution increases, enhanced ozone concentrations along with increased temperatures are expected to cause greater stress on plants than previously experienced. Forest degradation caused by a changing climate, enhanced ozone and other air pollution may also damage watersheds. The decline of red spruce forests in the New England states of the US over the past 100 years has been attributed to climate warming (Hamburg and Cogbill, 1988). This decline has been further exacerbated by concurrent increases in anthropogenic changes in atmospheric chemistry. In Europe where managed forests occupy a much larger portion of forest land than in North America, acidification of sensitive soils has occurred over several decades. These effects can be extrapolated from the damage already occurring on managed forests in Europe from anthropogenic air pollution.

Susceptibility to and infestations of insects and diseases is expected to increase (Pollard, 1987; Winget, 1987; Woodman, 1988; Harrington, 1989; Zoltai, 1989). For example, diseases may increase in *Pinus radiata* plantations in Australia where temperatures and precipitation increase (Booth and McMurtrie, 1989). Infestations of spruce budworm in eastern Canadian forests (Winget, 1987) and bark beetles in northwestern American forests (Pollard,1985) are expected to increase as temperatures rise.

Managed forests require that a higher level of protection be given their investment; insects and diseases cause significant losses in these forests. Distribution of insects, pests and their associated predators is closely related to climate. Damage to the northern forests by spruce budworm and bark beetles has already been attributed to recent occurrences of warmer weather (Pollard, 1985). Managed

Table 2.2 Summary of forest resources

	Indonesia	China	India	Brazil	Kenya
Forest land (million ha.)	122	135	67	565	3.7
Productive forest land (million ha.)	45	122	45	350	1.1
Managed forest (thousand ha.)	1,918*	12,733*	2.062*	3.855*	181*
Remarks					

* FAO, 1988a

	Zambia	Finland	New Zealand	Chile
Forest land (million ha.)	29.5	23.3	10.6	15.5
Productive forest land (million ha.)	4.1	18.2	2.8	4.7
Managed forest (thousand ha.)	38*	145/ann.	1200 (20/1987)	817*
Remarks		Regen. is a mean		

	Canada	USA	Austria	Germany
Forest land (million ha.)	452	265	3.2	7.3
Productive forest land (million ha.)	244	210	3.0	7.3
Managed forest (thousand ha.)	450 (1987)	917 (1980)	25 (1980)	70/ann.
Remarks	Regeneration annual mean			Regeneration annual mean

forests consisting of monocultures are expected to be even more susceptible to a particular insect or disease infestation because of the reduced genetic diversity in these forests.

The ability to respond to damage from insects and diseases varies widely from country to country. Consequently the levels of damage and loss to the various economies will be variable. Nations which rely on hard currency acquired from the sale of high quality wood could be particularly sensitive.

Fire damage is expected to increase with the susceptibility of forests (Fosberg, 1989; Street, 1989). Even if precipitation remains roughly the same, increased temperatures will lead to increased evapotranspiration and thus drier sites (see Manabe et al., 1981; Manabe and Wetherald, 1986, for supportive views, and Mitchell and Warrilow, 1987 for a contrary view). Warmer drier sites could have a higher incidence of severe fires, especially where stands are in a state of decline because of climatic changes. Likewise, the potential increases in blocking high pressure patterns, more lightning strikes and increased fuel loadings are a dangerous combination causing more and larger fires.

The ability to detect and control fires varies greatly around the world. In Canada, where prevention, detection and suppression strategies are well developed, large fires still occur. During the decade of the 1970s in Canada, the average annual area burned was one million hectares, but during the warmer 1980s this has doubled to over two million hectares. In 1989, over 6.4 million hectares of forest land were burned; fortunately, little of this was intensively managed forest. There have been suggestions that this change in the level of fire activity is the result of climatic changes in this portion of the boreal forest. It is, of course, too early to make an assumption of this type; however, the coincidence has been noticed by forest managers.

3.4.2 Shifts in climatic zones affecting forest ecosystems

Major climatic zones which govern species ranges are projected to shift under current global warming scenarios. Under a 2 x CO_2 atmosphere, conditions currently supporting boreal forests could shift north into the current tundra zone.

This would then lead to a reduction in area potentially supporting boreal forests of approximately 37%. Under this scenario, the area of subtropical forest conditions would decrease by 22%, but the rain, wet, moist, and especially dry areas of tropical forest conditions would increase by 28%.

Under conditions of rapid climatic change, existing species in their habitats will be stressed as some are better able than others to cope. There may be a net mortality in existing species, but now well adapted and intensively managed species will become more prominent in managed forested ecosystems. Because many habitats are isolated from the surrounding environment and species need continuity of habitat to move, many species may be unable to survive in their current habitats. As climate continues to change in response to human activities, the species in any given area will be increasingly asynchronous with their environment.

Shifts in tree species ranges could be important for several reasons (Moomaw, 1988). First, climate is expected to change faster than tree species can respond through migration. Second, new sites may not be edaphically hospitable, having evolved over thousands of years in a different environment. Finally, future forest climate zones leading to new forest ecosystems will not be related to current administrative boundaries which are used to defined wood supply areas, ownership, parks and nature reserves. Forests in areas of projected large climatic changes over the next 50 years will require massive readjustments, with consequent increases in the area of stressed forests (Smith and Tirpak, 1988).

For each 1°C of warming, tree ranges have the potential to expand 100 km northward while southern boundaries retreat, a process which has been tracked quite accurately since the last glaciation (Davis, 1989). The asynchrony will be greatest in the disturbed plant communities. These lags will persist a decade or two at most, then logging or fire or both, will cause a rapid adjustment to the prevailing climate. Intensively managed forests can respond to actual changes in the environment, but these could be out of synchrony with the environment unless proactive strategies are adopted that capitalise on our knowledge of anticipated climates. Depending on the rates of climatic change, stresses could increase as the environment changes, and without careful species-climate planning and allocation, the intensively managed forests could become more and more out of tune with its environment.

Miller et al. (1987) projected significant shifts in the climate suitable for loblolly pine, to the north and northeast of the current range in southeastern US. The current range may expand by almost 20% by the year 2080, with large decreases in the south and large increases to the north. The climatic habitats suitable for *Pinus radiata* and *Eucalyptus regnans,* could disappear from the Australian continent (Eckersley, 1989).

Managed forests incorporate high levels of investment with the expectation of concomitant economic returns. These forests have been established for superior quality products: teak and mahogany in tropical areas, radiata pine and Douglas fir in temperate areas, and Scots pine and black spruce in boreal forests. Impacts of climatic changes are expected to be significant on these forests and consequently on the associated economic and social systems of the dependent regions. Countries with a secure economic infrastructure will be less affected economically than those which may depend to a higher degree on forest products and have economies which are less resilient to large-scale biological damage.

3.4.3 Forest production and renewal

A variety of effects on forest productivity has been discussed (Warrick et al., 1986; Booth and McMurtrie, 1989). Increases are proposed in some cases (Kauppi and Posch, 1985; 1987) and decreased in others (eg Solomon and West, 1986). In stands where a favourable combination of climatic changes, site conditions, and stand composition and development stage exists, productivity could be enhanced. This would occur in a boreal stand on a wet site in the northern part of the boreal climate. However, productivity could decrease where moisture or nutrients are strongly limiting, or where species are already at their upper temperature or lower moisture limits.

In northern boreal forests, large areas of forested land are harvested in winter to minimise site damage. Shorter winters and/or higher temperatures will reduce the opportunity to continue this harvesting technique with consequent reduction in employment and wealth in rural communities.

Managed forests provide a variety of products (eg biomass, veneer and pulp) over a range of harvestable periods (1-2 to 100+ years). The most critical time for any plantation is during the establishment phase. During this phase, the availability of moisture controls whether or not the plantation can be established. While virtually all projections show a rise in temperature there is a greater degree of uncertainty as to the magnitude of the change and the seasonal distribution of precipitation. Changes in the amount or in the seasonal distribution of precipitation would be severe, depending on the current availability of moisture.

There are uncertainties concerning the implications of climatic changes on forest renewal because of the uncertainties in the prediction of regional climate (Woodman, 1987). It could be enhanced for species with both seed and vegetative reproductive strategies (Maini, 1988). Success rate of plantation establishment could be reduced because of increased harshness of site conditions and increased competition from other vegetation (Wheaton et al., 1987).

Marked changes in species composition could occur in the absence of intervention (Solomon et al., 1984); however, these would be determined largely by stand-level factors such as site, current stand composition and development stage, and local climatic changes. Thus, species are less limited by water availability, and near the higher latitude limit of their ranges could increase their frequency (Andrasko and Wells, 1989).

3.5 Role of forest management in potential forest responses to climatic changes

3.5.1 Managed forests

Managed stands are different in many ways from 'unmanaged' or 'less managed' stands. For example, forest land in Vietnam comprises more than 20 million hectares. On average, annual growth of the natural forest is only 1-2 m^3/hectare although pine shows a growth of 3-5 m^3/hectares. The calculation of potential productivity shows that with the same forest trees the productivity would be 10-15 x greater if the forests where intensively managed (Ngo-Si-Giai, 1989).

There are concerns in tropical America and Africa that afforestation is largely out of proportion with deforestation. Arguments for improving high-yield forest plantations, intensively managed on suitable land, have never been more justified than now (de las Salas, 1989). Understanding future climates coupled with short-rotation forestry, should make managed stands less susceptible to undesirable effects of climatic changes.

Intensive management is characterised by one or more of: species/provenance selection, planting spacing control, stand tending, one or more thinnings, protection from insects, diseases and fire and, possibly, irrigation and fertilisation. Known production forest examples are those from Venezuela (200,000 hectares of *Pinus caribaea* on lowland) and Brazil (more than 2 million hectares of Eucalyptus managed for pulp production), both on savannah landscapes (de las Salas, 1989).

There is considerable pressure to expand and intensify agricultural land in the humid tropics which, in turn, increases the demand for forest land. For example, a complete supply of wood for the production of 1 million tons of bleached short-fibre pulp a year from Eucalyptus, using the forest technology of Aracuz (Brazil), will take 90,000 hectares of forest land (Brandao, 1984).

In other countries the need for alternative energy and forest products led to the successful development of hybrid varieties and, at the same time, preserved and enhanced diversity within the gene pool of forest trees. Short-rotation forestry can fall back to a certain extent on the methods technology and experience gained from conventional plantation forestry, but under a changing climate, time is more pressing. The need for proactive management strategies within future climatic scenarios are needed to mitigate negative socioeconomic impacts of climatic changes on the forest sector. Examples of some of these accomplishments for elite plantations are particularly noteworthy (Table 2.3), including the flexibility of movement within the global environment (Table 2.4).

Intensive forest management usually entails the use of sophisticated inventory practices and forecasting tools for planning and scheduling of forest interventions compared to those employed in unmanaged forests. However, if we are unable to harvest managed stands before they become overmature, or if inadequate attention is paid to thinning schedules (Kuusela, 1987), these stands will be more susceptible to decline caused by climatic changes.

3.5.2 Agroforestry - managed forests with agriculture

The combination of livestock with trees planted for fuel, shelter and shade, fodder or fence posts is usually an ecologically sound procedure. Many successful examples exist in the American tropics. In hilly locations, however, this combination can lead to severe soil erosion. There are reports of such damage under Eucalyptus in East Africa and Ethiopia and the same can be seen in the Andean countries of South America (de las Salas, 1989).

Results from the International Research Institute for the Semi-Arid Tropics (IRISAT), India, suggest that inter-cropping can provide substantial yield increases where the shared crops compliment each other (Huda and Ong, 1989).

Table 2.3 Yields from hybrid plantation species

Location	Hybrid species	Yield (oven dry tonnes/ha/yr)
Pennsylvania, USA	poplar	8.5
Ontario, Canada	poplar	7.0
Ontario, Canada	willow	20.0
W. Kentucky, USA	black alder	7.2
Sweden	willow	22.0
Kansas, USA	silver maple	6.7
United Kingdom	willow	14.0

Source: Christopherson et al., 1989

In the central Ethiopian highlands, farmers derive multiple uses from their intercropping. They produce coffee beans, seeds, vegetables, loppable browse for their cattle and fuelwood from the branches of trees (Negah, 1989).

Budawski (1981) comments that for at least 80 years, a local alder species (*Alnus acuminata*) has been successfully planted at elevations between 1300 and 2500 m above sea level with high rainfall (200-300 mm) on good soils in the dairy region of Costa Rica. The trees are planted at wide spacings within pastures that are grazed or cut.

As populations continue to increase, there will be a greater need for integrated land use strategies to accommodate the multiple benefits of producing agricultural and forestry crops on the same shared land base.

3.5.3 Urban forests

Longridge and Mcwilliams (1989) suggest that temperature becomes increasingly important as a determinant in the survival and distribution of plants the further a plant deviates from its biological norm. Carbon partitioning to shoots and roots in response to root temperature is species dependent (Ingram et al., 1986).

Trees growing in urban areas have already spent the last 50-100 years growing under conditions of increased warming trends caused by the 'urban heat island' effect. This means that they have developed under different conditions from those same species in the natural forest. Today's urban forests, therefore, can serve as appropriate observatories for tomorrow's rural forests under a changing climate.

In temperate climates, species of *Acer, Platnus* and the *Ginkgo* are favoured as ornamentals because of their tolerance to the urban stresses. This knowledge has been gained by observation and selection, a process which may reflect the apparent tolerance to industrial pollutants, automobile exhausts, soil compaction and cultural disturbances.

The American Forestry Association (1989) estimates that planting '100 million trees could affect America's CO_2 emissions by 18 millions tons a year, saving consumers (energy conservation with shading and wind breaks) $US4 billion each year'.

3.5.4 Summary assessment of forest sensitivity to projected climatic changes

The degree to which managed forest stands are sensitive to future climatic changes depends on:

- the characteristics of the new temperature regimes. Forest ecosystems will be more sensitive with large overall increases in temperature in the northern latitudes with boreal forests and where there are temperature fluctions/extremes, or a greater frequency of non-seasonal frosts;
- the characteristics of precipitation patterns. Stands will be more sensitive if there are large changes in precipitation, especially decreases in areas currently arid and semi-arid.
- the characteristics of forest soils. Forest ecosystems will be more sensitive on more rapidly drained sites which limit tree survival and growth, such as the Mediterranean regions and North Africa; the southern boreal forest; and sites that are currently temperature-limiting on tree survival and growth such as the northern limits of boreal forest. Also at risk are forests at high elevations in North America, Europe and USSR and elsewhere.

Table 2.4 Performance of 15 species at Kaunamano, Ka'u, Hawaii Island, evaluated after 23 months (Schubert and Whiteshell, 1989)

Species and source	Growth (ht m)			Dbh (cm)	Survival (per cent)
	Mean	Range	Annual		
Eucalyptus salignia Hawaii Island, Hawaii	8.1a	2-10	4.2	6.7a	94a
Eucalyptus grandis New South Wales, Aust.	7.8a	2-11	4.1	6.7a	92a
Eucalyptus globulus Hawaii Island, Hawaii	7.3ab	2-11	3.8	6.3ab	81ab
Eucalyptus viminalis Victoria, Australia	6.6abcd	3-11	3.4	5.7abc	81ab
Eucalyptus urophylla Flores, Indonesia	6.4abcde	2-10	3.3	5.6abc	90a
Eucalyptus nitens Victoria, Australia	7.1abc	3-10	3.7	7.0a	65abc
Eucalyptus tereticornis Nigeria, West Africa	5.6bcde	2-8	2.9	4.5bcd	91a
Eucalyptus camaldulensis New South Wales, Australia	5.1def	2-8	2.7	3.8cde	66abc
Eucalyptus robusta Queensland, Australia	5.4cde	2-8	2.8	5.1abcd	93a
Eucalyptus citriodora Queenland, Australia	4.6efg	2-8	2.4	3.7cde	66abc
Albizia falcataria Sri Lanka	4.8def	3-6	2.5	6.1ab	85ab
Acacia confusa Taiwan	2.8h	2-4	1.5	2.2e	69abc
Acacia auriculaeformis India	2.9gh	2-4	1.5	2.1e	56bc
Acacia mangium Queenland, Australia	2.9gh	2-4	1.5	3.3de	47cd
Mimosa scabrella Parana, Brazil	3.4fgh	2-5	1.8	2.4e	18d

144 trees per species initially planted. Means with the same letters are not significantly different (5% level).

- the characteristics of the age of the forest. Stands in the establishment and late maturity phases will be most impacted. At the time of establishment, moisture is critical for seedlings to develop deep roots to withstand future dry periods. Juvenile stands that are free of non-tree competition, and immature and young mature stands, are more vigorous and hence resilient to environmental stress. Stands at maturity are less able to stand stress of any type and are therefore at a high risk in Canada (Woodbridge, Reed and Associates, 1988), USSR (Barr and Braden, 1988) and central Europe (Kuusela, 1987; Nilsson et al., 1989). Also susceptible to damage are those composed of species at or near the limit of their natural ranges such as the temperate deciduous forests in North America. If climatic changes are more severe for specific age classes with a stand, the chances of the stand maintaining some semblance of continuity are greater if it is an all-aged stand rather than an even-aged stand. Managed even-aged forests may have an additional risk in this respect.

The above factors do not take into account the degree to which human intervention has and can ameliorate or exacerbate stand sensitivity to climatic changes. For the moment, ignoring human intervention in forests, the forests that would seem to be most sensitive to future climatic changes include:

- boreal forests, where stands are mainly even-aged and often temperature limited, and where temperature changes are expected to be large, positive effects are probable; and

- forests in arid and semi-arid regions where increased temperatures and stable or decreasing precipitation could render sites inhospitable to continued existence of current forest stands, negative effects are probable.

3.6 Socioeconomic implications of climatic changes on forests and the forest sector

Forest products data are based largely on roundwood production, which is a common industrial output from the forest. In northern countries most of this goes to pulp and paper, whereas in the tropics the pulp and paper market is shared with the high-quality lumber market. Tropical countries rely on teak/mahogany and other valuable hardwoods.

There have been few studies of the socioeconomic effects and implications of projected climatic change on forests and the forest sector. In a recent study it would increase substantially, that growth rates in other forests of the world would increase marginally, and that Canada, Finland, Sweden and USSR would all experience increases in total exploitable forest area (Binkley, 1988). With larger inventories in northern forests, harvest rates would increase, timber prices would fall, industrial profitability in those areas would increase and new investments in production capacity would be channelled there. This would lead to an overall drop in timber prices everywhere. In general, most countries with boreal forests would witness a net increase in timber income, while most other countries would experience net decreases due to both declining harvest volumes and lower prices.

Higher costs, however,have been predicted for management interventions, especially stand establishment, in the US southeast and Pacific northwest (Regens et al., 1989). In addition, higher raw material costs have been estimated in the US southeast if climatic changes result in lower wood density of pulping timber. Other projections include:

- Significant costs associated with flooding (due to sea-level rise) of southeast US coastal loblolly pine forests and pulp/paper mills;

- lower quality and quantity of lumber yields of southern pines;

- massive costs if processing infrastructure must follow the northward and inland movement of the range of southern pines, or if log-hauling distances increase; and

- major disruptions to employment in forest sector communities, but would lie outside the southern pine range with climatic change.

Overall, Regens et al. (1989) conclude that, even though there are many opportunities for compensatory responses (ie mitigative action), the effects of climatic changes on US forest products would be negative.

Van Kooten and Arthur (1989) found that despite assumed increases in forest productivity in the boreal forests of western Canada under 2 x CO_2 climates, the welfare of Canadian forest-products producers would be reduced more than the welfare of Canadian forest-products consumers would increase. The economic benefits of the increased productivity of western Canadian forests would accrue mainly to Canada's trading partners. Contrary to these findings for Canada are the speculations of Babcock (1989) who stated that with climatic change influences on North American forests, there would be net undesirable socioeconomic impacts in the US and net desirable socioeconomic impacts in Canada.

The socioeconomic consequences of climatic changes for the world forest sector could be severe, especially where the Gross National Product has a high forestry component (Table 2.5). This conclusion is reach under a great deal of uncertainty; however, intensively managed forests have the potential to mitigate many of the anticipated undesirable impacts of climate changes. No doubt they also have the potential to intensify the effects if they are poorly designed and implemented.

Table 2.5a Summary of forest resources and forest management species (1986)

		Canada	USA	Austria	FRG
Productive forest land (million ha)		244	210	3.0	7.3
Impact of forestry on economy ($billion Cdn)	GNP	506	415,000	95	898
	Import	1.59	15.44	1.1	8.9
	Export	16.87	8.73	2.48	4.98

Managed species:

Canada: *Picea* spp., *Pinus* spp., *Abies balsamea, Populus*

USA: *Picea* spp., *Pinus* spp., *Quercus, Carya, Acer, Fagus, Betula, Ulmus*

Austria: *Picea abies, Pinus sylvestris, Larix decidua, Abiel alba, Fagus sylvatica*

Federal Republic of Germany: *Picea abies, Pinus sylvestris, Abies alba, Pseudotsuga menziesii, Larix decidua, Fagus sylvatica, Quercus robur*

		Indonesia	China	India	Brazil	Chile
Productive forest land (million ha)		45	122	45	350	4.7
Impact of forestry on economy ($billion Cdn)	GNP	85	260	246	250	16.4
	Import	0.22	3.38	0.22	0	0.16
	Export	2.00	0.68	0.2	1.22	0.48

Managed species:

Indonesia: *Meranti romin, Tectonia grandis, Pinus merkusii, Pterocarpus indicans, Eucalyptus deglupta, Acacia decurrens*

China: Dawn redwood, Cathaya, Golden Larch, Chinese swamp cypress, folkiena cedar, larches, Chinese fir, Korean pine

India: *Dipterocarpus* spp., *Shorea rubusta, Cedrus deodara, Pinus roxburghii, Abies densa, Picea smithiana*

Brazil: *Eucalyptus* spp., *Tectonia grandis, Khaya* spp., *Swietenia macrophylla*

Chile: *Pinus radiata, Eucalyptus* spp., *Populus, Pinus*

		Kenya	Zambia	Finland	New Zealand
Productive forest land (million ha)		1.1	4.1	18.2	2.8
Impact of forestry on economy ($billion Cdn)	GNP	1.7	2.1	96.9	23.2
	Import	0.02	0.09	0.4	0.16
	Export	0.004	0	7.15	0.55

Managed species:

Kenya: *Ocotea* spp., *Myrica salicifolia, Acacia labai, Acacia abyssinica, Podocarpus gracilis, Juniperus procera*

Zambia: *Brachystegia* spp., *Jubernardia angelensis, Eucalyptus grandis, Pinus kesiyia*

Finland: *Picea abies, Pinus sylvestris, Betula pendula*

New Zealand: *Pinus radiata, Podocarpus totara, Rimu compressinum, Kanaki, Rata*

Table 2.5b Roundwood production, imports, exports and their value

	Indonesia	China	India	Brazil
Roundwood production (thousand m^3)	159,768	268,835	237,774	33,763
Roundwood imports (thousand m^3)	0	12,310	27	64
Value (Cdn$000)	0	1,310,400	4,314	10,305
Roundwood exports (thousand m^3)	404	44	16	9
Value (Cdn$000)	15,984	9,644	1,213	1,538

	Kenya	Zambia	Finland	New Zealand
Roundwood production (thousand m^3)	33,763	9,946	41,297	9,341
Roundwood imports (thousand m^3)	0	9	5,258	3
Value (Cdn$000)	0	1,453	223,037	1,321
Roundwood exports (thousand m^3)	34	0	1,523	997
Value (Cdn$000)	1,274	0	157,791	54,146

	Chile	Canada	USA	Austria	FRG
Roundwood production (thousand m^3)	16,364	180,419	484,551	13,622	30,411
Roundwood imports (thousand m^3)	0	5,269	2,842	4,756	3,182
Value (Cdn$000)	0	230,132	82,904	281,899	405,908
Roundwood exports (thousand m^3)	1,169	5,068	20,410	768	4,176
Value (Cdn$000)	54,021	371,860	1,973,704	76,468	308,674

Our ability to cope with the projected impacts will depend on the near-term acquisition of knowledge through focused research and assessment and on prudent timely and proactive forest management policies and strategies.

4 Summary and conclusions

4.1 Agriculture

4.1.1 Effects on food security

Sufficient evidence is now available from, a variety of different studies, to indicate that changes of climate would have an important effect on agriculture. Yet the fact that there are major uncertainties regarding likely effects in specific reasons should be a cause for concern. Studies have not yet conclusively determined whether, on average, global agricultural potential will increase or decrease.

On balance, the evidence is that food production at the global level can, in the face of estimated changes of climate, be maintained at essentially the same as would have occurred without climate change, but the cost of achieving this is unclear. Moreover, there may well occur severe negative effects at the regional level, particularly in regions of high present-day vulnerability least able to adjust technically to such effects. Increases in productive potential at high mid latitudes and high latitudes, while being of regional importance, are not likely to open up large new areas for production. The gains in productive potential here due to climatic warming are unlikely to balance large-scale reductions in potential in some major grain-exporting regions at mid-latitude.

4.1.2 Magnitudes of possible dislocation

Under the estimate of changes in productive potential for a 2 x CO_2 climate outlined in this report prices of some mid-latitude crops such as maize, soy-bean and wheat could increase, reflecting a small net decrease in the global food production capability of these crops. Rice production could, however, increase if available moisture increased in Southeast Asia. The average global increase in overall production costs due to climate could thus be small (perhaps a few per cent of world agricultural GDP).

Much depends however, on how beneficial are the so-called 'direct' effects of increased CO_2 on crop yield. If plant productivity is substantially enhanced *and* more moisture is available in some major production areas, then world productive potential of staple cereals could increase relative to demand and food prices could be reduced as a result. If, on the contrary, there is little beneficial direct CO_2 effect *and* climate changes are negative for agricultural potential in all or most of the major food-exporting areas, then the average costs of world agricultural production due to climate could increase significantly, these increased costs amounting to perhaps over 10% of world agricultural GDP.

4.1.3 The most vulnerable regions and sectors

On the basis both of limited resource capacity in relation to present day population and of possible future diminution of the agricultural resource base as a consequence of reduced crop-water availability, two broad sets of regions appear most vulnerable to climatic change: (i) some semi-arid tropical and subtropical regions (viz western Arabia, the Maghreb, western West Africa, Horn of Africa and southern Africa, eastern Brazil) and (ii) some humid tropical and equatorial regions (viz southeast Asia, Central America).

In addition, certain regions that are currently net exporters of cereals could also be characterised by reduced crop-water availability and thus reduced productive potential as a result of climatic changes. Any decrease in production in these regions could markedly affect future global food prices and patterns of trade. These regions include: southern Europe, southern US, parts of South America, western Australia.

4.1.4 The effect of altered climatic extremes

Relatively small changes in the mean values of rainfall and temperature can have a marked effect on the frequency of extreme levels of available warmth and moisture. For example, the number of very hot days which can cause damaging heat stress to temperate crops could increase significantly in some regions as a result of 1° or 2°C increase in the mean annual temperatures. Similarly, reductions in average levels of soil moisture as a result of higher rates of évapotranspiration could increase substantially the number of days with a minimum threshold of water availability for given crops.

Although at present we know little about how these frequencies of extreme events may alter as a result of climatic change, the potential impact of concurrent drought or heat stress in the major food-exporting regions of the world could be severe. In addition, relatively small decreases in rainfall or increases in évapotranspiration could markedly increase both the risk and the intensity of drought in currently drought-prone (and often food-deficient) regions. Change in drought risk represents potentially the most serious impact of climatic change on agriculture both at the regional and the global level.

4.1.5 Effects on crop growth potential, land degradation, pests and diseases

Higher levels of atmospheric CO_2 are expected to enhance the growth rate of some staple cereal crops such as wheat and rice, but not of others such as millet, sorghum and maize. The use of water by crop plants may also be efficient under higher CO_2 levels. However, it is not clear how far these potentially beneficial 'direct' effects of enhanced atmospheric CO_2 will be manifested in the farmers field rather than in the experimental glasshouse.

Warming is likely to result in a poleward shift of thermal limits of agriculture, which may increase productive potential in high latitude regions. But soils and terrain may not enable much of this potential to be realised. Moreover, shifts of moisture limits in some semi-arid and subhumid regions could lead to significant reductions of potential here, with serious implications for regional food supplies in some developing countries.

There are indications that precipitation in a warmer world would be received in more intense storms at the expense at the expense of more widespread and less intense showers. This would tend to encourage higher rates of soil erosion, especially if higher rates of evaporation lead to greater differences in soil moisture between dry periods and wet periods of the year.

Temperature increases may extend the geographic range of some insect pests and insect diseases, allowing, for example, the expansion of those pests at present limited to tropical countries to current subtropical and temperate regions.

4.1.6 Regional impacts

Impacts on potential yields are likely to vary greatly according to types of climatic change and types of agriculture. In the northern mid-latitude regions where summer drying may reduce productive potential (eg in the south and central US and in southern Europe) studies have estimated yield potential to fall by ca 10-30% under an equilibrium 2 x CO_2 climate. Towards the northern edge of current core producing regions, however, warming may enhance productive potential in climatic terms. When combined with direct CO_2 effects, increased climatic potential could be substantial - though in actuality it may be limited by soils and terrain.

There are indications that warming could lead to an overall reduction of cereal production potential in North America, and to reduced potential in southern Europe but increased potential in northern Europe.

Warming could allow increased agricultural output in regions near the northern limit of current production in the USSR, but output in the Ukraine and Kazakhstan could only increase if corresponding increases in soil moisture were to occur, and this is at present uncertain.

Under the estimates of changes in climate outlined in this report, reduced output in North America, particularly of maize and soybean, would lead to increases in world prices in these crops and resultant increases in costs of livestock food and livestock products. The prices of wheat, rice and other staples would, however, depend on changes in yield potential in other major producing regions, and insufficient is known at present about possible changes of climate in these areas.

Little is known about likely impacts in semi-arid and humid tropical regions, because production potential here largely depends on crop water availability and the regional pattern of possible changes in precipitation is unclear at present. It is wise, however, to assume that crop water availability could decrease in some regions. Under these circumstances there could be substantial regional dislocation of access to food supply.

4.1.7 Rates of adaptability

In some parts of the world climatic limits to agriculture are estimated to shift poleward by 200-300 km per degree of warming (or 100 km per decade under a scenario) of a 3°C global warming by 2060. The warming-induced upward shift in thermal zones along mountain slopes would be in the order of 120-200 m.

There are indications that agriculture has an ability to adjust, within given economic and technological constraints, to a certain, limited rate of climatic change. This capability probably varies greatly between regions and sectors but no thorough analysis of adaptive capacity has yet been conducted for the agricultural sector.

In some currently highly variable climates, farmers may be more adaptable than those in regions of more equable climate. But in less developed economies, and particularly in some marginal types of agriculture, this intrinsic adaptive capability may be much less. It is important to establish in more detail the nature of this adaptability, and thus help determine critical rates of climatic change that would exceed those that could be accommodated by within-system adjustments.

4.1.8 Future tasks

This report has emphasised the inadequacy of our present knowledge. It is clear that more information on potential impacts would help us identify the full range of potentially useful responses and assist in determining which of these may be most valuable.

Some priorities for future research may be summarised as follows:

- Improved knowledge is needed of effects of changes in climate on crop yields and livestock productivity in different regions and under varying types of management. To date, less than a dozen detailed regional studies have been completed, and these are insufficient as a basis for generalising about effects on food production at the regional or world scale.

- Improved understanding is needed of the effects of changes in climate on other physical processes, for example on rates of soil erosion and salinisation; on soil nutrient depletion; on pests, diseases and soil microbes, and their vectors; on hydrological conditions as they affect irrigation water availability.

- An improved ability is required to 'scale-up' our understanding of effects on crops and livestock to effects on farm production, on village production, and on national and global food supply. This is particularly important because policies must be designed to respond to impacts at the national and global levels. Further information is needed on the effects of changes in climate on social and economic conditions in rural areas (eg employment and income, equity considerations, farm infrastructure, support services etc).

- Further information is needed on the range of potentially effective technical adjustments at the farm and village level (eg irrigation, crop selection, fertilising etc) and on the economic and political constraints on such adjustments. In particular, it is recommended that international centres of agricultural research consider the potential value of new research programs aimed at identifying or developing cultivars appropriate for altered climates.

- Further information is needed on the range of potentially effective policy responses at regional, national and international levels (eg reallocations of land use, plant breeding, improved agricultural extension schemes, large-scale water transfers etc).

4.2 Forestry - future deliberations

Countries must develop and perfect technologies to attain sustainable production from trees in all aspects, food, fodder, shelter, fuelwood and soil protection. Policy makers at all levels must be aware of the local perceptions of the use of trees, choice of species and the attitudes on management and protection of natural forest resources.

Two observations may be made. First, the problems of forest ecosystems are usually region-specific; therefore, analyses of the impacts must be region-specific. Universal issues include the conversion of all-aged multispecies, natural closed forests to high-yielding, intensively managed, mono-specific forests or to other uses including; non-forest land use, inadequately regenerated natural forest, or low-yield managed plantations. The latter three conversions often fall short of local needs in developing countries and make forest product industries vulnerable to fibre shortages while at the same time biodiversity is reduced, wildlife habitat is degraded and carbon emissions to the atmosphere increase.

The second observation concerns the uncertainty as to whether fifty years hence, these same issues will affect world forest ecosystems. The future of these forestry problems like the effects of climatic changes on the forest sector is largely dependent on society's successes or failures in addressing and solving them. Nevertheless, if these issues and tensions continue over the next 50-100 years, climatic changes might relieve or aggravate them (Table 2.5).

An initial assessment leads to the conclusion that climatic changes are more likely to exacerbate these issues and tensions than to reduce them. This finding depends on the assumption that during the next 30-50 years in response to climatic changes, forests everywhere in the world will be sensitive to some decline. If, forests in some regions are largely unaffected by climatic changes, or subject to intensive forest management resulting in increased growth rates, then many of the statements in Table 2.5 will not occur. As future climatic changes become more apparent the necessity for strong and proactive intensive forest management, agroforestry and urban forestry programs will become obvious.

The following research and assessment initiatives should be developed or pursued in the near future to reduce the level of these uncertainties.

- Studies on biological responses to various rates and magnitudes of change to obtain reliable parameters for simulation models. The genetic variability needs to be investigated simultaneously. Earlier established experiments are of special value because the final response may occur after several years of variable weather.

- Detailed regional climate scenarios are needed for the development of forest impact studies (eg see Gibbs and Hoffman, 1987; Cohen, 1989). Studies of impacts must be global in scope, international in organisation, institutional in focus and historical in breadth.

- Studies at the stand-level are a prerequisite for credible socioeconomic assessments of forest-sector responses to climate. Stand-response studies require regional climate scenarios as input, and should employ suitable stand-dynamics simulators (eg Pastor and Post, 1985; 1986; 1988).

- Better understanding of the relationship between species and sites is required. Progress is being made in identifying and mapping the climatically suitable and sustainable areas for a wide variety of tree species (eg Booth et al., 1989).

- Improved knowledge is required concerning the potential role of forest management at the management unit scale, in mitigating undesirable impacts and capitalising on desirable impacts due to climatic change. In industrial forests, management units are composed of several thousand stands and cover 10^5-10^6 ha. Forest-level analyses require inputs from stand-scale models employing suitable forest-dynamics simulators (eg Attebring et al., 1988; Wang et al., 1987).

- Analyses are required at the regional-scale (10^5 ha +) of the possible effects on wildlife habitat and recreational potential resulting from climate-induced forest-structure changes. These studies require scenarios of the dynamics of wildlife habitat, which can be developed using forest simulators as noted above.

- Analyses are required at the regional scale (10^7 ha +) of the potential socioeconomic repercussions on rural communities, industrial concerns, markets and trade in forest products, and on governments, resulting from timber-supply fluctuations due to climatic change.

- Socioeconomic impacts should focus on the transitional climate that may occur over the next several decades, rather than on a single future long-term 'equilibrium' climate.
- In the face of great uncertainties about rates and magnitudes of climatic changes, forest responses to potential climatic change and socioeconomic repercussions of climate induced forest changes,

it is prudent to prepare for severe undesirable impacts to ensure that viable and flexible options are implemented to maintain sustainable forest ecosystems.

- The relationships between rates of biophysical processes, socioeconomic and technological processes must be known in order to understand and respond satisfactorily to socioeconomic impacts of climatic changes on the forest sector.

Examining biogeochemical changes on a global scale is so complex that adding humans as an additional variable further complicates the issue; nevertheless, humans are the critical element in the study of ecological systems. We must consider the institutional imperatives, and the economic and political influences on people in different nations with the cultural diversity that distinguishes and may dominate our actions.

Figure 2.1 Sensitivity of world agricultural prices to yield changes

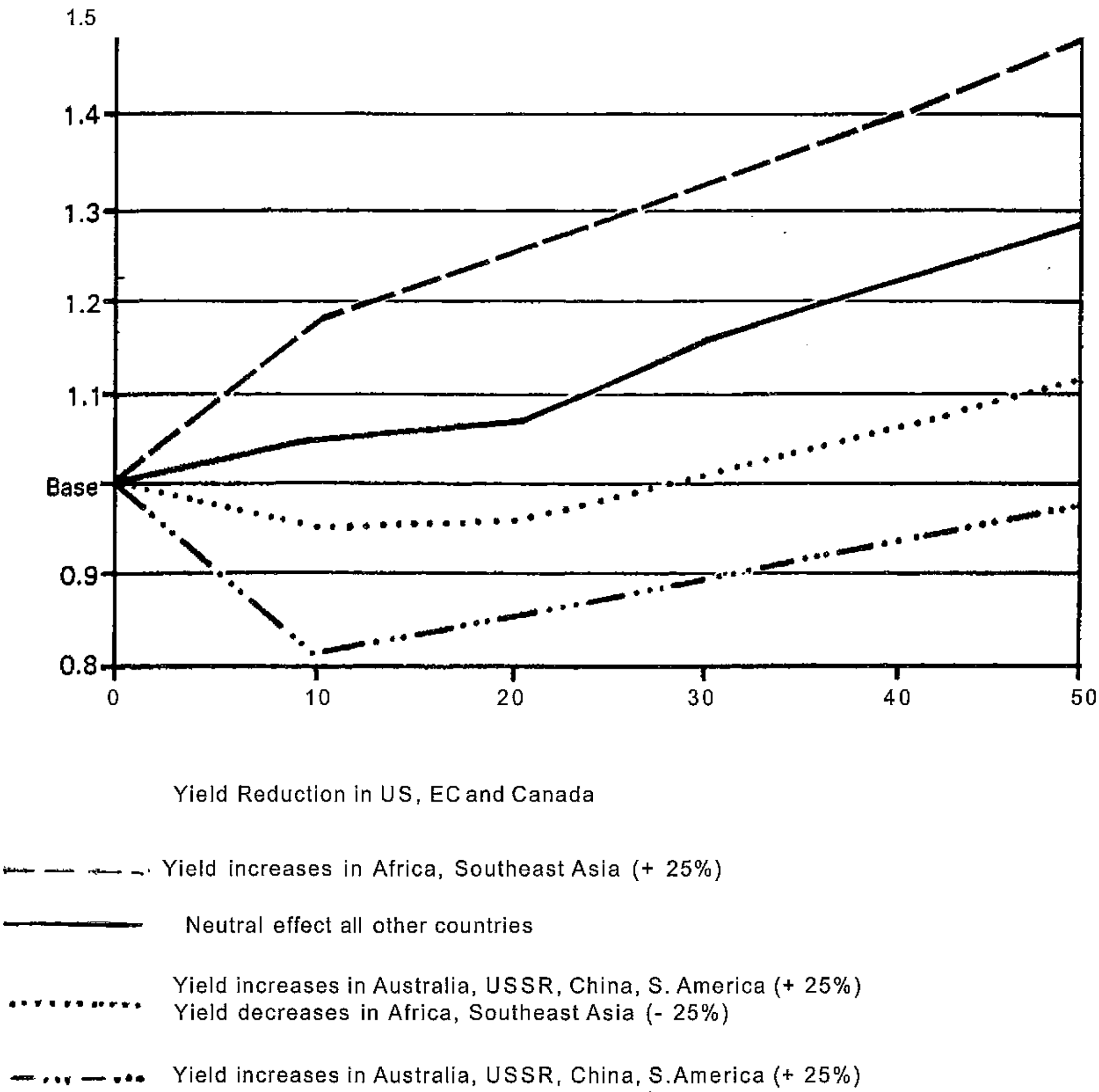

Figure 2.1 Estimated changes in price of agricultural commodities for a range of concurrent yield reductions in USA, the European Community and Canada. The estimations are for four scenarios: 1) no change elsewhere; 2) yield increases of 25% in Africa and SE Asia, but no change in other countries; 3) yield increases of 25% in Australia, USSR, China, S. America and decreases of 25% in Africa and SE Asia; and 4) yield increases in Australia, USSR, China and S. America, but no change in other countries. The estimations assume present-day economic conditions and technology (Kane, et al., 1 989)

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