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Agriculture and forestry-related issues

The work carried out under this task is discussed under the headings of:

Agriculture and forestry
Natural terrestrial ecosystems
Hydrology and water resources

IV Agriculture and forestry

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IV Agriculture and forestry

I Agriculture

Progress since 1990

Since the publication of the first IPCC Impacts Assessment, progress in the study of agricultural impacts of climate change has continued on many fronts. In this update, we have adopted the structure of the original IPCC report on agriculture and forestry and for each section of the original report,we identify first, what, if any, new work has been done and second, whether this new work leads to any different conclusions from the 1990 report. New sections are added where necessary.

1 Climatic scenarios

While assumptions about climatic scenarios have not changed for the purposes of the ongoing IPCC assessment, it is important to note that improvements in methods for generating climate change scenarios are under development. One such method is the nesting of meso-scale meteorological models within general circulation models (GCMs) to improve regional climate change prediction (Giorgi and Mearns 1991). Another method is the use of stochastic weather generation models to generate synthetic daily time series with changes in variance, as well as means (Wilks 1991; Mearns et al. 1992). This is helpful because most impact studies so far have been limited to the investigation of the effects of mean changes in climate variables.

Some studies have begun to investigate the effect of potential changes in climate variance on the variability of crop yields, a key factor of agricultural stability. The question of agricultural sensitivity to climatic variability has been researched by superimposing past variations on altered average conditions to assess impacts for crop yields, farm returns and risks, and regional production in Ontario, Canada (Brklacich and Smit 1992), and the American midwest (Easterling et al. 1991). The effects of a range of temperature and precipitation variance changes, as well as future changes in variance predicted by one GCM, on simulated wheat yields in Kansas have been analysed by Mearns et al. (1992). Further investigation of climate and crop yield variabilities should be encouraged.

Improved prediction of potential future hydrological regimes (including estimates of changes in soil moisture and groundwater availability) continues to be a critical need for agricultural impact studies. Recent work on climate change scenarios suggests that the frequency of heavy rainfall events at almost all latitudes may increase with global warming, while the numbers of raindays in mid latitudes may decrease (Pittock et al. 1991; Whetton and Pittock 1991). These changes may bring a nearly global increase in flood and high runoff events, leading to soil degradation and flood control problems, as well as reductions in the return period of droughts. Observations of hydrological variables, such as the recently published soil moisture dataset by Vinnikov and Yeserkepova (1991), should be useful in testing understanding of current and projected hydrological relationships. Still critically needed is the development of improved regional scenarios for monsoonal areas (Yoshino 1991).

Another key point which is emerging is that the emphasis of previous climate change studies on the arbitrary doubling of atmospheric CO_2 levels (or their equivalent) may be limiting estimation of impacts (Cline 1992). Atmospheric CO_2 concentration is projected to increase beyond doubling to 1600 ppm by the year 2250 (Sundquist 1990) and GCM simulations have shown large warming effects of CO_2 at such levels (Manabe and Bryan 1985). Greater warming beyond the equivalent doubled CO_2 level has implications for projections of agricultural impacts, because higher temperatures may lead to earlier maturity and lower yields of determinate crops in temperate regions, higher levels of potential evapotranspiration and water stress, and possible high temperature damage to yield quality (Wang and Hennessey 1991). While the climatic effects of CO_2 may negatively affect agricultural production at concentrations higher than doubled, the beneficial direct effects of CO_2 on crop growth may level off at higher CO_2 concentrations, as seen in experimental work on leaf photosynthetic rates (Akita and Moss 1973), leading to potentially greater negative impacts later.

2 Assumptions concerning technology and management

Since the publication of the first IPCC Impacts Assessment, there has been a growing emphasis on the need for 'moving' pictures of how agriculture may respond to transient climate changes over time. Research has begun to grapple with how such transient projections of agricultural technology should be estimated (Rosenberg and Crosson 1991). For example, conventional plant breeding and biotechnology are each expected to improve yields on the order of 1–2%/year (Pimentel et al. 1992) and such estimates should be factored into projections of future impacts of climate change. Other probable future changes in agriculture include higher fossil fuel prices and greater use of crops for fuel and paper fibre.

The vulnerability of crops to climate change may be either increased (by design) or diminished (inadvertently) by future technological changes. If technological advances narrow the optimal range of input conditions for agricultural production (eg need for high levels of fertiliser), and if climate change results in increased variability such as increases in frequency of droughts as well, production risks may also be expected to increase.

3 Potential impacts on agriculture and land use

3.1 Critical types of climatic change

In the area of direct climatic effects on crop growth, recent work shows that continued concern for future agricultural production appears warranted, a confirmation of the IPCC conclusions. Drought frequency may indeed increase in low and mid latitudes owing to increases in the demand of the atmosphere for water (potential evapotranspiration) over the supply (precipitation) (Rind et al. 1990) and to higher frequency of occurrence of dry spells (Pittock et al. 1991), although direction of change in climate variability of temperature and precipitation overall is still uncertain (Mearns et al. 1992).

Other critical types of newly identified climate effects are slight amounts of warming in the early stages of the projected climate change or increases in variability. These types of climate change may increase frost damage to crops (demonstrated by simulating wheat growth in Kansas), as slight warming or augmented variability actually lessens winter hardiness while not eliminating hard frosts altogether in some regions (Mearns et al. 1992).

3.2 Regions of risk

Conferences since the advent of the IPCC have echoed the concept of regions at risk, based on preliminary projections of adverse climate change and present-day resource ability to support existing populations. More detailed descriptions of vulnerable regions and methodologies for integrated regional assessment of the potential effects of climate change have been brought forward, with emphasis on sensitive regions where farmers lack financial resources, fertile land, irrigation, drought-tolerant seeds, alternative employment options, or reasonable prices for inputs and products (Houston Advanced Research Center 1991). Jodha (1989) has shown that traditional farming systems encompass a wide range of adjustments to loss and advocates the preparation of an inventory of current farming practices available for transfer to regions with changing climates. However, Jodha also cautions that unequal social structures and international positions, as well as unequal land tenure, high numbers of landless rural dwellers, low incomes and high national debts may increase vulnerability to climate change.

4 Direct effects of elevated CO_2 and other greenhouse gases

4.1 Combined effects of climatic and direct effects of CO_2

A fundamental question that remains despite continued research since the publication of the initial IPCC assessment is the overall relative importance of direct and indirect effects of CO_2 on future crop production. On an individual cultivar and crop basis these effects have been shown to vary considerably, depending on plant physiology and the coincident levels of CO_2, temperature and water availability. Some scientists weight the beneficial effects of CO_2 as the dominant factor, while others are sceptical that the large benefits seen in experimental settings will be seen in farmers' fields under changing climate conditions. Free air release of CO_2 experiments on cotton are continuing in Phoenix, Arizona (Hendrey et al. 1992), and other free air release experiments are under way elsewhere (Miglietta 1991).

While the separate effects of atmospheric CO_2 concentration and temperature on specific plant processes have been studied extensively, the interactive effects of temperature and atmospheric CO_2 concentration over the entire growing season continue to be less well understood. Combined studies of direct and indirect effects of CO_2 on crops have intensified to provide clarification. A recently published review of these experiments showed that as temperature increased (levels not given), relative increases in plant growth and photosynthesis were greater under CO_2 enrichment (Allen et al. 1990). The extent of the temperature-CO_2 interaction differed considerably among species: C4 species were less responsive (as they have been shown to be to CO_2 increases alone) than C3 crops, and sorghum showed no response. The relative decrease in stomatal conductance to water vapour due to CO_2 was greater (as much as 25%) as temperatures rose.

There is a further need for studies of temperature and CO_2 interactions on crops and cultivars from diverse agricultural systems. These studies should be designed to test a wide range of levels of both factors and to quantify a full complement of crop physiological and phenological responses. Preliminary work suggests that potential crop responses to combined higher CO_2 and higher temperature may counter, at least in part, negative effects of climate change through gains in water use efficiency. From a regional perspective, however, water consumption per unit of land area may not change significantly due to plants with larger biomass (Eamus 1991). Furthermore, given the trajectories for projected increases in greenhouse gases (GHGs) other than CO_2, greater warming may occur with lower amounts of CO_2 and thus lower levels of CO_2 fertilisation (Cline 1992).

Because experimental settings are limited and costly, crop growth models are required tools for simulating the combined responses of crops to elevated CO_2 and climate change, especially at scales beyond one or several plants. Some of the efforts under way are described in Hesketh and Alm (1992) and Reynolds et al. (1992). Simulation models for wheat growth have demonstrated that higher temperatures cause earlier maturation, which can cancel out any gain in yield from higher CO_2, and that only cultivars adapted to high temperatures may do well in a warmer and CO_2-enriched environment (Wang and Hennessy 1991). These authors also cite experimental work showing that wheat quality can be significantly reduced by spells of high temperature above 35°C.

4.2 Competition

A review of the implications of increasing CO_2 and climate change on competition in agricultural ecosystems has confirmed the original IPCC conclusion that differential growth responses to both CO_2 concentration and climate change will affect future competitive ability and fitness of plants (Patterson and Flint 1990). The relative importance of various weed species in agro-ecosystems may change, but selection of adapted crop varieties and management methods may minimise negative impacts. Weedy species with broad ecological amplitudes are likely to prosper at the expense of endemic species or those already in marginal habitats. In the tropics, important C4 crops such as maize and sugarcane, which are adapted to hot, dry conditions, may experience yield reductions because of the improved performance of C3 weeds (Bazzaz and Fajer 1992).

4.3 Pest interactions

While experiments have tested some isolated aspects of pest infestations at elevated CO_2 concentrations, it is still hard to project future pest-CO_2 interactions. Some experiments have shown that some insect populations may decline owing to lower nutritional quality of leaves; this could lead to reconfiguration of many ecological interactions. Other experimental work has shown that insects consume more leaves in order to compensate for lower nutritional quality; this could work to negate benefits in crop yields caused by higher CO_2 levels (Bazzaz and Fajer 1992).

5 Multiple stresses

It is important to emphasise that the future is projected to bring simultaneous multiple stresses, such as elevated UV-B radiation and augmented tropospheric ozone, in combination with high CO_2, and that these may negate the beneficial physiological effects in some crops. Higher levels of CO_2 may partially offset damage from tropospheric ozone, sulfur dioxide and other pollutants, through stomatal closure (Allen 1990). Experiments reported by Teramura et al. (1990) show that no increase in wheat or rice grain yield occurred under conditions of combined elevated UV-B and CO_2. Soybeans, on the other hand, produced more yield under the same conditions. A review of experimental literature has shown that susceptibility to plant pathogens may increase with higher UV-B radiation (Pimentel et al. 1992).

6 Effects of climate change on soil properties

New work has improved knowledge of the soil as a source of GHGs and of the potential impacts of climate change on soils (Buol et al. 1990; Bouwman 1990; Scharpenseel et al. 1990; US National Science Foundation 1992). Global climate change will affect soils primarily through changes in soil moisture, soil temperature and soil organic matter. Higher air temperatures will cause greater potential evapotranspiration and higher soil temperatures, which should increase solution chemical reaction rates and diffusion-controlled reactions. Solubilities of soil and gaseous components may either increase or decrease, but the consequences of these changes may take many years to become significant.

A study of potential land degradation in New South Wales, Australia, predicted significant increases in soil erosion, sedimentation and salinity if rainfall intensities increase (Aveyard 1988), while a study of soil erosion potential in the US using the Universal Soil Loss Equation found that national average sheet and rill erosion changes are projected to range from about -5% to 16% (Phillips et al. 1991).

Higher temperatures will accelerate the decay of soil organic matter, resulting in release of CO_2 to the atmosphere and decrease in carbon/nitrogen ratios, although these two effects should be offset somewhat by the greater root biomass and crop residues resulting from plant responses to higher CO_2. The tendency of increased temperature to increase decomposition may also be offset by the negative impact of increased carbon/ nitrogen ratios on decomposition, and the negative impact of drought on decomposition, if droughts become more frequent in a warmer climate. Higher temperatures could also increase mineralisation rates, improving availability of phosphorous and potassium and speeding colloid formation.

7 Effects of climate change on the distribution of agricultural pests and diseases

Recent reviews echo the earlier IPCC conclusion that ecological conditions for insect growth and abundance are expected to improve overall through lengthening of breeding seasons and extension of ranges (Porter et al. 1991; Pimentel et al. 1992), but also suggest that drier conditions may decrease pest damage in some regions. Porter et al. (1991) investigated the impact of one GCM climate change scenario on the European corn borer (*Ostrinia nubilalis*) in Europe, finding northward shifts in potential distribution of up to 1220 km, and an additional generation in nearly all regions where the insect is currently known to occur.

Pimentel et al. (1992) considered the effects of a 2°C temperature rise in the US and Africa and found that, if North America becomes warmer and drier, crop losses due to plant diseases are expected to decline as much as 30% below current levels. If Africa becomes warmer and wetter, crop losses to diseases will increase up to 133% above current levels for some crops. High percentages of crop losses to pests are expected to be sustained in Africa because effective pest control technologies are not extensively in use, nor are they expected to improve appreciably in the future. US crop losses to weeds are estimated to rise between 5% and 50% (depending on the crop), because of intensified competition from weeds, which are often better adapted to arid conditions than are crops. Herbicidal controls tend to be less effective under hot/dry conditions than they are under the more cool/wet current conditions (Pimentel et al. 1990).

8 Research on regional impacts

Note: the following section summarises recent research on both 'Potential effects on crop yields and livestock productivity' and on 'Effects on regional and national production,' determining if the research upholds previous IPCC findings or indicates new conclusions.

Another focus of substantial amounts of research activity since the first IPCC synthesis has been regional assessment. Some of the regional assessments have been conducted or are under way in the EC (Carter et al. 1991a, 1991b; Parry et al. 1992a), Rhine basin (Wolf and van Diepen 1991), US (Adams et al. 1990), US midwest (Rosenberg and Crosson 1991; Easterling et al. 1991), agricultural regions in Canada (Cohen 1991; Singh and Stewart 1991), East Asia (Yoshino 1991), Southeast Asia (Parry et al. 1992b), Caribbean region (Granger 1991), and Mexico (Liverman 1992; Liverman and O'Brien 1991). Fewer national assessments have been published, some exceptions being Hungary (Farago et al. 1990 and 1991), Ireland (McWilliams 1991), UK (UK Department of the Environment 1991), and New Zealand (Salinger et al. 1990; Martin et al. 1990).

As these regional studies come forward, they highlight the IPCC conclusion that impacts will vary greatly according to types of climate change and types of agriculture. Both beneficial and detrimental effects of climatic change are projected, although these will not be evenly distributed over the world. In particular, it appears more certain now that cool and temperate climatic zones may benefit, but in the tropics a further increase in temperature will be undesirable. At mid and high latitudes, increased temperatures can benefit crops presently limited by cold temperatures and short growing seasons. In the tropics, crops may be subjected to growing season temperatures higher than optima, and continue to suffer from nutrient shortages, which impair the potential to utilise the beneficial direct effects of increased CO_2 (Goudriaan and Unsworth 1990).

Newly published agricultural impact studies continue to emphasise the uncertainties inherent in such research as long as regional climate change scenarios remain unreliable. Other key uncertainties are projections of future technology and adaptation strategies. Methodological improvements are slowly accruing in dealing with such factors as direct CO_2 effects, pests and pathogens, increasing fuel costs and resource substitution, but many studies neglect one or more of these possibly key factors. Given these considerable caveats, researchers concur that regional impact studies should continue to be regarded as sensitivity studies only.

8.1 North America

8.1.1 United States

Further results from the US EPA national study published since the IPCC Impacts Assessment imply a range of possible outcomes for US agriculture, depending on the severity of climate change and the compensating effects of CO_2 on crop yields (Adams et al. 1990). Simulations combining results from climate, crop and economic models indicate that the role of the US in agricultural export markets may change, regional patterns of agriculture are likely to shift, and demand for irrigation water is likely to increase.

An integrated research project on the US midwest region (Missouri, Iowa, Nebraska and Kansas) used the 1930s climate (1.1°C increase in temperature) as a warmer and drier analog. Methodology included a crop simulation model and its use for evaluation of both available and induced adaptations; inclusion of technological change; analysis of climate variability effects on crop yield variability; and integration of impacts on multiple sectors including agriculture, forestry, water resources, and energy. The research found that impacts on agriculture overall would be small given adaptation (Rosenberg and Crosson 1991; Easterling et al. 1991). Relating these results to the IPCC best estimate of 2.5°C warming implies agricultural losses of about 10% for equilibrium warming of doubling of CO_2 equivalent (Cline 1992). However, at the margins of the region losses could be considerable with a shift in irrigation from west to east. Effective adjustments to the 1930s climate change scenario in the US midwest were earlier planting combined with longer season varieties of annuals and shorter season varieties in perennials, and the use of furrow dyking in warm season crops. Wheat benefited from reduction of cold stress and earlier break in dormancy.

Other recent research that used a simple relationship between yield and CO_2 and temperature reports similar yield declines for the US Great Plains (up to 42–45°N) (Okamoto et al. 1991). In summer, warming caused by increases in atmospheric CO_2 appears to be undesirable for spring wheat, soybean and corn even if positive effects of CO_2 are taken into account. Several CO_2 emissions rates were tested.

These studies support the IPCC conclusion that US grain production would decline with global warming. Another simulation with a mechanistic crop growth model with a soil water component found that grain yields at one site in Illinois increased, or decreased only slightly with temperature increases, except when the climate change was assumed to result in severely decreased rainfall (Muchow and Sinclair 1991).

For the southern US, research using a climate model, a crop growth model, and a field level pesticide transport model studied the impacts of climate change on various aspects of maize production (Cooter 1990). The results suggest that substantial changes in agricultural production and management practices may be needed to respond to the climate changes expected to occur in this region. These changes include the need for heat tolerance as the controlling factor in the introduction of new varieties, decrease in use of existing pesticides because of excessive loss on intensively cropped, rapidly leaching soils and an increase in the potential risk of aquifer contamination by long-lived agricultural chemicals. Irrigation did not appear to be a viable solution to heat-stress-related maize yield losses in Texas and Oklahoma.

8.1.2 Canada

Research on potential agricultural climate change impacts in Quebec indicates that for one GCM (Goddard Institute for Space Studies (GISS)) climate change scenario, yields of corn, soybeans, potatoes, phaseolus beans and sorghum would increase and yields of cereal and oilseed crops, ie wheat, barley, oats, sunflowers and rapeseed would decrease (Singh and Stewart 1991). Apple and grape production might be enhanced and the northern part of the province would benefit most. However, even if climatic conditions in Quebec were to improve, limitations of soil fertility would still effectively constrain the significant expansion of the agricultural land base.

8.2 Central and South America

Several conferences have echoed the IPCC projections of possible negative impacts of global warming in Central and South America (Fundacion Universo Veinteuno 1990; Universidad de São Paulo 1990). Liverman (1991) and Liverman and O'Brien (1991) have used GCM output to project declines in moisture availability and maize yields at several sites in Mexico, following on from earlier studies cited in the initial IPCC Impacts Assessment. In contrast, a study of the implications for climate change and direct CO_2 effects in the Caribbean region found that agriculture and food supply should benefit, although more intense hurricanes and higher storm surges could bring added damage to low-lying coastal areas (Granger 1991).

9 Europe

9.1 European Community

Ongoing work for the European region, with a focus on the EC countries, is using a combination of techniques including large-scale mapping of agricultural potential, crop-climate simulation modelling and laboratory experimentation, to evaluate the possible effects of climate change on agricultural and horticultural production. Early results for grain maize, sunflower and soybean, all of which are constrained by low temperatures in northern Europe, indicated that northward shifts in crop suitability of 200–335 km per 1°C warming could be expected, with these estimates varying locally by a factor of two owing to terrain and regional climate (Carter et al. 1991b).

For different GCM estimates of an equilibrium climate response to equivalent CO_2 doubling, estimates of northward shifts in potential due to warming varied from 700 to 1900 km. Rates of northward shift depend critically on the rate of warming. Regional estimates by the GISS GCM of transient climate response to low, middle and high emissions scenarios in Europe give shifts varying from 10 km per decade to well over 100 km per decade up to the 2050s (Carter et al. 1991a,b).

Further mapping work is examining the thermal and moisture constraints on grain maize production at a European scale. Crop yields are being estimated at individual sites, including winter wheat (different EC countries and four different crop models), cauliflower (ten locations in northern Europe), and soybean (France). CO_2 enrichment and temperature experiments with lettuce and carrot are also under way (Parry et al. 1992a).

9.2 Commonwealth of Independent States

Since the first IPCC Impacts Assessment, additional work has been conducted in Russia based on outputs from several GCM-based $2xCO_2$ climate experiments. These indicate that the agricultural production level in Russia is expected to drop by 5–15% without direct physiological effects of CO_2 on crop growth and water use (Sirotenko 1991). In contrast, predictions based on palaeoclimate analogs show a significant rise in productivity in Russia for a doubling of atmospheric CO_2 (Sirotenko et al. 1990), especially when direct CO_2 effects are taken into account (Menzhulin 1992). A crop modelling investigation of winter and spring wheat yields with GCM scenarios combined with direct CO_2 effects has shown that winter wheat may respond more favourably to climate change than spring wheat (Menzhulin et al., 1992).

A review published since the IPCC assessment summarises research on climate change agricultural impacts in Russia with similar conclusions to those cited by the original IPCC (MacCracken et al. 1990).

9.3 Hungary

The Hungarian Meteorological Service of the Hungarian Ministry for Environment and Regional Policy has published several studies on climate change and its potential socioeconomic impacts. These volumes consider specific potential effects on Hungarian agriculture (Emanuel and Starosolszky 1990; Farago et al. 1990; Farago et al. 1991).

9.4 Ireland

The agricultural production potential of Ireland may be enhanced with climate change (McWilliams 1991). Production options could increase, new crops could be cultivated, and the overall costs of agricultural production could likely be less than at present. While cereal crops may have little or no increase in yields, yields of other crops like sugar beet and potatoes could increase by up to 20%. Crop regions could extend northward and new crops, such as maize, sunflower, and flax, may become viable over much of the south. Vegetable crops and fruit crops could be grown over wider areas than is currently the case, because warming should bring a reduction in the frequency of late spring frosts.

9.5 United Kingdom

In the UK, higher temperatures would decrease cereal crop yields, and increase yields of such crops as potatoes, sugar beet and forest trees (UK Department of the Environment 1991). Viability of grassland, animal production and forestry in the uplands would improve, but might require considerable investment. New crops and tree species could be introduced into the UK. Maize and sunflower might be grown for their grain yield as well as for fodder. Horticultural crops may benefit from warmer winters and reduced glasshouse heating costs. However, soils are likely to be seriously affected by climate change which encompasses variations in moisture, because cultivation may become more difficult under drier conditions, and because soil shrinkage could lead to more cracking with consequences for moisture balance, efficiency of fertilisers, herbicides and pesticides, and groundwater pollution. Land use policy for agriculture and agro-forestry may need to be reviewed in light of climate change effects.

9.6 Rhine Basin

Wolf and van Diepen (1991) estimated the effects of one climate change scenario (+3°C with seasonally varying precipitation changes) and doubled levels of atmospheric CO_2 on crop production and agricultural land use in the Rhine basin. Using a crop growth model, they found that the climate change and CO_2 scenario tested had generally positive effects on simulated crop production in the Rhine basin. Average grain production of winter wheat increased by 35%, average production of permanent grassland by 53%, while silage maize production decreased. Changes in land use induced by climate change projected on the basis of a literature review included an increase in area of permanent crops, especially for vineyards; decrease in area of permanent grassland; decrease in areas cultivated with root crops, oats, rye, rape and turnip rape; and increase in areas cultivated with grain maize, sunflower and soybean.

10 Africa

Downing (1991) has presented a methodology for research on the potential impact of climate change in Africa that focuses on vulnerability to hunger (or food security), combining sensitivity to climatic variations with the multiple dimensions of regional and household food security. Downing et al. (1992) assessed the relative vulnerability of food production and needs to arbitrary climate change scenarios in several African countries. In Senegal, a 4°C warming would reduce crop yields by 30% by the middle of next century, which could leave an additional one to two million people without domestically produced cereals. In Zimbabwe, under a 2°C warming, yields that are currently achieved in seven out of ten years would be reached in only two to four out of ten years. In Kenya, climate change could increase total potential national production, while exacerbating food shortages in semi-arid areas.

A analysis of current crop yields and potential crop yield changes due to changes in temperature, moisture, UV-B radiation, CO_2, pests, improved technology and losses to pests in Africa concluded that, if rainfall increases 10%, crop yields will improve to a limited extent (Pimentel et al. 1992). Water shortages may well persist, however, as well as serious crop losses to pests. The potential impacts of the greenhouse effect on Africa are a subject of regional concern (Suliman 1990).

11 Asia

A review paper on the climatic impacts on agriculture in East Asia suggests that year-to-year fluctuation of rice yields may become bigger, even though average yield may be greater (Yoshino 1991). This is based on statistical analysis of historical rice yields in Japan, which suggests that the fluctuation of yields is affected not only by climatic variability, but by step-wise development of technological and socioeconomic development as well.

A climate change agricultural impacts study in Southeast Asia has been completed which used a climate change scenario developed from the GISS GCM and crop modelling techniques (Parry et al. 1992b). In Indonesia, average rice, soybean, and maize yields are projected to decrease about 4%, 10% and 50% respectively. In Malaysia, simulated rice yields decreased from 12% to 22%, while demand for irrigation increased 15%. The east coast of Peninsular Malaysia may become too wet for rubber cultivation. Additional adverse effects on agriculture were estimated to occur in both Indonesia and Malaysia, and Thailand as well, as a result of land losses due to sea-level rise.

12 Australia/Oceania

12.1 New Zealand

In New Zealand, higher temperatures may result in substantial shifts in agricultural potential, with temperate crops, especially cereals, being grown 200 km further south and 200 metres higher for each 1°C temperature increase. At the same time, the potential range of these crops could contract southward if winter chilling requirements are not fulfilled (Salinger et al. 1990). The main horticultural crops (apples and kiwifruit) face displacement south of the present day main production areas. This could have serious implications for kiwifruit production, given the assumed climate change scenarios. Viticulture may expand south into the South Island with a change to red winegrapes in northern areas. Citrus and subtropical production might undergo expansion particularly in northern New Zealand. Animal industries could show substantial changes reflecting the change in the quantity and quality of seasonal pasture production and changes in pests and diseases. Dairying may decline in the far north, but could increase in the far south with temperature increases, resulting in an overall increase in production. At the same time, sheep numbers might show an overall decline, except in southern New Zealand. Beef cattle numbers are projected to increase in many areas of New Zealand with climate change.

13 Global assessments

The US Department of Agriculture has conducted studies of the sensitivity of world agriculture to potential climate changes (Kane et al. 1991, 1992). Preliminary results of these studies were presented in the first IPCC Impacts Assessment; recent results continue to indicate that the overall effect of moderate climate change on world and domestic economies may be small as reduced production in some areas is balanced by gains in others. However, further accumulation of GHGs could intensify the climate effects.

A recent global study of climate change and crop yield changes has estimated changes in yields of world crops in both major production areas and vulnerable regions caused by GCM climate change scenarios and the associated direct effects of increasing levels of CO_2 (Rosenzweig and Iglesias 1992). Yield changes were estimated by crop specialists in 18 individual countries using compatible crop growth models and common climate change scenarios. Adaptations to the possible climate changes were also tested at two levels of effort. Preliminary results appear to amplify the IPCC conclusion that agriculture in lower latitude regions may be more vulnerable to the projected changes, even with adaptation efforts, because simulated yield declines tend to be greater in these areas in contrast to less negative or even positive yield changes at mid and high latitudes. When the economic consequences of the yield changes were projected in a world food trade model, results showed that cereal prices and the number of people at risk of hunger could increase with climate change (Rosenzweig and Parry 1992).

14 Adaptation

While some recent reviews and studies have emphasised the possibilities of adaptation to climate change especially in developed countries (US National Academy of Sciences 1991; Rosenberg and Crosson 1991), conference statements and studies in the last eighteen months also suggest that it is important to remember that adaptation may not be complete and that some adaptive measures may have detrimental impacts of their own (Second World Climate Conference 1990; Smit 1991, 1992; Bazzaz and Fajer 1992). For example, changes in planting schedules and readily available cultivars may be easily adopted to minimise impacts on agricultural incomes, but modifying the types of crops grown does not guarantee equal levels or nutritional quality of food production or equal profits for farmers.

Similarly, irrigation is beginning to be perceived as a limited option for regions with increasing aridity caused by climate change. The integrated US midwest study found that agriculture may be less able to compete for surface water and that declining groundwater supplies would hasten the abandonment of irrigation in the western portions of the region (Rosenberg and Crosson 1991). Excessive overdraft of groundwater, soil salinisation, waterlogging, and potential increased demand from competing sectors may limit the viability of irrigation as an adaptation to climate change. However, studies continue to show that the need for irrigation is likely to increase with global warming, as was concluded in the first IPCC assessment. In the US, irrigation has been predicted to increase for a variety of climate change scenarios with higher temperature (Peterson and Keller 1990).

Regarding nutrient applications, Buol et al. (1990) project differing regional fertiliser use, as did the first IPCC Impacts Assessment. In temperate countries where crops are already heavily fertilised, there will probably be no major changes in fertilisation practices, but alterations in timing and application method (eg careful adjustment of side-dress applications of nitrogen during vegetative crop growth) are expected with changes in temperature and precipitation regimes. Fertilisation rates may need to be raised to utilise the beneficial direct effects of increased CO_2 (Goudriaan and Unsworth 1991). In tropical countries, where currently recommended fertiliser application rates are not always applied, augmentation of fertiliser applications will be needed in any case.

Adaptation to more intense pest infestations by increasing application of chemical control may increase chemical loadings in agricultural regions and may not be efficacious in regions where effective pest control technologies are not extensively in use nor expected to improve appreciably in the future. Therefore, high percentages of crop losses to pests may be sustained in such regions.

Research has continued on the process by which farmers adapt, taking into account that imperfect information on climate change will be translated into incomplete and imprecise reactions by farmers (Yohe 1992). In this work, a utility-based decision model is used to test how farmers in the US midwest may decide to switch crops, or at least their mix of crops in response to growing evidence that the climate appears to be changing. Yohe suggests that consistent integration of these imprecise decisions over larger systems could add a sense of transition to static portraits of potential futures.

Kaiser et al. (1992) have similarly studied the process of economic adjustment in the US midwest to synthetic climate scenarios consistent with GCM predictions. This work finds that farmers in southern Minnesota can make some adjustments to mildly changing climate that may significantly moderate initial negative effects. This was due primarily to excellent water-holding capacity of the soil in the region tested.

Adaptation in agricultural policy is emerging as a necessary focus. Inertia and current policy structures may actually inhibit agricultural adaptation to climate change and variability (Smit 1991, 1992). Another study suggests that current US commodity programs may well slow adaptation to climate change by providing financial incentives for farmers to remain with existing cropping systems, rather than to switch to more climatically appropriate ones (Lewandrowski and Brazee 1992).

15 Gaps in research and monitoring

Critical research and monitoring gaps that remain to be filled include:

- Further experimental studies of temperature and CO_2 interactions over the full growing period on crops and cultivars from diverse agricultural systems are needed. These studies should be designed to test a wide range of levels of both factors, at varying water-stress levels, and to quantify a full complement of crop physiological and phenological responses and their effects on both biomass productivity and grain production. Studies should also be conducted on the interactions of CO_2, high temperature, and other stresses such as elevated UV-B radiation and tropospheric ozone.
- Initial studies of changed climatic variability should be amplified by many more research efforts. The ability to test changes in climate variance is a needed advance in impact studies on agriculture, particularly for investigation of the effect of changes in climatic variances on variability of crop yields, farm returns and risks, regional production and key factors of agricultural stability.
- The viability of a wide variety of adaptation options (both biophysical and socioeconomic) needs to be tested for differing agricultural environments and systems. Research should be expanded in identifying the range of adaptability that exists within current crop species, in tracking the expansion of crop production into new environments, and in determining the physiological mechanisms whereby limits to production in stressful environments have been reduced so that the climatic range of successful production has been expanded. Research initiatives should continue to emphasise the processes by which farmers and institutions (both public and private) adapt, taking into account that imperfect information on climate change will be translated into incomplete and imprecise reactions by farmers, agricultural organisations and government agencies. Both economic and environmental costs and benefits of proposed adaptations should be evaluated.
- A needed focus is a better understanding of the linkages between climate impacts and socioeconomic structures and the critical thresholds where significant change takes place. Regions suffering from food poverty today need to be evaluated for vulnerability to the potential for increased stress from climate change. Much can be done to study ways to enhance resilience of agricultural activities to climate variability. Development of improved analytical models either generic or specific to different agricultural systems in different regions of the world should be encouraged.
- While the agricultural sector (especially in regard to productivity) is probably among the most monitored of human activities, much could be done to analyse current and historical data for climate and CO_2 sensitivity. These types of studies can investigate, for example, how crop production regions have shifted geographically in the past, if they shifting now, and whether shifts are climate-related.

16 Recommendations and conclusions

Since the publication of the first IPCC Impacts Assessment, study of agricultural impacts of climate change has continued in many areas. The findings of these studies reinforce the conclusion of the IPCC Assessment Report that, globally, climate change should not compromise our ability to produce sufficient food. These findings also indicate that previous work may have overestimated negative, and underestimated positive, impacts due to climate change. However, there is a need for improved regional climate models and the extension of GCM simulations beyond the equivalent CO_2 doubling point, as well as a need for projecting how our agricultural systems will be configured in the future.

The available studies suggest, however, that the impact of global warming on agriculture may be significant, especially if warming is at the upper end of the range projected by Working Group I. Impacts of climate change must be considered in the context of the necessity for continuing increases in regional agricultural production as the world's population grows from 5 billion to a projected 8.5 billion by 2025. The following points summarise the contributions that recent studies have made to the field of agricultural climate change impacts.

Present studies have focused attention on how transient projections of agricultural technology should be estimated. For example, conventional plant breeding and biotechnology are each expected to improve yields on the order of 1-2%/year, and such estimates should be factored into projections of future impacts of climate change. Evaluation of a wide variety of adaptation options is needed for differing agricultural environments and systems.

Many regional assessments have been conducted since the IPCC, or are under way in the EC, Russia, the US midwest and agricultural regions of Canada, Southeast Asia and Mexico. Additional national assessments have been published by the Hungarian Ministry for Environment and Regional Policy, the Ireland Department of the Environment, UK Department of the Environment, and the New Zealand Ministry for the Environment. Additional integrated regional impact studies linking biological, physical and socioeconomic factors should be carried out wherever possible.

As these regional and national studies come forward, they highlight the IPCC conclusion that impacts will vary greatly according to types of climate change and types of agriculture. Beneficial and detrimental effects of climatic change will not be evenly distributed over the world. In particular, it appears more certain now that cool and temperate climatic zones may benefit, but in the tropics a further increase in temperature will be undesirable.

Research continues to address the relative importance of direct and indirect effects of CO_2 on future crop production. Some scientists weigh the beneficial effects as the dominant factor, while some are sceptical that the large benefits seen in experimental settings will be seen in farmers' fields under changing climate conditions. Combined studies of direct and indirect effects of CO_2 on crops have been intensified to provide clarification. A key point which is emerging is that the warming effects of CO_2 are projected to increase beyond doubling point, but direct physiological effects may level off. The future is also projected to bring simultaneous multiple stresses, such as elevated UV-B radiation and increased tropospheric ozone, in combination with high CO_2, and these may negate some of the beneficial physiological effects in some crops.

Recent studies have reinforced the concern for increased incidence of both droughts and floods, and on water resources for agricultural in general. Changes in water resource availability (both in timing and quantity) pose the greatest risks to agriculture resulting from climate change. Thus, water resource management for food and fibre production (in relation to water needs for other sectors as well) is a crucial task.

Current reviews confirm the earlier conclusion of the IPCC that ecological conditions for insect growth and abundance are expected to improve overall.

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II The managed forest and the forest sector

Scope of the issue

For the purposes of this report, the managed forest includes all forests in which some harvest takes place, with particular emphasis on forests where there is some degree of management. The majority of these managed forests are still of natural origin. This classification excludes forest parks/reserves and wilderness areas.

Projected changes to forest ecosystems suggest changes in the geographic distribution of forest species and changes in the growth rates with the most significant changes likely in the temperate and boreal areas. New information available indicates that the productivity of the forest sector due to increased greenhouse gas concentrations and associated climate change may have been underestimated. However, the socioeconomic consequences of climate change for the forest sector could be significant in regions where economic and social welfare and development is highly dependent on the forest sector. The global ability of the forest sector to cope with climate-induced changes 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.

Progress since the IPCC Impacts Assessment in 1990

1 Socioeconomic importance of forests

Clearly, the dependence and the importance of forests to the national economies has not diminished. This was demonstrated in the previous assessment and the updates in Tables 1 and 2 serve to reinforce this statement. Likewise, management strategies are urgently needed for the adaptation, mitigation and protection of the forest sector.

Countries must continue to address the socioeconomic issues related to forests in their response to the impacts of global and climate change. For example, the São Paulo Conference in 1990 stated clearly that 'The warming of the earth is clear evidence that current patterns of economic activity are not sustainable.'. The conference identified the vulnerability of a number of patterns of activity for the developing countries.

2 Reforestation/afforestation and more managed forests

The need for reforestation/afforestation is a global issue that must involve all countries.

A recent report from the USA states that 'Except for CO_2 scrubbing, which is not a proven technology at this time, reforestation is the only known post-combustion carbon abatement measure.' (Sanghi and Michael 1991). Various options for reforestation/afforestation explore the methods for the establishment of a variety of species and the potential increase in productivity. (Schroeder and Ladd 1991). The data are based on experiences in a developed country, but the approach has potential application in many countries, with different species, economic and forest sector infrastructures.

Data from the IPCC Impacts Assessment demonstrated the benefits associated with increasing levels of management and recent reports have continued to emphasis the need for precise costing of all options and the accounting of the multiple benefits of environmental, human, spiritual, ethical and economic values associated with forests.

There is an important and unpredictable, human component involved in the questions of impacts and subsequent responses concerning species and vegetation conservation. This is further compounded by the lack of change in the sociological and economic sciences to calculate the multiple benefits with any degree of certainty. For example, there has been no improvement on the regional scale, of the science, either in climate change or in the putative response since the publication of the IPCC Impacts Assessment (1990) although efforts in this field continue (Woodward and McKee 1991).

The human population must be seen as both a part of the solution (ability to respond) and part of the problem (population growth). Within this context, Forestry Canada, as part of Canada's 'Green Plan' (Anon 1991), has begun a community tree-planting program designed to encourage the planting of up to 325 million trees in urban and rural areas across Canada. By the year 2000, this will result in the absorption of some 5.2 million tonnes of CO_2, thus helping to offset future carbon emissions by including the involvement of the public at large in this issue. In addition to Canada's Green Plan, the US has the Global Releaf Program of the American Forestry Association.

Recent public opinion polls indicate that, at least in developed countries, people are willing to pay for carbon sequestration via reforestation, although this will not address the whole problem. The potential willingness of society to exceed the costs associated with the desired level of sequestration would 'make possible even larger reforestation benefits.' (Sanghi and Michael 1991).

3 Tropical deforestation

The rate of deforestation has increased by 90% during the 1980s, mainly by shifting cultivators, and is expected to continue to increase during the foreseeable future (Myer 1991). Most efforts to reduce deforestation have concentrated on commercial enterprises, such as loggers/ranchers, but they account for only 40% of all current deforestation.

Further work is needed to liberalise current economic theories to account for the human demands and behavioural shifts within society. For example, current studies indicate that the greatest impact on atmospheric carbon can be realised by halting deforestation compared to promoting reforestation. However, the former solution may not be realistic as 'the depletive pressure is likely to increase if only through growing human numbers and growing human demands.' (Houghton 1991). In addition, the IPCC Impacts Assessment (1990) summarised the substantial potential that exists to increase the growth performance of managed tropical stands with rates of carbon sequestration that are more than twice the rates of managed forests in temperate or boreal regions.

4 Research and monitoring gaps

The IPCC Impacts Assessment (1990) listed many items worthy of support in relation to forest ecosystems in general. These were echoed in more detail in the Bangkok Forestry Conference report (June 1991): 'There was a need for better information on the extent of forests, including further effort to ensure that appropriate definitions were used for each forest type and objective.'. Other problems cited included the use of various nomenclature and the failure to include tree crops associated with agriculture and agroforestry in discussions of forest responses. Numerous urgent data needs are becoming increasingly apparent, including (but not limited to):

- the need for regional climate change impact studies (Graham et al. 1990, Overpeck et al. 1990, Smith et al. 1990).
- an improved understanding of the genetics/physiology of tree species.
- the identification of critical points within the carbon cycle such as soil carbon contributions and the response of plants to elevated CO_2 and climate change (Reynolds et al. 1992).
- a better understanding of the linkages between climate impacts and socioeconomic structures and the thresholds where change takes place. The Bangkok Technical Workshop to Explore Forestry Options (April 1991) stated explicitly that 'better information on the cost effectiveness of the social and economic basis for different options for global forest management, and on quantifying the multiple roles of forests, was an urgent research priority'. All results since then would seem to confirm the urgency of this statement. For example, the Bangkok Forestry Conference (June 1991) recommended that the nations of the world should be 'living off the interest and not drawing down the principal of the earth's ecological capital (and this should be accomplished by) integrating economics and the environment into decision-making.'. This attitude, also stated at the São Paulo Conference (São Paulo 1990) and elsewhere (Woodward and McKee 1991; Schroeder and Ladd 1991) reflects a universal concern and the need for action.

Forest health monitoring programs, including forest climate observations above and within forests, need to be established to detect damage to forest trees and soils that may have been caused by anthropogenic causes by isolating damage not attributable to natural causes or management practices (Hall and Addison 1991, Miller 1991). Integrated monitoring systems based on observed or proxy climate data sources should also include changes in vegetation and soils attributable to other impacts on representative forest ecosystems. These health monitoring systems need to be flexible and adaptable to allow for their transfer to other countries within the global community. The ability to close this research and monitoring gap can be immediately and highly successful given the demonstrated state of science and technology for electronic climate and biological monitoring systems.

Forests are a most significant renewable resource of biomass, timber, and fibre. Due to their extent forests have a large effect on the global carbon cycle. They are at the same time sinks, sources and reservoirs of carbon. The role of forests to the global carbon cycle is universally recognised as a sink for carbon, especially in the temperate and boreal regions (Sedjo 1992, Kauppi et al. 1992), but forests also provide valuable benefits as resources in the short term and in the long term to biodiversity. However, there needs to be an increased effort to quantify the global carbon estimates and the socioeconomic benefits. This includes the development of analytical models that account for the exchanges of carbon within the ecosystem and the relative contribution of forests, under different assumptions such as species types, soil conditions and various land use patterns etc. Robust estimates of the costs of carbon sequestered through afforestation are needed. These science-based models would have wide applicability in other countries as a shared resource and should not be restricted by proprietary rights. The universality of this type of scientific transfer should be encouraged to facilitate changes in policy.

5 Recommendations/conclusions

- The data on resources reinforces the vulnerability of the forest in all countries. Climate change will impinge on the social and economic sustainability of these forests. Results since the 1990 IPCC Impact Assessment reinforce the political and economic urgency in this sector.
- More reforestation and afforestation programs are recommended. The major goal is to sequester carbon but other benefits must not be neglected. Policies must take a holistic view and consider the cumulative benefits of forests.
- Research needs must centre on regional impacts studies, process studies, and the establishment and definition of the socioeconomic linkages.
- Forest monitoring and development of analytical models are essential, and must be widely applicable, acceptable and consistent for all countries.
- Research leading up to the IPCC Impacts Assessment and subsequent work, has amply demonstrated the continuing need for intensive and accurate technical and financial cooperation to optimise the management of our global forest. This assumes that there are or will be programs in place that take advantage of local and regional opportunities, particularly, and wherever possible within institutional infrastructures.

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TABLE 1A. Summary of forest resources and forest management species (1987)

		Canada	*USA*	*Austria*	*FRG*
Productive Forest Land (million ha.)		244	210	3.0	7.3
Impact of Forestry GNP on Economy		506	415 000	95	244
($billion Cdn)	Import	1.59	15.44	1.1	506
	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, Populus, Abies, Larix, Pseudo Tsuga, Tsuga, Juglanis

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

Fed. Rep. of Germany: Picea abies, Pinus sylvestris, Abies alba, Pseudotsuga menziesii, Larix decidua, Fagus sylvatica, Quercus robur

TABLE 1B. Summary of forest resources and forest management species (1987)

		Indonesia	*China*	*India*	*Brazil*
Productive Forest Land (million ha.)		45	122	45	350
Impact of Forestry GNP on Economy		85	260	246	250
($billion Cdn)	Import	0.22	3.38	0.22	0
	Export	2.00	0.68	0.2	1.22

Managed species:

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

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

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

Brazil: Eucalyptus spp., Tectona grandis, Khaya spp., Swietenia macrophylla

TABLE 1C. Summary of Forest Resources and Forest Management Species (1987)

		Kenya	*Zambia*	*Finland*	*New Zealand*	*Chile*
Productive Forest Land (million ha.)		1.1	4.1	18.2	2.8	4.7
Impact of Forestry GNP on Economy		1.7	2.1	96.9	23.2	16.4
($billion Cdn)	Import	0.02	0.09	0.4	0.16	0.16
	Export	0.004	0	7.15	0.55	0.48

Managed species:

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

Zambia: Brachystegia spp., Jubernardia angolensis, Eucalyptus grandis, Pinus kesiya

Finland: Picea abies, Pinus sylvestris, Betula pendula

New Zealand: Pinus radiata, Podocarpus totara, Rimu cupressinum, Kamaki, Rata

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

TABLE 2A. Roundwood production, imports, exports and their value (1989*)

	Indonesia	*China*	*India*	*Brazil*
Roundwood production (thousand m^3)	175 730	274 590	269 451	255 455
Roundwood imports (thousand m^3)	0	13 383	902	26
Value (Cdn$000)**	0	1 435 171	104 260	6 574
Roundwood export(thousand m3)	1 131	21	76	46
Value (Cdn$000)	38 910	21 749	1 032	4 525

	Kenya	*Zambia*	*Finland*	*New Zealand*
Roundwood production (thousand m^3)	35 650	12 204	46 262	10 557
Roundwood imports (thousand m^3)	0	0	6 784	5
Value (Cdn$000)	0	0	307 774	3 383
Roundwood exports (thousand m^3)	0	0	1 047	2 470
Value (Cdn$000)	0	0	97 825	138 254

TABLE 2B. Roundwood production, imports, exports and their value (1989*)

	Chile	*Canada*	*USA*	*Austria*	*FRG*
Roundwood production (thousand m^3)	16 864	176 976	533 168	16 086	35 332
Roundwood imports (thousand m^3)	0	4 268	3 471	4 832	3 909
value (Cdn$000)	0	223 542	149 221	298 007	445 675
Roundwood exports (thousand m^3)	4 679	5 093	28 232	1 722	5 489
value (Cdn$000)	188 362	424 400	3 348 651	93 118	366 181

* FAO Yearbook Forest Products 1989—Published in 1991

** Exchange Rate 1 CDN$ = 1.183432 US$

V Natural terrestrial ecosystems

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V Natural terrestrial ecosystems

1 Background

As identified in the IPCC Impacts Assessment (1990), natural terrestrial ecosystems could face significant environmental impacts as a result of the global increases in the atmospheric concentration of greenhouse gases and the associated climatic changes, as well as from the increasing UV-B radiation due to the atmospheric ozone depletion and the combined effect of biospheric oxidants and acidic depositions. The rate of these changes will be the major factor determining the type and degree of impacts. The type of disturbances resulting from climate change will be unique for each ecosystem and the community within, as each responds to the added pressure of a changing environment. Adding to the complexity of assessing these changes is that they could occur as a series of 'jumps' rather than in a uniform manner across an area like a 'moving wave' (Holten and Carey 1991).

The social and economic consequences of these impacts will be significant, especially for those regions of the globe where societies and related economies are dependent on natural terrestrial ecosystems for their social and economic welfare. Projected changes within natural terrestrial ecosystems suggest that changes in the availability of food, fuel, medicine, fibre, construction materials and income are possible.

2 Progress since the IPCC Impacts Assessment

One of the major issues arising from the impacts of climate change on terrestrial ecosystems is water availability. This will be of increasing concern as populations increase and the need for water for drinking and economic activity (eg irrigation) increase concomitantly. Recent studies suggest that while water use efficiency should be increased in a higher CO_2 atmosphere, the same amount of water could be used per unit area because of increased leaf area ratios due to greater biomass produced through CO_2 fertilisation. Furthermore, any benefits accruing from the more efficient use by plants of soil water would be lost if wasteful irrigation technologies, such as flood irrigation, persist.

There is evidence (Holten and Carey 1991) suggesting that:

- in boreal, alpine and arctic regions, mesic and hygric plant communities will in general be more sensitive to climate change than the xeric communities;
- in temperate and southern to middle boreal regions in Europe, major floristic and faunistic changes may take place in some of the thermophilous deciduous forests as a result of projected improved conditions for Dutch elm disease;
- rare and mainly middle and high alpine species may be threatened with extinction (directly or indirectly) by climate change; and
- migration barriers, both natural and anthropogenic, could prevent or delay dispersal of more temperate plant and animal species into Scandinavia.

The process of reduction of tropical forest on the African continent, first noted in the tropical rain forest areas of Zaire and Uganda about 9000 BP (Livingston 1975) with the arrival of humans, will continue unabated and even be reinforced by global warming, resulting in an accelerated reduction of tropical forest and the expansion of the arid zones of Africa (Magadza 1990). Projected climatic change is likely to lead to an encroachment of the Sahel syndrome into the savannas. This region supports approximately 200 million people and any adverse effects of climate warming could result in the worsening of already precarious production systems in the area.

The degradation of the savanna ecosystems has a further implication for animals and migratory birds. Many animal and bird species utilise savanna wetlands and shallow lakes, such as Lake Abiata in Ethiopia, Lake Turkana in northern Kenya and other rift valley lakes, the Kafue flats of Zambia and, in West Africa, the flood plains of the Niger and Senegal rivers, Lake Chad and several other water bodies. Decreased rainfall or soil moisture as projected by several climate models for the African savanna ecosystems suggests that large-bodied animals, such as the elephant, hippopotamus and the large bovines, are liable to be affected more adversely than smaller species. Many migratory bird species utilise seasonal wetlands, locally known as dambos, vleis or bugas in eastern and southern Africa. Songbirds (eg common whitethroat, sedge warbler) breeding in Europe and wintering in the Sahel have declined in years following droughts in the Sahel, apparently owing to reduced habitat and survival in the wintering grounds. Projected climate change of the order anticipated by several climate models will probably result in the reduction of many such habitats (Magadza 1990) and, therefore, could negatively impact on these animals and migratory birds.

Seasonal wetlands are also critical to waterfowl and other migratory birds in the Great Plains region of North America (Diamond 1990; Diamond and Brace 1991).

In sub-humid savannas, climate change projections suggest increased aridity. It is therefore likely that rivers in these regions that show marked seasonality in flow would have reduced flows during periods of drought. Furthermore, many shallow water bodies, such as Lake Chad, could experience complete aridity during extended drought periods, or experience very high salinity levels. Such episodes would result in eventual extinction of the fish species in those water bodies. Since many river basins display some degree of endemicity, such species decimation could lead to reduction in species diversity, where only those types, such as the Claridae, which can readily migrate between river basins, would have the potential to survive.

Projected climate change may be one of the most important factors affecting fisheries now and in the next few hundred years. The level of the impact could vary widely and may depend on attributes of the species as well as on their regional specificity. Freshwater fish populations are contained within the bonds of their watershed and in most cases cannot migrate, but must endure (Shuter and Post 1990), adapt, suffer population declines or become extinct (Coutant 1990) when their environment deteriorates.

The added stresses to the freshwater ecosystems accompanying projected climate changes can be expected, in the short term, to reduce species number and genetic diversity within freshwater populations (Everett, in press). Species that survive a changing environment will likely be the ones with adequate existing genetic variation to allow survival and selection of at least some individuals. Whether the projected rate of climate change is within the capability of freshwater species to adapt genetically will depend on the existing genetic variability and on the rapidity of change (Mathews and Simmerman 1990).

With projected climate change, profound impacts, both beneficial and destructive, can be expected for the distribution and productivity of valuable fisheries and the industries associated with them (Healey 1990; Hill and Magnuson 1990; Johnson and Evans 1990). Among the first fish populations responding to climate change will probably be those in streams (a high rate of heat transfer from the air) on the warm or cold margins of their species' native ranges (Holmes 1990). With warming, a longer growing season is expected which should lead to greater fish productivity where temperature is currently a limiting factor, such as in high latitude lakes and reservoirs (Schlesinger and McCombie 1983). Species whose current distribution is confined to cool waters may be eliminated from parts of their range, leading to reduced fisheries, in spite of higher growth rates of the species that can tolerate warmer water.

Photosynthesis in plants grown at elevated concentrations of carbon dioxide is often reported to be reduced after a few days or weeks exposure. This reduction is often attributed to acclimation of carbon metabolism. Some studies of photosynthesis response to elevated CO_2, however, show either an increase or no reduction in photosynthesis capacity. For example, data collected over four growing seasons on two monospecific stands: one dominated by a C3 sedge and the other by a C4 grass (in a mesohaline salt marsh on the Chesapeake Bay) exposed to twice normal CO_2 concentrations showed increased carbon accumulation of 88% and 40% respectively.

Callaghan and Carlsson (in press) showed that high productivity is not necessarily commensurate with successful reproduction and greater fitness. This is particularly true in short growing seasons (eg due to temperature limitations in the tundra or aridity in the tropics) when climate conditions within the growing season allow high productivity, but the shortness of the growing season restricts successful reproductive development. Climate change projections suggest that in tundra areas, the growing season may lengthen as a result of warming; however, in other areas, increased aridity may shorten the growing seasons. This suggests the importance of considering population dynamics of plants as well as productivity. Such approaches also consider age-related processes and show that long-lived plants (eg trees), and those reproducing sporadically (eg many high-latitude and high-altitude plants), are threatened more by climate change than short-lived plants (eg annuals) because of the limitations on adaptive responses within each generation.

The report 'Arctic Interactions: Recommendations for an Arctic Component in the International Geosphere-Biosphere Programme' (1988) stresses the point that estimates suggest that 200–400 GT (109 metric tons) of non-oxidised carbon is stored in circumpolar peatlands (mostly in the boreal zones of Canada, the USSR and Fennoscandia). If a major part of this carbon were released because of changes in surface temperature and moisture—a physical possibility under projected climate changes over a few decades or centuries—then northern regions could emit a substantial additional amount of carbon to the atmosphere (potential positive feedback).

In their draft map of ecoclimatic sensitivity regions, Holten and Carey (1991) have suggested that within Norway, mountain and subalpine environments are the most sensitive to climate change, through climate-induced changes in snow cover (depth and duration) and hydrology. The arctic and flat river valley regions appear to be as sensitive as the alpine and subalpine environments.

3 Uncertainties and knowledge gaps

Uncertainties and gaps in the knowledge base exist in terms of our understanding of the environmental impacts for natural terrestrial ecosystems and associated socioeconomic consequences of climate changes. These uncertainties and gaps exist as a result of deficiencies in our theoretical knowledge of:

- Fundamental ecological process: effects of a changing set of interactive environmental parameters on plant net primary productivity and water use, ecosystem carbon and nutrient budgets, vegetation structure, species composition, forage quality, plant-animal and vegetation-soil interactions; population dynamics of major species and vegetation types as well as of pests and noxious species; and migration rates and mechanisms for species dispersal and settlement including the impacts of barriers and corridors.
- Linkages between climate and atmospheric chemistry changes (ie elevated levels of atmospheric pollutants such as SO_2, NO_X etc and atmospheric fertilisers) on the one hand and population and ecosystem dynamics (including implications for competitiveness, reproduction and productivity) on the other, can provide an assessment of the sensitivity (including buffering capacity, plasticity and resilience) of key species, communities or ecosystems.
- Linkages between ecosystem dynamics and human social and economic development and welfare under a changing climate can provide an assessment of the vulnerability of social and economic systems to changes in natural terrestrial ecosystems.

The significance of the environmental impacts and socioeconomic consequences as a result of climate change (IPCC Impacts Assessment 1990) and the need to develop viable and effective response strategies warrants the allocation of sufficient resources to tackle these deficiencies through climate impacts research, management, awareness raising, national and international cooperation etc.

Within many developing countries, most of the climate change impacts activities (and for the environment in general) are orchestrated by outside agencies with little input from local scientific/technical experts. The capability of developing countries of taking long-term views and to initiate programs on climate change impacts is hampered by lack of the necessary institutional framework. In addition, the monitoring networks within many developing countries are either too sparsely distributed or unserviceable to allow for a worthwhile assessment of the impacts of, and responses to, climate change at the regional level.

The most urgent need is for fundamental research on the sensitivity and likely response of key physical and biological constituents of critical ecosystems (including those locally defined) to climatic variability and change. This research should also include wildlife and freshwater fish populations for which currently there is very little information available.

There is also a need for more attention on the implications of climate change for heritage sites and reserves. It has been estimated that 25–60% of the present heritage sites and reserves could be unfit for the current species/communities they protect under projected changes in climate. This suggests that areas of adaptation will be required and that management strategies (ie in relation to dessication and pest/disease control), adjustment of policies on selection/siting of protected areas and the development of specific studies and protective measures, should be required for 'transferral' of threatened plants and animals to suitable habitats.

The correlative relationships between climate and plant and animal species need to be experimentally evaluated to establish causal relationships and the relative impacts of changes in climate compared to other controlling factors. This comparative analysis is essential as there are other factors that can and are contributing to ecosystem disappearance and degradation (eg urbanisation, atmospheric pollutants, land conversion, agricultural land management practices, water course alterations). This requires that fundamental ecological research be done in parallel with research on socioeconomic responses (eg development of impact models that bridge the gap between environmental impacts and social and economic consequences) as ecological response may well be determined as much by socioeconomic reactions to climate change as by climate change itself.

4 Addressing the uncertainties and knowledge gaps

To reduce these uncertainties and gaps in our knowledge, integrated national, regional and global programs and networks of research and systematic observations are required. These should include the improvement and further develpment of the global network of research and integrated systematic observation sites (eg Terrestrial Ecosystem Monitoring and Assessment (TEMA) of UNEP, Global Change and Terrestrial Ecosystem or using previous IBP research sites) with the aim of examining the linkages and relationships essential to defining environmental impacts and identifying where and what action is necessary. Also essential is the need to increase the skills of human resources and level of supportive funding available for participation in global programs and networks, especially for developing countries.

Integrated, representative, long-term systematic observation programs including biophysical, hydrological and meteorological parameters on a regional, national and global basis, as well as coincident economic and social (including health) data are a necessary building block towards reducing the uncertainties. These observation programs should combine relatively coarse data based on remote sensing with ground-based sampling over transects on carefully chosen terrain covering the latitudinal/altitudinal extent of selected ecotones and ecotypes.

Systematic observations of population dynamics and ecosystem responses should support and be supported by field experimentation and modelling. Specific attention should be paid to vulnerable and critical (including those locally defined) habitats, typical ecotonal areas (eg Holten and Carey 1991) and species along steep climate gradients including margins and isolated populations, and coastal and island ecosystems as well as concentrating in transects across ecotones (desert-steppe/forest, savanna-steppe/forest, alpine timberline, forest-steppe and forest-tundra). These data should be archived in such a manner that they could be readily accessible. Heritage sites and reserves are excellent benchmarks against which to monitor the impacts of climate change and, therefore, should be considered as a priority when establishing a network of benchmark sites. Monitoring of more sensitive ecosystems and species should be given priority since they would provide early indication of impact of climatic change.

Remote sensing (satellite and radar, and the use of GIS) can be extremely useful for some aspects of monitoring ecosystem status and dynamics (eg geographic boundaries of vegetation zones). Ground-based or field observation, however, is also essential as a means of ground-truthing the remotely sensed data and for monitoring the subtleties in ecosystem and species responses which cannot be measured remotely.

Considerable progress could be made in a relatively short time by assembling and analysing existing data on interactions among climate, ecosystem and species dynamics, and social and economic parameters with the objective of identifying likely sensitivities and responses. The initial focus should be on ecosystems and regions considered most likely to be affected in the short term.

5 Fundamental ecological processes

An essential step in climate impacts assessments is to establish a consistent baseline of resources at risk through assembling relevant inventories of species and ecosystems on a national, regional and global basis. This will require development and acceptance of consistent protocols for identifying and making inventories of the boundaries, extent and dynamics of plant and animal populations (including disease and pest infestations) supported by field and laboratory manuals. Existing protocols should be evaluated for their sensitivity to the identification of the impacts of climate change, including whether or not they provide observation across current ecosystem boundaries and include vulnerable species/communities.

A comprehensive observation program designed to improve understanding of fundamental ecological processes should include two elements:

- broad-scale, low intensity, randomly or regularly dispersed sampling units (transects, plots, or points)to detect regional scale changes in the distribution and abundance of biota and distribution and integrity of ecological zones; and
- site-specific integrated monitoring projects located in sensitive ecosystems. These intensively monitored sites would also contribute to the understanding of cause/effect relationships between climate change, biota and ecosystems that is necessary to interpret the changes detected through the element noted above.

Peat dynamics is a key element in the prediction of future climate change. Studies of thermal and hydric regimes of peatlands should have high priority for research and systematic observation. In order to quantify the emission and storage of carbon by northern peat-rich ecosystems, refinement is needed of their present extent and carbon content.

Long-term ecological research sites should be present in each major ecological zone. Where possible, use should be made of existing sites where long-term information is already available. Strengthening the international agreements on ecosystem monitoring such as the US, USSR, Canada ecological transect in the northern latitudes should be promoted as a key component of the required research and monitoring program. Other monitoring programs, including the Man and the Biosphere (MAB) Reserves and UNEP/TEMA's Global network, should be instituted through appropriate agreements to develp a global standardised dataset. These long-term ecological research and monitoring sites would provide opportunities for intensive process-oriented research in addition to monitoring of effects.

Research efforts should include model development and assessment (both correlative and dynamic) and supportive controlled environment experiments and field experiments. Field manipulation techniques, at different levels within the ecosystem (ie at species, population or plant community level) are an essential component in addressing the uncertainties in understanding ecosystem processes and functions.

More field programs should focus on natural terrestrial ecosystem process research (eg what are the key climatic, hydrologic, geomorphological, biological and chemical processes that occur within these ecosystems and their interactions in determining ecosystem responses). Research topics to be addressed at the intra-specific level include physiology, phenology, regeneration and reproduction, dispersal and migration. At the inter-specific level, research should focus on changes in plant-animal interaction (eg pollination), predation and competition, decomposition, and pest and disease dynamics.

With regard to entire life communities and vegetation complexes, research questions to be considered include changes in surface covering, vegetation structure, species composition, biomass, diversity and succession patterns.

Experimental work on specific interactions or specific variables are also required to understand cause and effect because of the complex interactions between environmental variables in nature. The International Tundra Experiment (ITEX) being developed for arctic studies, which includes basic systematic observations and environmental manipulations is one example of the type of program required.

6 Identifying the linkages with climate change and greenhouse gas concentrations

A focus for systematic observations of natural terrestrial ecosystems should be the identification of a set of wildlife and vegetation indicator species which could be used for detecting climate-induced ecosystem changes and to assist in quantifying vegetation, wildlife and freshwater fish sensitivity to climate and possible responses to climate change. Rather than trying to predict what will happen when climate changes, focus should be placed on assessing the sensitivity of species for climate change (thresholds/limits) in order to select indicator species which may be used to detect effects of climate change 'in the field'. In selecting indicator species consideration should be given to species which are expected to expand their range of distribution (horizontally and/or vertically), species which are expected to retreat or become extinct, and species which have a wide distribution with many ecotypes which may increase or decrease in abundance within the present range of distribution (Ketner and de Groot, in press).

Once identified, the distribution of indicator species should be systematically mapped using a grid system that lends itself to various modelling approaches, including computer-based models.

Related research should focus on identifying the cause/effect relationships between climate, ecosystems processes (eg biophysical, biochemical, geochemical processes), functions (eg habitat, water quantity and quality), distribution and productivity and associated wildlife and freshwater resources. Such research programs should be interdisciplinary by nature and not only assess the impacts of direct changes in climate, but also the effects of associated changes in soils, water regimes, and landscape structure and functions.

7 Identifying social and economic consequences

To identify and assess the social and economic consequences of climate change there is a need for directed monitoring and research programs at the national, regional and global levels. These programs should be multi-disciplinary, involving not only physical and biological scientists, but also representatives from the social sciences, including economics. National and international research funding should be capable of recognising and supporting this type of research.

These research programs should explicitly address impacts and consequences in the context of changes in non-climatic factors (eg population changes, economic growth, land use changes, lifestyle changes). Also included is the need to develop more realistic projections of supply, demand and use of natural resources 50 to 100 years from now, and to develop methods for characterising non-economic values of natural terrestrial ecosystems, such as scenic vistas, recreation, wildlife habitat and biodiversity.

Of particular interest when undertaking this type of research is information on the combined effect of both direct and indirect impacts on species and ecosystems. Examining the impact of a particular variable on a static environment and society, although interesting, is limited in its applicability. It would be more realistic to examine the impacts and consequences with fixed societal and environmental changes or, better still, with a responsive society and environment. These types of studies would lead to the identification of thresholds within both the natural terrestrial ecosystems and associated social economic structures.

Essential to these programs is the need to combine biological monitoring that can identify the ecological consequences of climate change with coincident data and information on associated social and economic systems. As a first step, existing databases comprising coincident physical and biological data, as well as social and economic information, should be identified. Assembling these databases will provide a means of undertaking the required impacts research and assist in refining the definition of the required research and monitoring programs.

To facilitate implementation of research and monitoring programs directed at identifying and assessing social and economic consequences of climate change, national and regional teams of experts representing the physical, biological and social scientific and economics communities should be assembled to undertake impact studies in an integrated fashion. This can be accomplished through strengthening existing programs at the global and regional levels. At the global level, the World Climate Programme and in particular, its World Climate Impacts and Response Strategies Programme should be encouraged to play a more active role in stimulating and facilitating regional assessments. The establishment of regional programs such as the Landscape-Ecological Impact of Climate Change (LICC) program for Europe should be encouraged.

8 Conclusions

Promotion of the high and irreplaceable values of natural terrestrial ecosystems is essential in gaining public support for sustaining them in a changing climate. Action is also necessary to increase public awareness and to encourage support in their defence, as well as for enhancing the transcending importance of climate change impact studies and the assessment of their consequences and of the response options.

Managers, decision makers and local people need to be aware that policies and practices should be flexible to accommodate the implications of climate change and the dynamics of this change.

In the near term, the identification of sensitive species, communities and ecosystems should be one of the most important tasks undertaken. This sensitivity should be defined not only from an environmental perspective, but should also consider social and economic implications. As far as possible, the scale at which sensitivities are defined should be consistent with that at which decision can be made.

On the basis of these identified sensitivities, appropriate response strategies should be developed and implemented for those species, communities and ecosystems which face the most deleterious impacts (eg semi-arid and arid regions and tundra regions). Humans must be prepared to intervene where vital ecosystems or species are in jeopardy. In developing and implementing response strategies, consideration should be given to a wide range of response options, the specific local environmental; social and economic circumstances and the degree of uncertainties and risks.

Consideration should also be given to reducing major human-caused stresses such as pollution and those resulting from the impacts of other human activities such as logging and the grazing of domestic animals at subsistence level. These stresses may originate outside the boundaries of the affected ecosystem but often, once they are reduced, the elasticity of that ecosystem increases, possibly decreasing the impacts of climate change.

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VI Hydrology and water resources

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VI Hydrology and water resources

1 Introduction

Since the IPCC Climate Change Impacts Assessment report (1990b), a substantial number of studies have been undertaken that deal with the hydrologic effects and water resources management impacts of global warming. Although the body of information is growing rapidly, especially the proliferation of case studies of hydrologic impacts, few new insights have been offered by these studies, especially for water resources management impacts. This is due largely to the reality that the analyses are based on General Circulation Model (GCM) outputs which simply do not provide the information required for such analyses, nor are the results compatible with one another for the five GCMs most frequently cited (US National Academy of Sciences 1992). Overall, the recent studies have confirmed the findings and conclusions of the 1990 Impacts Assessment, albeit with nuances and refinements that were not explicitly considered then.

Among the difficulties in trying to interpret and compare the findings was that a great majority of studies were conducted without regard to conventional impact assessment and evaluation principles, while also ignoring IPCC global warming scenarios. This diminished their direct value in trying to understand the hydrologic response sensitivity, not to mention the comparative value in examining cross-regional impacts of global change on the vulnerability of comparably managed water resources. The impacts of climate change on watershed response and the vulnerability of managed systems presents a greater degree of evaluation difficulty; the few studies that have attempted to deal with these issues should be viewed in the context of an evolving yet tenuous methodology.

Even though evidence for global warming and its long-range impacts is becoming more compelling with each new report, like it or not, there is still considerable disagreement about the foreseeable regional hydrologic effects of global warming, not to mention the more complex socio-economic and environmental impacts associated with water resources management. *The reality is that generic global warming scenarios do not lend themselves to simple cause-and-effect extrapolations. There are countless simultaneous positive and negative feedback mechanisms to consider just to account for hydrologic processes alone. Water resources management impacts add an additional level of complexity.*

> The hydrological cycle has emerged as the central element in studies of climate change

yet

> at present a full 'systems view' of climate and the hydrological cycle has yet to emerge . . . . Climate models have yet to be developed which account for the full hydrological cycle and its interactions with the atmosphere, oceans and land.
>
> (Chahine 1992).

Water resources management, by its nature, is intended and has served to ameliorate the extremes in climate variability. It stands to reason, then, that managed watersheds, ie those under some form of water control and distribution, are apt to experience less dramatic water resources impacts than those without such water management systems even though the natural hydrologic response may be similar. However, specific regional changes in precipitation and runoff are as yet impossible to predict with any degree of confidence (US National Academy of Sciences 1992; Chahine 1992). For hydrologic studies, precipitation is the variable of greatest interest, but GCM simulations of precipitation for *present* climate conditions are notoriously poor (Wood et al. 1992). Much attention has been focused on decreases in mean annual runoff, but some areas may well experience increased runoff, at least during the traditional seasonal peak flood period. Most model results do seem to forecast increased spring runoff for all the major rivers, although a comparative analysis by Kuhl and Miller (1992) and Miller and Russell (1992) suggest the reason may be that at least when considering the GISS GCM, that model uniformly overestimates mean annual streamflow and peak spring runoff when compared to historical records.

Thus far, the numerous impact studies are largely suggestive in nature, serving to prompt planners and policy analysts to search for worthwhile ways by which to account explicitly for and deal with potential changes in average runoff and a greater variability in climate in the foreseeable future. Water resources impacts are considered to be among the most significant consequences of climate change, along with ecological impacts, affecting especially the all-important agricultural sector. Hence, a degree of educated guessing is warranted as a way of better preparing for the uncertainties that lie ahead, at least in terms of preparing robust national strategies for coping with uncertainty. Potential effects in the agricultural, forestry and urban sectors, although of justifiable concern to warrant separate inquiries, are actually derivative problems stemming from the fundamental effects of climate change on water availability (quantity, quality, distribution and timing); and we must not forget that while the long-term implications of global warming have focused on water deficits and droughts, there is reason to believe that climate variability could also increase considerably, so that societies must contend with large uncertainties at both ends of the hydrologic spectrum — floods as well as droughts.

Since the first assessment of the IPCC (1990a,b,c), scientists participating in the Impacts Assessment Working Group II realised that producing an estimate for water resources availability and other conditions extant within a climate that may exist 50 or 100 years hence, could be misleading at best, and completely unrealistic at worst. The reason is that the first step of analysing the cumulative consequences of global warming requires that the physical changes of hydrologic effects associated with climate change be differentiated from 'normal' climate variability as derived from historic records. Second, future water resources management impacts (water use, availability, distribution, operation and maintenance etc) should be viewed only as an increment (or decrement) to the water supply and use trends that are likely to occur under the 'baseline' or 'without' climate change scenario. The indicators of water use that reflect the baseline condition, projected over a period of 50 to 100 years will, in all likelihood, be dominated by population growth, economic growth, and patterns of land use and settlement. These socioeconomic changes would severely stress existing water management systems even under a benign climate scenario.

Clearly, climate change could exacerbate an increasingly complex resource management problem. Yet, the expectation is that, despite all the large uncertainties that infuse this issue, water resources management opportunities for adapting to climate change are perhaps better understood and offer more realistic promise to mitigate whatever adverse consequences that may materialise than our collective ability to predict, understand and manage future socioeconomic changes. This theme had been emphasised first in the IPCC (1990c) Response Strategies report and in subsequent reports by the US National Research Council (NRC 1991), the US National Academy of Sciences (NAS 1992), American Association for the Advancement of Science (Waggoner (ed.) 1990), and a conference of practising US federal water resources agencies and water utility managers (Ballentine and Stakhiv (eds) 1992).

The task of predicting regional hydrologic and water management consequences of climate change is a formidable one. At present, we can offer only a semblance of consensus on insights about how certain managed and uncontrolled watersheds could respond under a variety of climate change scenarios. Using the GCMs currently available, it is not possible even to replicate accurately current average climate conditions, much less forecast regional climatic conditions over annual and decadal time scales (Lins et al. 1990; Kuhl and Miller 1992; Chahine 1992).

The inability to forecast precipitation, runoff and evapotranspiration accurately should not be used as an argument to negate the application of GCMs to river basin level assessments, nor to diminish the value of undertaking hydrologic sensitivity analyses of the various postulated climate change scenarios. Rather, the caveats are intended to be cautionary in tenor - as a way of recognising that much too little is 'known' with certainty and spurious conclusions are drawn too often from information that is, at best, suggestive in nature. Towards this end, *the focus of future IPCC efforts should be to develop a more uniform methodology for impact assessments as part of a continuing effort of targeting regional river basin and country studies in order to obtain a reasonably comparable basis for evaluation.*

Hence, this update and assessment of recently available information is presented in the spirit of simply compiling the latest information, without a rigorous comparative analysis and evaluation, *for it is simply too difficult to judge the relative merit of various inquiries inasmuch as a formal and consistent evaluative framework is yet to be formulated. There are no accepted standards for analysis.* However, a number of principles and preliminary guidelines for assessing impacts of climate change were developed by an expert group assembled by the IPCC (1992d), but they have yet to be applied.

2 Overview of new information

This supplement to the first IPCC Impacts Assessment report summarises recent materials (1990–1992) that were solicited and received from many countries (Australia, Belgium, Venezuela, Canada, Indonesia, Israel, New Zealand, Norway, Peru, Switzerland, Poland, Romania, Senegal, USSR, USA, Uruguay, Finland, France, Chile, Japan), international organisations (WMO, UNESCO, IIASA, Commission on Mekong). Proceedings of international and national symposia and meetings on this problem held during the period 1991–92 in Japan,Denmark, Australia, Iceland, Uruguay, USA and Indonesia are also included, as are selected papers from conferences held on the subject and supplemented by published literature.

The studies and analyses that were made available subsequent to the IPCC Impacts Assessment which assessed the hydrologic and water resources management consequences of climate change reflected the range of approaches that have been pursued in the past by scientists, hydrologists and water resources engineers. These include: water balance methods; use of GCMs to obtain estimates of changes in climatic and hydrologic characteristics; use of deterministic hydrologic models; statistical analysis of long-term records; use of palaeo-analogues; and a combination of the aforementioned approaches. It is recognised that since the publication of the first IPCC Impacts Asessment, many studies have been initiated that rely on a comparison of GCMs but, with few exceptions, the final results were not yet available for this report. Similarly, many recent publications delve into better understanding of historical climate changes as an implicit analog or baseline for extrapolating future changes (eg studies of the El Niño phenomenon or the Sahelian drought). These studies were not included as they did not explicitly deal with evidence of hydrologic changes induced by *anthropogenic* global warming. Most studies focused on understanding the sensitivity of hydrologic response to climatic perturbations. Far fewer studies attempted to take on the more complicated problem of directly analysing the relationship between hydrologic watershed sensitivity and the vulnerability of managed water systems.

Methodological approaches varied widely, so it would be inappropriate to infer that the studies portray distinguishable patterns of regional or geographic response, despite the fact that the recent suite of water-resources-related climate studies cover a much larger and diverse geographic area. *It is impossible to draw any specific insights or conclusions about regional, river basin or watershed-level impacts because of wide differences among the GCMs and different analytical approaches that were used in these studies.* In other words, the impacts will depend on the characteristics of the river basin, the GCM selected, and on the particular analytical method pursued. Given the large uncertainties associated with GCM outputs, it is premature to use them for predictive purposes. At best, they may have a heuristic value for setting the stage for the next phase of detailed hydrologic impact studies.

Nevertheless, there are several recent noteworthy studies that shed some new light on the difficulties of conducting hydrologic sensitivity studies and potential water management responses, and which serve as cautionary reminders of a few principles and insights that may serve future endeavours. For example, Kuhl and Miller (1992) compared the GISS GCM hindcasts with observed runoff of the 20 largest rivers in the world and found systematic overestimation of the mean annual runoff. Furthermore, for several of the rivers (Mississippi, Amur, Colorado, Indus, Murray) the model's spring maximum runoff was significantly larger than observed, and the minimum summer and autumn runoff was too low.

Nash and Gleick (1991) studied the hydrologic response of the Colorado River (US) and compared their results, using a well-calibrated water balance accounting model, with several previous statistical studies for the same river. The authors concluded that the previous studies *overestimated* the decreases in runoff for the various scenarios involving increasing temperatures and that:

> conceptual models of arid and semiarid basins suggest that streamflow is less sensitive to climate change than previous statistical models have indicated. . .

Furthermore, they conceded that changes in runoff to be expected under the selected range of temperature changes (up to $\pm 4°C$) would:

> not be statistically different from the historical record unless precipitation changed by more than 10%. This confirmed a pathbreaking study by Klemes (1985) that had long been neglected by many analysts.

A critical aspect of water resources management is an understanding of the statistical properties of climate and weather-driven events, such as floods and droughts. For it is the extremes of precipitation and runoff that influence design criteria and management strategies. Little research has been done linking climate change with frequency of flood or drought, although several earlier attempts were made to place the implications of climate change and variability within the context of water resources system yield reliability using methods based on stochastic hydrologic analysis (Lettenmaier and Burges 1978; Matalas and Fiering 1977; Nemec and Schaake 1982; Klemes 1985; Fiering and Rogers 1989). A recent study by Wood et al. (1992) laid out a procedure for assessing the impact of climate change on the flood frequency distribution for a river basin and tested the methods for CO_2 doubling scenarios produced by the GFDL GCM. First, the authors note that the GFDL GCM failed to reproduce the historical climate characteristics for all seasons, uniformly underestimating precipitation for the two watersheds in the State of Washington in north-western US In fact, the differences between historical precipitation and the present GCM climate simulations *were larger than the differences predicted between the GCM 1xCO_2 scenario (present) and the 2xCO_2 scenario.* Hence, the authors caution that while the effect of GCM model biases on their approach may be diminished by making relative comparisons, one could not be entirely certain because the models are highly nonlinear. Notwithstanding the caveats, the authors concluded on the basis of their test that stochastic transfer models offer a quantitative means of linking large-scale circulation conditions, as inferred from GCMs to local surface meteorological conditions, and can provide information for evaluating climate change impacts on flood frequencies.

A study conducted for a large semi-arid agricultural area in the US, the Missouri-Iowa-Nebraska-Kansas (MINK) area, was important for several innovative approaches and implications for water management (DOE 1991). The study approach was to postulate a recurrence of the most severe drought of record (1931–40) under conditions of a doubled CO_2 climate in the year 2030, both with and without adjustments (such as water conservation, pricing, technological innovation etc). Detailed sectoral water uses, demands and projections were developed. For the MINK area, irrigation withdrawals were projected to increase by 14% and consumptive uses by 23% without employing rational adjustments. Crop yields would decline from 10 to 25% in the absence of adjustments, and plant requirements for irrigation water would *increase* by about 20%. However, as a compensating factor, it is expected that the direct effects of increasing CO_2 concentration from 350 to 450 ppm would *reduce* irrigation requirements by 10% (Easterling et al. 1991). Wollock and Hornberger (1991) examined changes in assumptions about the effects of plant stomatal resistance changes due to the CO_2 enrichment effect on the sensitivity of catchment runoff. They found that lack of good information led to large variability in the projections of runoff response. Most importantly, perhaps, is that despite all the uncertainties, the adverse regional economic impacts of such a drastic drought condition was found to be small, in the order of several percentage points reduction in total regional production (DOE 1991, p27).

A somewhat different approach to analysing the hydrologic effects of climate change was undertaken by McCabe et al. (1990). The authors examined the response of the Thornthwaite moisture index to climate change scenarios generated by three GCMs (GISS, GFDL, OSU). Their reasoning was that the Thornthwaite moisture index is a useful and early measurable indicator of water supply (precipitation) relative to its demand (potential evapotranspiration). Results showed that all three GCMs (steady state CO_2 doubling) predicted drier conditions for most of the US, although the amount of decrease depends on the GCM climate scenario selected. *Results also suggested that changes in the moisture index are related mainly to changes in the mean annual potential evapotranspiration as a result in changes in the mean annual temperature, rather than to changes in the mean annual precipitation.*

The greatest decrease in the index is expected to occur in the northern US, especially in the Great Lakes region, but only small decreases in the moisture index will occur in the already dry areas of the south-west US. It is important to note at this point that the parameterisation of continental evaporation in many atmospheric general circulation models is demonstrably inconsistent with observed conditions. In the turbulent transfer relation for potential evaporation, GCMs use the modelled actual temperature to evaluate the saturated surface humidity, whereas the consistent temperature is the one reflecting cooling by the hypothetical potential evaporation. Milly (1992) demonstrated that in GCM experiments where soil moisture is limited the models produce rates of potential evaporation that exceed, by a factor of two or more, the rates that would be yielded by use of the more realistic consistent temperature. This explains why most GCMs have produced excessively low values of summer soil moisture and raises further questions concerning the results of studies of soil-moisture changes induced by an increase in greenhouse gases.

Finally, in one of the few available studies of the vulnerability of managed *urban* water resources systems, Kirshen and Fennessey (1992) analysed the potential impacts of climate change on the water supply of the Boston metropolitan area, which represents a large, well-managed urban water supply system. The study included a hydrologic analysis of various climate change scenarios, comparing the outputs of several GCM models (GISS, GFDL, UKMO and OSU) and an associated analysis of water management impacts, including financial and economic consequences and potential responses. The authors showed that the GISS and GFDL models generally predicted decreased watershed yield whereas the OSU and UKMO GCM scenarios indicated increases in runoff and increases in system safe yield. *As a result of these contradictory outcomes, the Massachusetts Water Resources Authority (MWRA) is taking a 'wait and see' response similar to that of other urban US water utility managers (Schwarz and Dillard 1990) because they believe that the impacts of climate change are too uncertain and the costs of action are too high to warrant such actions.* However, the MWRA has engaged in an aggressive program of cost-effective demand management and water conservation actions that, in effect, represent the foundation of a sensible anticipatory adaptive strategy. Similar institutional responses are expected in most urban metropolitan regions, whether the cause is growth in water demand or in water shortages caused by droughts or global climate change (Rhodes, Miller and MacDonnell 1992; Frederick 1992; Rogers 1992; and Stakhiv 1992).

3 Case study summaries

Studies have been carried out for the river basins and regions located in various natural climatic zones (temperate, high and middle latitudes, arid and semi-arid and humid tropical) as well as by using palaeoclimatic scenarios for the continents of the Earth as a whole. Temperate zones are most comprehensively presented in the studies on European countries for the river basins where most of the annual runoff is formed as a result of snowmelt in spring.

In Finland, a CO_2 doubling scenario generated by the GISS GCM model was used to estimate changes in runoff for 12 watersheds of 600 km^2 to 33 500 km^2. Temperature increases of 2 to 6°C and monthly precipitation increases of 10 to 30 mm were produced by the GISS model. The results showed 20 to 50% increases in mean annual runoff for individual watersheds, and a more stable interannual monthly runoff pattern for most watersheds (Vehvilainen and Lohvansuu 1991). Maximum spring discharges were found to decrease considerably (up to 55%) and minimum monthly flows to rise dramatically (up to 100 to 300%).

Hydrologic sensitivity studies in Norway relied on a comparison of two assumed (non-GCM) scenarios for CO_2 doubling by the year 2030. According to the first scenario, winter temperature would rise by 3.0 to 3.2°C, summer by 1.5 to 2.0°C and annual precipitation by 5 to 15%. According to the second scenario, by 3.5 to 5.0°C and 15 to 20%, respectively. The changes in runoff for seven regions in Norway were calculated by using an existing simplified conceptual hydrological model for a 30-year historic period and the two climate scenarios (Saelthun et al. 1990). The results show that annual runoff increased somewhat (up to 10 to 15%) in the mountainous regions and in the regions with large annual precipitation. In low forested areas, it decreased slightly. *Seasonal* runoff changes significantly: spring floods decrease; winter runoff increases substantially, while summer runoff decreases. The frequency of floods increases in autumn and winter (Saelthun et al. 1990).

Kaczmarek and Krasuski (1991) obtained very similar results for one of Poland's largest rivers, Varty (area is 54 530 km^2), using CO_2 doubling scenarios generated by the GFDL model coupled with a monthly water balance hydrological model. With global warming the *annual* runoff of this river changes, but slightly. However, winter runoff rises (21%) and summer runoff decreases (24%). Similar results have been obtained for small and medium-sized watersheds in Belgium and Switzerland. Studies were conducted by Bultot et al. (1991) and Gellens (1991a;1991b) who applied GCM scenarios with the conceptual hydrological model of the Royal Meteorological Institute of Belgium with a diurnal time interval. For example, comprehensive studies of an experimental basin in Switzerland reveal relatively insignificant changes in annual runoff with increasing winter runoff by 10% and decreasing the summer one by 11% (Bultot et al. 1991)

For the nations of the former USSR, a set of improved scenarios of future climate with a 1°C and 2°C global warming based on palaeoclimatic analogues was developed in 1991 by a group of climatologists guided by Professor M I Budyko. These scenarios were used to obtain approximate estimates of potential changes in annual and seasonal runoff of main river watersheds. Methodologically, these computations are based on water balance methods (for average annual runoff) and hydrological models of river watersheds with 10-day time intervals. They show that there are no statistically discernable changes in annual river runoff in the basins of Volga, Dnieper, Don, Ural, Zapadnaya, Dvina and Neman with a 1°C warming. There is an expectation of increased annual runoff (by 5 to 10%) on the rivers of the Caucusus and West and East Siberia. Somewhat larger increases are expected in the mountain rivers in Central Asia. However, the estimates obtained for mountainous regions are very crude because of great uncertainty of palaeoclimatic scenarios.

With a 2°C global warming, annual runoff in the major river basins of the former USSR increases more significantly. In particular, in the Volga basin annual runoff increases by 5 to 7%; in the Dnieper, Don, Dniester basins as well as in the Baltic River basins by 20 to 25%; in Siberia and the Far East by 10 to 20%. This trend also occurs in the mountain rivers in the Caucasus and Central Asia.

As to changes in monthly and seasonal runoff, the most detailed reconstructions have been made for the three largest rivers of the European part of Russia: the Volga, Dnieper and Don. Proxy records indicate considerable potential change in seasonal runoff. Winter runoff increases dramatically and spring runoff decreases significantly (Shiklomanov and Lins 1991), ostensibly in response to a shift in the snowmelt season from spring to late winter as temperature rises.

For most of Canada, global warming would increase annual river runoff and its intra-annual distribution except for the Great Lakes basin, where according to all the GCM scenarios, an increase in air temperature and decrease in river runoff are most probable. This could result not only in a changed water balance and lake level, but also in serious economic and ecological consequences (Hartmann 1990; Croley 1991; Quinn 1992).

The impacts of climate change on groundwater has received little attention, although a recent evaluation of Australia's major aquifers represents an awakening to the importance that groundwater recharge and management has in the overall scheme for water resources management. Ghassemi et al. (1991) have noted that precipitation trends have changed markedly in this century over Australia and they expect trends and patterns to continue with global warming. Overall, they conclude that for a large area of Australia, especially the populated south-eastern quadrant, where groundwater is already overdrafted, groundwater recharge will increase. The shallow aquifers in the arid and semi-arid zones of Australia (eg the Amadeus basin) will also benefit from increased precipitation and recharge. However, global warming will likely be detrimental for a number of major regional aquifers in south-western Australia, in the Perth basin and Murray basin, because of decreased rainfall.

Considering the qualitative results of the various studies of global warming effects on annual and seasonal river runoff in the northern and temperate zone of the Northern Hemisphere, *it would appear that* in the regions where a considerable part of annual runoff is formed during the spring flood, the intra-year runoff distribution appears to be more sensitive to air temperature changes than to annual precipitation. In this connection, projections of variations of seasonal runoff in these regions could be more reliable than of the absolute magnitude of annual runoff because the GCM temperature forecasts are thought to be more reliable than precipitation. Yet, research by Karl and Riebsame (1989) contradict that impression by showing that hydrologic (runoff) variability is almost entirely controlled by precipitation variability.

Estimates of global warming effects on hydrology in arid and semi-arid regions have been made for the southern area of the European part of the former USSR, Australia, some regions of the US, South America and Africa including Sahel (Nash and Gleick 1991; Urbiztondo et al. 1991; Australian Bureau of Meteorology 1991; Sirculon 1990; Vannitsem and Demaree 1991). The most recent case studies provide mixed and often contradictory implications, most likely stemming from the diverse methods applied and the divergence among GCM scenarios. However, there are indications that the earlier conclusions about the sensitivity of watersheds in arid and semi-arid regions to even small changes in climatic characteristics may be overstated (Nash and Gleick 1991). Nevertheless, it is apparent that annual runoff appears to be more sensitive to changes in precipitation than in air temperature for arid areas.

Analysing the hydrological implications of global warming in arid regions, the problem of the Sahelian zone should be emphasised, as a severe drought of the past decades caused disastrous consequences in many countries. The comprehensive analysis of climate change impacts on water resources of Sahel is presented in a study by Sirculon (1990) who emphasises a strong sensitivity of river systems to changes in climatic characteristics and consequent vulnerability of the water management system. As for the future of water resources in Sahel, there is a large amount of uncertainty because of contradictory data on future climate obtained by GCM computations and from palaeoclimatic analogs. Palaeoclimatic analog information suggests that global warming should lead to a large increase in precipitation in this region with relatively small increases in temperature, resulting in a considerable increase in runoff. However, according to the outputs of three types of GCMs (IPCC 1990a) which show that the air temperature in the Sahelian region rises by 1 to 2°C, with a doubling of CO_2, the models show winter precipitation decreases of 5 to 10%, whereas summer precipitation increases up to 5%. With this scenario, it is unlikely that runoff will increase because evapotranspiration will result in a net reduction in runoff.

In wet tropical regions, the assessment of global warming effects on water resources has been done for two river basins of Venezuela (Andressen and Rincon 1991); for the basin of the Uruguay River in Uruguay (Tucci and Damiani 1991; the Lower Mekong River basin (Mekong Secretariat 1990); the Ellagawa catchment area in the central part of Sri Lanka (Nophadol and Hemantha 1992) and Indonesia (Rozari et al. 1990). In these studies, the scenarios used are those inherent in the selected GCM, with CO_2 doubling and hydrological implications estimated by using a variety of conceptual, deterministic simulation models of river basins.

In the Sri Lanka study, Nophadol and Hemantha (1992) chose to compare three GCMs (GISS, UKMO and GFDL) with respect to their ability to replicate historic temperature and precipitation conditions. They concluded that for Sri Lanka the GFDL was least compatible and chose to continue analysis with the GISS and UKMO models. The authors concluded that under a doubling of CO_2, the mean monthly and daily precipitation would increase during the peak rainy season, although no significant change in mean annual precipitation would occur. The peak precipitation period would shift from April–July to September–November. However, low flows would increase, as would severity of droughts.

The study by Rozari et al. (1990) relied solely on the GISS GCM transitional CO_2 doubling scenario. The authors selected this model because it generated rainfall results that best reflected the situation in Indonesia, according to their judgment. The study analysed the overall impacts on hydrologic sensitivity for Indonesia and then focused on three catchment areas in Java. Based on a general water balance analysis for the three watersheds, the analysis showed that, in general, the periods of water deficits are shortened by at least a month, with significant increases on monthly runoff for all months in all three watersheds. An associated study (Rozari 1991) analyses in greater detail the agricultural impacts of increased precipitation and runoff, citing increased erosion rates, reduction of soil productivity with consequent reduction in crop yields of up to 9%. Although the three watersheds are regulated by large reservoirs for flood control, hydro-electric power irrigation, municipal and industrial water supply and inland water fisheries, no analyses on water management impacts were conducted.

Andressen and Rincon, in a personal communication (1991), provide preliminary results of a study of climate change on the hydrology of three drainage basins in western Venezuela, ranging from 1000 to 25 000 km². A relatively simple (6-parameter) monthly hydrologic simulation model was used in conjunction with a Thornthwaite water-balance model. Three different (non-GCM generated) climatic scenarios were developed:

(1) a low sensitivity scenario with no precipitation change and a +2°C increase;
(2) a medium sensitivity scenario with a 20% precipitation increase and a +3°C increase; and
(3) a high sensitivity scenario with a 40% precipitation increase and +4°C increase.

Based on these hypothesised scenarios, the authors conclude that the streamflow peaks will not shift; that average annual streamflow will increase for the low and medium scenarios, but decrease slightly for the high sensitivity scenario.

In perhaps the best existing suite of comparative water management studies available, the US Environmental Protection Agency (1990) initiated a comparison of five complex river basin management schemes of the La Plata/Uruguay, Mekong, Indus, Zambezi and Nile Rivers. Only preliminary analyses of the Mekong, Uruguay and Zambezi Rivers were available for this assessment. A similar effort, undertaken by the United National Environment Programme (Parry, Magalhaes and Ninh (eds) 1991) compared impacts for Brazil, Indonesia, Malaysia and Thailand, although the analysis for Brazil examined only the impacts of current climate variability and drought on agriculture. Overall, the analysis for Southeast Asia was conducted by comparing three GCMs (GISS, GFDL, and OSU). CO_2-doubling analyses for Indonesia were focused on agricultural impacts, showing higher levels of precipitation, which increased the area of potential agriculture, but also increased soil erosion and loss of productivity. In Malaysia, there did not appear to be a significant change in the seasonal pattern in rainfall. Rice yields were expected to decrease because of an increase in temperature and decrease in solar radiation due to increased cloudiness. Results of CO_2-doubling for Thailand (GISS model) shows a warming of 3 to 6°C, and a significant reduction in precipitation. Northern Thailand would be drier in most months, which would be a benefit to agriculture in that area. Overall, the methods used were not comparable, and the results presented in these studies were inconsistent and highly variable among the three countries, as they were conducted by different groups.

The Mekong River is among the largest rivers in the world, with almost three-quarters of the watershed lying within the tropical zone; its climate is controlled largely by seasonal monsoons. In a study conducted by the Mekong Secretariat (1990), equilibrium scenario outputs of three GCMs (GISS, GFDL, UKMO) were compared for water resources impacts analysis, along with two transient scenarios (exponential and arithmetic growth of CO_2). For all the hydrologic stations analysed, all the climate scenario forecasts showed longer dry periods and wet periods. Also, the patterns of monthly rainfall generally shifted one to two months *earlier* in the monsoon season, along with the time of occurrence of the driest and wettest months. Generally, rainfall increased significantly in the wet months, while the decrease in the dry months was smaller, although the duration of rainfall-deficient months increased. Reservoir operations would have to change to accommodate the greater variability in peak flows and low-flow periods. Hydro-electric power production will be affected, but irrigation releases would not be affected. The authors concluded that new reservoir operation rules would mitigate many of the potential adverse effects.

In the study of the Uruguay River (Tucci and Damiani 1991), which was part of the triad of studies conducted for the US Environmental Agency, the authors generally followed the same approach as for the Mekong River. They compared three GCMs (GISS, GFDL, UKMO) with both equilibrium and transient CO_2- doubling scenarios. They found that *all* the models underestimate total historic rainfall, but that the GISS model performed the best in terms of replicating modern historic conditions. A hydrologic model was used to estimate flows in the Uruguay River from the precipitation generated by the GCMs. The predicted flows indicated an 11.7% *decrease* with the GISS model; a 21.5% *increase* with the GFDL and a 6.4% *decrease* with the UKMO model. The GISS transient model also showed an 11.7% reduction in mean flows.

All the GCM models predicted lower dry-season flows for the Uruguay River, but the models differed widely on the inter-annual variation of flows and on the magnitude of peak flows. The study did focus on water management impacts, as the basin is developed and managed for hydro-electric power, flood control, irrigation and water supply. Much more hydro-electric power is planned for the basin, hence the impacts on hydro-electric production was considered very important. However, the different models generated contradictory results. For example, the UKMO and GISS models predicted a *decrease* in hydro-electric power output of 2.5 to 4.75%, whereas the GFDL model showed an *increase* of 17.3%. Three of the four model scenarios predict smaller and fewer floods, resulting in flood damage avoidance benefits. However, reduction in low flows and lengthening of low flow duration was forecast, showing *decreases* of 3 to 18%. This implies a greater frequency of failure and water rationing, especially for irrigation withdrawals.

Analysis of the impacts of climate change on water resources management of the Zambezi River was conducted by Urbiztondo et al. (1991) for the US Environmental Protection Agency (1990). Preliminary results of a rainfall runoff simulation analysis and comparison of GCM scenarios generated by the GFDL, UKMO and GISS models showed that runoff based on GFDL and GISS steady-state CO_2 doubling was consistently lower than the base scenario, representing current climate. The UKMO scenario projects an increase in river flow. The GISS Transient A and Transient B scenarios show decadal variations in precipitation, with decades of increases and decreases. The Middle Zambezi River is regulated by the Kariba Reservoir, a large multipurpose storage dam. A highly simplified reservoir optimisation model was used to examine the impacts that GCM-generated inflows would have on hydro-electric power generation. Kariba Reservoir generates up to 70% of Zimbabwe's electricity, so that any pronounced reduction in runoff or changed seasonality of flows would have a major adverse economic impact on that country. However, the simulation and comparison of various GCM scenarios, both stationary and transient, showed that annual target energy demands, based on a plant load factor of 65% and an efficiency of 95%, would be met under virtually all scenarios. Nevertheless, the impacts during dry years would be severe, as is the situation under present climate conditions.

4 Water resources management impacts

Global warming is expected to catalyse changes in water management in many regions of the world. The quality and quantity of groundwater; the structure and character of water consumption might alter; the conflicts and contradictions among individual water users and consumers would heighten; and design and operational changes would need to be re-examined. All these issues have been treated, to varying degrees, for several river basins with prescribed climate scenarios both in the Northern and Southern Hemispheres.

Climate uncertainty and water management was the topic of two recent conferences in the United States (NRC 1991; Ballentine and Stakhiv (eds) 1992). Rogers (1992) addressed the role that uncertainty of climate change information played in decision making related to water management issues. Rogers essentially concluded that even if the GCM models were scientifically well grounded and their prediction considered perfect, the information provided is largely peripheral to practical engineering decisions. The reason is that hydrology and availability of water is only one among several important factors in water management decisions, which include economic, political, sociological, technological and demographic consideration. There are three categories of decisions in water resources planning and management: planning and design that goes into *new* investments; those dealing with the operation and maintenance of existing systems; and those that modify the operational capacity of existing systems. There are many uncertainties faced by water managers and planners, not the least of which is future population and demand. Hydrologic uncertainty, ironically, may be among the less important considerations.

Sheer (1991), Fiering (1992), and Stakhiv (1992) make similar points in that planning water resources systems involves making many interrelated design and operating decisions under uncertainty. These decisions are made continuously and focus on the extremes and variability of the present climate. Various levels of buffering capacity, redundancy and resilience are built into individual design criteria and components of a water management project and its operation within a larger system as an inherent hedge against an unforeseeable event. Hence, managed water systems, while not entirely fail-safe, are designed to be robust enough to guarantee a high degree of reliability for rare or extreme events within the historic record. These rare events may become more frequent as part of a potential shift in the climate mean and variability. But planners and designers are constantly adjusting their design criteria and, in effect, are anticipating subtle changes in the statistical properties of the evolving record of precipitation and streamflow. In addition, new and more sophisticated techniques are employed to optimise the capacity, operating rules and economic efficiency of the upgraded water management systems.

Furthermore, water resources management is a highly dynamic and adaptive endeavour in the sense that new technologies, economic instruments, institutional and legal changes, and demand management measures are constantly being introduced, tested and employed as water scarcity becomes a chronic problem (Frederick 1992). Hence, the various strategies outlined in the Resource Use and Management Subgroup of the IPCC Response Strategies Working Group III (1990c) are largely in place or are being implemented in most of the developed countries.

For a number of existing water management systems, comprehensive estimates have been developed, as examples of potential climate change effects on water consumption and use, socioeconomic and ecological consequences of global warming and changes in hydrological characteristics. Few comprehensive and detailed water management studies (as opposed to hydrologic sensitivity analysis) have been conducted, employing the full range and hierarchy of models required for such an undertaking. Among the better studies are those of Kirshen and Fennessey (1992); Lettenmaier and Gan (1990); Lettenmaier et al. (1990); Lettenmaier and Sheer (1991) and Fiering and Rogers (1989).

Two studies (Lettenmaier and Gan 1990; Lettenmaier and Sheer 1991) explicitly modelled large managed river basins in California, wherein hydrologic simulation models were coupled with snowmelt and soil moisture accounting models developed by the US National Weather Service. The studies used GCM outputs and stochastically created 100 years of rainfall and temperature records from 30 years of historic data. Snow accumulation, ablation and runoff were the primary variables of concern. The response of all four catchments to changed climate conditions were dominated by temperature-related changes in snowmelt and were relatively unaffected by GCM-predicted rainfall changes. Reservoir system performance for the Sacramento–San Joaquin River basin was analysed using the hydrologic information. While the average annual runoff did not change markedly, the shift in seasonal runoff to the winter months had a large impact on the reliability of water deliveries to the various water supply users and on the flood control capabilities of the system.

Two conceptual studies for sizing the optimal capacity and developing ideal operating rules for the design of hypothetical reservoirs under climate uncertainty were undertaken by Fiering and Rogers (1989) and Lettenmaier et al. (1990). Both studies attempted better to understand the vulnerability, resilience and robustness of reservoirs and managed systems under climate uncertainty as a way of improving the design of new systems and operation of existing systems. Essentially both studies confirmed an intuitive notion, that water supply performance, ie the minimisation of shortages or failures (or maximisation of reliability) is controlled more by reservoir storage capacity than by any variation in operating policy. Lettenmaier and Gan (1990) varied reservoir capacity from 0.25 to 0.50 of mean annual runoff. Fiering and Rogers (1989) showed that reservoir reliability did not change much with changes in the climate-induced variation in runoff if the reservoir capacity was larger than 0.5 of the mean annual runoff.

As a whole, the studies on water resources and water management effects of climate change allow the corroboration of the following inference: under the condition of global warming and a great uncertainty of local climate variability, large water management systems are capable of greater flexibility in adapting to changes in timing and magnitude of runoff. In this connection, the watersheds with a large degree of control over river runoff under global warming would have considerable advantages for redistributing the available water supply and flood control compared to the regions with natural unregulated runoff regimes.

5 Conclusions

Since the publication of the IPCC First Assessment Report, several studies on impacts of climate change on hydrology and water resources have been conducted. Unfortunately, there is not yet adequate information on regions affected by aridity and desertification and an effort should be undertaken to fill that gap. The new studies expanded the geographic scope of the original surveys, while confirming many previous conclusions; but few new insights were offered on hydrologic sensitivities and vulnerability of existing water resources management systems.

The principal conclusions suggested by the new studies are:

- *Significant progress has been made in hydrologic sensitivity analyses in developed countries, yet large gaps exist in the information base regarding the implications of climate change for less developed nations;*
- *Comparative sensitivity analyses that rely on existing GCMs offer generic insights regarding the physical hydrologic effects and water resources management impacts, but the differences in the outputs of the GCMs coupled with large differences in hydrologic sensitivity analyses makes it difficult to offer region-specific impact assessments;*
- *Temporal streamflow characteristics in virtually all regions exhibited greater variability and amplification of extremes, with larger flood volumes and peak flows as well as increased flow episodes and a shift in the turning of the seasonal runoff;*
- *The higher the degree of water control, regulation and management of sectoral water demands, the smaller the anticipated adverse effects of global warming. Conversely, unregulated hydrologic systems are more vulnerable to potential hydrologic alterations.*

The principal recommendations are:

- *Increased variability of floods and droughts will require a re-examination of engineering design assumptions, operating rules, system optimisation and contingency planning for existing and planned water management systems;*
- *More studies on hydrologic sensitivity and water resource management vulnerability need to be directed towards arid and semi-arid regions and small island states.*
- *A uniform approach to the climate change hydrologic sensitivity analyses needs to be developed for comparability of results.*

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