WORLD METEOROLOGICAL ORGANIZATION

TECHNICAL NOTE No. 196

CLIMATE VARIABILITY, AGRICULTURE AND FORESTRY

Report of the CAgM-IX Working Group on the study of Climate Effects on Agriculture including Forests, and of the Effects of Agriculture and Forest on Climate

WMO-No. 802

Secretariat of the World Meteorological Organization - Geneva - Switzerland
WMO

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FOREWORD

Climatic fluctuations affect all economic sectors to some degree, but food and fiber production is perhaps the most sensitive and vulnerable to such fluctuations. The impact of climatic variability on agriculture is felt most in developing countries in Africa, Asia and Latin America. Throughout history, many practices were developed to adapt to the variability of weather and climate conditions. Although in recent times, the use of irrigation, mechanization, inputs of fertilizers and pesticides appear to be crucial factors for increasing food production, agricultural productivity can be increased also through the judicious utilization of information and knowledge about climate and weather.

There exist many examples of such utilization which demonstrate benefits from agrometeorological advice and forecasting, as well as of early warning systems. It is particularly important that a positive experience has been obtained in a number of developing countries in Africa, Asia and Latin America.

Climatic variability will continue to affect agriculture whether or not the global climate changes. Thus, although longer term measures may have to be taken to cope with climatic change, policies to deal with climatic variability must continue to receive high priority, especially because climatic variability affects strategic world grain production and food security in many developing countries.

Improvements in medium- and long-range forecasting and climate predictions will greatly assist in planning and management decisions aimed at adapting to climate variability, especially in tropical regions. Further, the climate change issue is now a subject of much concern. In order to address this problem, WMO, jointly with UNEP, has established an Intergovernmental Panel on Climate Change (IPCC). The activities of this panel provide important input to the preparation of the UN Framework Convention on Climate Change. The present report takes into account the findings of the IPCC, especially with respect to assessment of climate variability and its socio-economic impact.

Climate was recognized by the UN Conference on Environment and Development (UNCED) as one of the principal factors to be taken into account in combating desertification. WMO has been very active in the negotiating process to elaborate an international convention to combat desertification. This report contains information which is relevant to the negotiating process and the implementation of the convention when it enters into force.

The WMO Commission for Agricultural Meteorology, recognizing the importance of application of knowledge of the impact of climatic variability on agriculture to reduce the vulnerability of agriculture to climatic fluctuations, appointed a working group to survey and summarize such information and to make proposals to cope with year-to-year variations in climate and their impact on agriculture.

The working group was composed of: Dr M.J. Salinger (New Zealand); Dr M. Heikinheimo (Finland); Mr S.B.B. O’tengi and Mr J. Mwikya (Kenya); Dr O.D. Sirotenko (Russian Federation); Dr W.Y. Sommers (USA); Dr A.P. Delmotte (FAO); Dr C.C. Wallen (UNEP) as members, with Dr E.M. Choisnel (France); Mr S. Nakagawa (Japan) and Mr N.B. Yelifiari (Ghana) as members taking part in the activities of the group by correspondence. In addition, Dr H. Pappalainen (Finland) contributed to the final report. It is with much pleasure that I take this opportunity to express the gratitude and appreciation of the World Meteorological Organization to all members of the working groups who contributed to the report and especially to its Chairman, Dr M.J. Salinger.

The report of the group addresses problems which are of great concern in all countries, especially developing ones. It is believed therefore that the publication of the report as a WMO Technical Note will contribute to the development of sustainable agriculture by WMO Members.

G.O.P. Obasi
(Secretary-General)
PREFACE

The ninth session of the Commission for Agricultural Meteorology (Madrid, 1986) established a Working Group on the Study of Climate Effects on Agriculture, including Forests, and of the Effects of Agriculture and Forests on Climate. The working group was given the following terms of reference:

(a) To update information on climatic influence on agriculture presented in CAgM Report No. 17;
(b) To collect examples of the types of climatic influences on specific crops and animals on agricultural operations, and on the transportation of agricultural produce in various geographical regions, together with estimates of their recurrence and severity;
(c) To review and present a report on the interrelationships between forests and rainfall variability;
(d) To compile information on the effects of the El Niño phenomenon on agriculture;
(e) To summarize available information, experience and knowledge of applications of the effects of climatic variations, including the effects of projected changes of carbon dioxide and other radiatively effective gases on agriculture;
(f) To survey and summarize the effects of agricultural activities on climate;
(g) To make proposals to reduce the vulnerability of agriculture to climatic variability.

The working group has addressed these terms of reference in this Technical Note. The subject of climatic variability, agriculture and forestry is a very broad one, but the treatment in this report has been confined to the terms of reference laid down by the ninth session of CAgM.

The group commenced work in 1987 and met in Geneva in June 1989 to consider the draft report. The main emphasis of the report is on the effects of climate variability, rather than climate change, on agriculture and forestry. The impact of climate change on agriculture and forestry and on deforestation was not dealt with in the report because the Intergovernmental Panel on Climate Change (IPCC) Working Group 2 was preparing a report at the same time on these aspects. Close communication was kept with the lead authors preparing the agriculture and forestry sections of the IPCC report.

The final report submitted in 1990 was reviewed by the tenth session of the Commission for Agricultural Meteorology (Florence, 1991) which approved the publication of the report as a WMO Technical Note. The Commission further appointed joint rapporteurs to update the contents of this Technical Note and study other aspects and other crops not treated in it.

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Substantial contributions to the editing and final preparation of this report were provided by E. Fouhy, B. Archbold, L. Coutts, E. Meiklejohn, and S. Turner, all of the New Zealand Meteorological Service.
CHAPTER 1
This chapter describes the nature of climate change and variability. It traces temperature trends during the last ice age and subsequent postglacial period. Trends since the 1850s, which show a global warming of 0.5°C are described in more detail. It is noted that the Southern Oscillation accounts for a significant proportion of the year-to-year variability. The impact of variability on agriculture and forestry ecosystems is often through extreme meteorological events: high temperatures, frost, heavy rainfall, drought, snow, gales and tropical cyclones, all disruptive.

Climate and its variability can change in a number of ways. Climate can change progressively or abruptly and extremes can mirror these changes. However, because extreme events are rare, the changes they provoke can be far more dramatic. Variability can also change without a change in mean conditions. The effects of climate and its variability on agriculture and forestry are very significant as climate affects many aspects of plant and animal biology. Agriculture and forestry also influence climate. The chapter concludes by describing the framework and approach that is to be found in this volume.

CHAPTER 2
This chapter considers in depth the effects of climatic elements and climate variability on agriculture and forests. Plants respond to climate in a number of ways. CO₂ directly affects photosynthesis and the regulation of gases and water vapour through the stomata of leaves. Although assessment of CO₂ is complex, generally photosynthesis in C₃ plants increases with elevated levels of CO₂, but C₄ plants respond much less or not at all. Stomatal aperture reduces in most plants resulting in less transpiration. Both optimum temperature for photosynthesis and leaf area increase.

As temperatures increase, so do plant development rates up to a temperature optimum. Beyond this, development rates decrease. Some temperate crops require a period of low temperatures in order to flower. Growth is most sensitive to temperature just above the threshold temperature for growth and near the maximum temperature where growth stops. In between, growth is little affected by temperature. Herbaceous plants, compared with woody perennials, do not develop a true dormancy, but most become hardened to low temperatures. High temperatures usually increase the growth rate but decrease the growth duration. Since growth duration is more affected by temperature increases than growth rates, yield usually declines with above average temperature.

Both dry air and low soil moisture cause stomatal closure in plants, with less transpiration, and leaf area expansion slows down. Plant growth ceases at high soil moisture deficits. Rainfall increases produce more days of plant growth, and rainfall decreases make fewer days available for plant growth. Therefore plant productivity is very dependent on rainfall. Changes in rainfall variability can have very significant impacts in arid, semi-arid and sub-tropical regions. In regions which receive dry strong winds, damage to plants can occur because of very high evapotranspiration rates. In other areas high winds cause mechanical damage.

Forest ecosystems respond differently from agriculture, because they comprise many species and communities. Major changes occur very rapidly when extreme events occur after stresses caused by variability have weakened the trees. Moisture stress through drought and extreme high or low temperatures will make the forest more susceptible to forest fires, attacks by insects and diseases, windstorms and ice storms.

Variation in CO₂ gives a mixed response in forests. If observed increases in CO₂ continue, competitive advantages will develop between communities within the forest ecosystems. The basic community composition is a response to light variability, but the variability of light is a microclimatic effect of the forest itself, given its latitudinal placement.

Temperature determines where forest ecosystems occur latitudinally and altitudinally. Within this temperature range extremes cause winter injury damage and forest fires. Warm temperatures increase the forests' photosynthetic rate and cold temperatures limit growth. Moisture determines forest existence: where the climate is too dry or droughts occur, non-forest lands occur. Wind is important in dispersing pollen, seeds, transporting insects and diseases. Strong winds drive forest fires and cause damage in the forest.

Animals respond both directly and indirectly to climate and climate variability. Depending on the activity, indirect responses, that is responses as a consequence of climate effects on other factors which affect animal productivity, can be more significant. Animals respond directly to temperature extremes, floods and drought. High temperatures can lead to reproductive failure, and both heat and cold stress can cause death in newborn animals. Floods cause starvation and death as a result of inundation of grazing land.

Indirect effects on animals are of considerable importance through changes in the amount and seasonal distribution of livestock feed resources, and through changes in the type and infectivity of pests, diseases and parasites. Markedly
Chapter 3

This chapter provides some case studies of impacts of climate variability on agriculture and forestry. Here, examples are taken from crops occurring in cold, temperate, sub-tropical and tropical latitudes. Cold latitude crops occur in those regions where temperature is the primary factor affecting growth and development, limiting the length of the growing season through early and late frosts. Substantial crop losses can occur in adverse years. However, in a continental cold climate, as in the Canadian Prairies, precipitation variability is the main cause of yield fluctuations. By contrast, the more maritime cold climates of northern Europe are limited by short cool growing seasons with reduced yields in Iceland and northern Finland, representing the northernmost margin of agriculture, when temperatures are cooler than average, and high yields in warm seasons.

For temperate crops, examples from climate models are used to evaluate sensitivities. Generally, yield fluctuations are determined by initial water storage in the soil over winter and by precipitation during the period of vegetative growth. Climatic variability has the most impact for wheat crops in those areas with continental climates, and large precipitation fluctuations. Tropical and sub-tropical agriculture is affected mainly by flooding and drought. In humid tropical areas not limited by rainfall, rainstorms and strong winds cause crop losses because of flooding and waterlogging. In contrast, seasonal rainfall distribution and variability between seasons limits production. Growing sorghum, millet and cotton, which are all drought resistant compared with groundnuts and beans, can provide some resilience for primary production.

Climate can force forest change on a large scale: boundaries between forests and other ecosystems are determined by rainfall and evapotranspiration, and forest type by temperature. At the regional scale, climate variability causes fluctuations in boundaries between ecosystems. Climate impacts are indirect through effects on species composition, forest fires, disease and pest epidemics, and other disturbances. By these means, climate variability lowers forest health which can lead to rapid decline during and after extreme events. The Southern Oscillation is a major cause of natural climate variability, particularly in the tropical Pacific, and low and mid latitudes of the southern hemisphere. The Southern Oscillation causes these regions to have a high rainfall variability resulting in significant effects on agricultural production and forests. The El Niño phase usually causes lower agricultural yields, and major disturbances to forests and fisheries. In contrast, the La Niña phase can give increases in agricultural yields.

Chapter 4

The purpose of this chapter is to discuss the effects of climate variability on agricultural and forestry operations, and measures to decrease the sensitivity of agriculture. The operations can be maximized by choosing zones which optimize productivity for a given crop, agricultural or forestry practice, and matching the seasonal climate cycle with the crop life cycle.

Agrometeorological planning can select the best location in terms of latitude, altitude and aspect. The impacts of extremes can be modified by choice of local aspect and shelter. After a system is established, day to day operations are still influenced by meteorological conditions. Agricultural and forestry products are often transported and stored; unfavourable conditions in this period account for large losses of agricultural products. The vulnerability of agriculture can be decreased by a number of measures. Matching agricultural activities with a region’s climate and its variability is the most important. Breeding of more resilient and adaptable crop varieties, management of the environment (e.g. irrigation), modification and diversification of agricultural systems, and pest and disease control all improve the resilience of agriculture to climate variability.

Chapter 5

CO2-induced climate change scenarios from the Villach and Bellagio UNEP/WMO 1987 workshops are used as a basis for assessing impacts on agriculture and forests. In most cases the middle scenario was used for regional impacts.
Agriculture in cold latitudes would benefit because crop production is limited by temperature and a short growing season. However, in the southern Prairies a more drought prone climate would reduce crop yields. Trends would differ in temperate latitudes. Agriculture in southern California and the Great Plains of the USA would suffer from a reduction in summer soil moisture. In contrast, eastern USA would experience little change. Growing seasons would lengthen in maritime areas of western Europe, and rye and wheat yields would increase in eastern Europe with a temperature increase. In Mediterranean areas either little change or a decline in rainfall would lower agricultural productivity. Unless higher rainfall balances evapotranspiration in Asian part of the Russian Federation, large irrigation schemes would be required to maintain yields. In northern China winter crops would benefit, but spring crops would be subject to drought stress. Temperature increases would benefit rice production in northern Japan, but be detrimental in the south. Areas of pastoral agriculture would increase in New Zealand, but would decline with wheat yields in western Australia. For wheat and cattle in Argentina, results are unclear.

The low latitudes contain the large desert regions of the world, and regions of monsoon and tropical climates. On the high latitude side of the arid- and semi-arid regions, rainfall is a winter phenomenon. In all these regions, rainfed agriculture would suffer and pasture lands would become rangelands. Rainfall is a summer occurrence on the low latitude side of the deserts. Model results are contradictory and rainfall mechanisms complex. If global warming were to lead to increased rainfall variability, agriculture would need to become less intensive, despite rainfall increases. In monsoon climates, a strengthened summer monsoon would benefit agriculture, especially in the rice growing areas of southeast Asia. However, impacts would depend very much on the warming rate. In the humid tropics, rainfall is usually efficient for agriculture. However, higher intensity rainfall would lead to more frequent flooding and soil degradation.

Forests are less adaptable than agriculture because the ecosystem is complex and slower to adjust to new conditions. Forest ecosystems also generate their own microclimates and growth conditions. Temperature increases would increase winter photosynthesis and growth at the upper tree lines. However, even short episodes of drought limit growth. Boreal forests in northern high latitudes would extend their range northward. The trends in temperate forest productivity in Europe and the southeast USA are unclear, but an increase in summer drought in the southern USA and Mediterranean regions would cause tree death.

Rainforests in the humid tropics and monsoon Asia would experience an enhanced hydrological cycle. The direct effects of CO\textsubscript{2} on growth in southern hemisphere temperate rainforests would be more important.

These conclusions are only tentative. In some cases very detailed studies are available, while in other areas there exist only some general conclusions on climate drawn from simulations of a doubling of CO\textsubscript{2} carried out by various general circulation models. In all regions, the direct impact of higher atmospheric CO\textsubscript{2} content might counterbalance adverse consequences of climate.

**CHAPTER 6**

This chapter examines the effect of agriculture and forests on climate. Agriculture is a contributor to the enhanced greenhouse effect. It has been a significant source of greenhouse gas build-up since 1800, and will continue to be so in the future because of growing human population demand for growth in food production. The main agricultural sources are rice paddies, enteric fermentation and animal wastes from the global livestock populations emitting methane (CH\textsubscript{4}), and the application of nitrogenous fertilisers for nitrous oxide (N\textsubscript{2}O). Currently these account for 15 per cent of greenhouse gas emissions. Livestock and fertilizer sources are projected to grow to maintain increased food production, with modest increases in rice paddy areas. Estimates, which are tentative, place the contribution of agricultural activities to the enhanced greenhouse effect since 1800 at 0.1–0.2°C at 1990, and 0.2–0.7°C when climate reaches equilibrium as a result of greenhouse gas doubling.

Forests of the order of one sq. km. are large enough to cause significant effects on local scale climate. Forests influence climate by the nature of their cover, aerodynamic effects, modification of the hydrological cycle and radiative processes. Wind is mechanically reduced in the forest and clearings. The cover intercepts the rainfall, reducing the percentage reaching the ground and runoff. Equatorial and tropical rain forests intercept less rainfall. As forest albedo is lower, the energy available for evapotranspiration is higher. Deforestation increases runoff by between 10 and 20 per cent, and decreases evapotranspiration. Tropical forests thus comprise a balanced system as a large proportion of the rainfall is generated by their own evapotranspiration. Deforestation of tropical forests causes significant effects on local climate by alterations of water availability, surface energy budgets and soil water retention.

Temperatures increase, rainfall interception and evapo-transpiration decrease, and runoff increases. Deforestation of a large area of forest such as the Amazon would significantly affect regional evapotranspiration, and could affect wind patterns and spatial rainfall distribution over South America.
RÉSUMÉ DES CHAPITRES

CHAPITRE 1
Ce chapitre décrit la nature des changements climatiques et de la variabilité du climat. Il retrace les variations de température pendant la dernière ère glaciaire et la période postglaciaire qui a suivi. Les variations de température depuis les années 1850, qui se sont traduites par un réchauffement de la planète de 0,5 °C, sont décrites plus en détail. On constate que l'oscillation australe compte pour une large part dans les variations d'année en année. C'est souvent par des phénomènes météorologiques extrêmes que les changements climatiques influent sur les écosystèmes agricoles et forestiers : températures élevées, gels, fortes précipitations, sécheresses, neige, tempêtes et cyclones tropicaux, qui tous causent des dégâts.

Le climat peut évoluer de multiples façons. Il peut changer progressivement ou brusquement; ces changements peuvent se traduire par des conditions météorologiques extrêmes. Mais les phénomènes extrêmes étant rares, les changements qu'ils entraînent peuvent être bien plus spectaculaires. Le climat peut également évoluer sans que les conditions moyennes ne varient. Les effets du climat et de sa variabilité sur l'agriculture et la sylviculture sont considérables du fait que le climat influe sur de nombreux aspects de la biologie végétale et animale. En retour, agriculture et sylviculture influent sur le climat. L'approche adoptée dans cet ouvrage est exposée à la fin du chapitre.

CHAPITRE 2
Ce chapitre étudie en détail les effets des changements climatiques sur les cultures et les forêts. L'influence du climat sur les plantes s'exerce de diverses façons. Le CO₂ agit directement sur la photosynthèse ainsi que sur les échanges gazeux et l'émission de vapeur d'eau par l'intermédiaire des stomates des feuilles. Bien qu'il soit difficile d'étudier l'influence du CO₂, généralement la photosynthèse des plantes C₃ augmente lorsque le taux de CO₂ est élevé, mais l'incidence sur les plantes C₄ est bien moindre, voire nulle. L'ouverture des stomates diminue, de sorte que la plante respire moins. La température optimale de photosynthèse ainsi que la surface foliaire augmentent.

Le taux de croissance végétale augmente avec la température, jusqu'à une température optimale. Au-delà de cette limite, le taux de croissance diminue. Dans les régions tempérées, certaines cultures nécessitent une période de basse température pour fleurir. La température a une incidence maximale sur la croissance lorsqu'elle est légèrement supérieure au seuil thermique de croissance et proche de la température au-delà de laquelle la croissance est nulle. A l'intérieur de ces deux limites, la croissance n'est guère affectée par la température. Les plantes herbacées, contrairement aux plantes ligneuses vivaces, ne connaissent pas de repos végétatif, mais la plupart d'entre elles durcissent lorsque la température est basse. Des températures élevées accélèrent généralement la croissance mais en réduisent la durée. Les hausses de température ayant une plus grande influence sur la durée de la croissance que sur le taux de croissance, la plupart du temps le rendement diminue lorsque la température est supérieure à la moyenne.

La sécheresse de l'air et le manque d'humidité dans le sol entraînent la fermeture des stomates des plantes; la respiration devient ainsi plus faible et la croissance de la surface foliaire est ralentie. La croissance s'arrête lorsque le débit en eau du sol est très important. Si les précipitations augmentent, les jours de croissance végétale sont plus nombreux; si elles diminuent, ils sont moins nombreux. La productivité des plantes est donc largement tributaire des précipitations. Des changements dans la pluviométrie peuvent avoir des effets considérables dans les régions arides, semi-arides et subtropicales. Dans les régions où soufflent de forts vents secs, les plantes peuvent souffrir d'une très forte évapotranspiration. Dans d'autres zones, les vents violents causent des dégâts de nature dynamique.

L'effet sur les écosystèmes forestiers n'est pas le même que sur l'agriculture parce qu'ils abritent de nombreuses espèces et communautés. Des conditions extrêmes entraînent très rapidement de profonds changements lorsque les arbres ont été affaiblis par des agressions dues à la variabilité du climat. Le manque d'humidité suite à une sécheresse ou à des températures exceptionnellement basses ou élevées rendra la forêt plus vulnérable aux feux de forêt, aux insectes ou à la maladie, aux tempêtes de vent et de verglas.

Les forêts réagissent de manière variable à l'augmentation de la concentration de CO₂. Si l'augmentation observée se poursuit, les communautés qui constituent les écosystèmes forestiers s'en disputeront les avantages. La composition fondamentale d'une communauté dépend de la variabilité de la lumière, mais celle-ci est déterminée par le microclimat de la forêt elle-même, en fonction de la latitude à laquelle elle se trouve.

La température détermine la latitude et la longitude auxquelles se situent les écosystèmes forestiers. A l'intérieur de cette ceinture thermique, les températures extrêmes causent des dégâts l'hiver et engendrent des feux de forêt. Des températures chaudes augmentent le taux de photosynthèse des forêts, tandis que des températures froides en limitent
RESUME DES CHAPITRES

La variation de l'humidité détermine l'existence même des forêts : si le climat est trop sec ou si des sécheresses surviennent, il n'y a pas de forêt. Le vent joue un rôle important dans la dispersion du pollen et des graines, dans le transport des insectes et des maladies. Des vents forts répandent les feux et portent préjudice aux forêts.

Le climat et la variabilité du climat ont un effet à la fois direct et indirect sur les animaux. L'effet indirect, c'est-à-dire les conséquences de l'incidence du climat sur certains facteurs relatifs à la productivité animale, peut être plus ou moins important selon les activités. Les températures extrêmes, les inondations et la sécheresse ont un effet direct sur les animaux. Des températures élevées peuvent entraîner l'infertilité, et aussi bien la chaleur que le froid peuvent causer la mort des nouveau-nés. En submergeant les pâturages, les inondations entraînent la famine et la mort.

Les effets directs sur les animaux revêtent une importance considérable : modification de la quantité et de la répartition saisonnière des aliments destinés au bétail et modification du types et de la virulence des ravageurs, maladies et parasites. Des températures nettement plus chaudes ou plus froides durant la saison de végétation influent directement sur la quantité et la qualité des aliments. La sécheresse, accompagnée d'une exploitation plus intense des pâturages est l'une des principales causes de baisse des rendements et de mortalité chez le bétail. Une hausse des températures et des taux d'humidité créent en général des conditions favorables aux ravageurs, aux maladies et aux parasites du bétail.

Les maladies des plantes et les insectes nuisibles subissent indirectement les effets du climat à travers l'influence qu'il exerce sur le bétail, les cultures, les variétés et les pratiques agricoles. Les effets directs sont plus sensibles.

Pour ce qui concerne les agents pathogènes des plantes, le risque d'épidémie croît à mesure que la température et l'humidité augmentent. Seuls quelques agents pathogènes prospèrent lorsque le climat devient plus sec. Nombre de maladies sont transmises par les insectes vecteurs. Les virus sont peu sensibles au climat, mais leurs vecteurs le sont. À l'inverse, le climat influe sur chaque phase du cycle de développement des champignons, et les températures jouent un rôle important dans la présence de bactéries et de nématodes dans le sol. La température exerce une influence sur les insectes et les acariens nuisibles : si elle est élevée, leur développement s'accélère, de sorte que le nombre de générations par an augmente.

Il existe deux méthodes pour étudier les effets de la variabilité du climat : l'analyse statistique des données sur les rendements d'une part, et l'utilisation de modèles agro-climatiques de l'autre. Dans le second cas, les modèles physico-statistiques donnent de bons résultats, mais les modèles dynamiques, s'ils sont correctement dérivés, sont plus fiables.

CHAPITRE 3

Ce chapitre contient certaines études de cas sur les incidences de la variabilité du climat sur l'agriculture et la sylviculture. Les exemples choisis concernent les cultures situées dans des zones froides, tempérées, subtropicales et tropicales. Les cultures de latitude froide sont situées dans des régions où la température est le principal facteur influant sur la croissance et le développement, la durée de la saison de végétation étant abrégée par des gels précoces et tardifs. Durant les mauvaises années, les pertes agricoles peuvent être très importantes. Cependant, sous un climat continental froid tel que celui des plaines canadiennes, la variabilité des précipitations est le principal facteur de fluctuation des rendements. À l'inverse, les climats froids de tendance océanique de l'Europe du Nord se distinguent par des saisons de végétation courtes et fraîches, qui limitent les rendements en Islande et en Finlande du Nord, où se situe la limite nord des cultures, caractérisée par des températures plus froides que la normale et des rendements élevés durant les saisons chaudes.

Pour ce qui concerne les cultures de climat tempéré, les exemples de modèles climatiques sont utilisés pour évaluer leur vulnérabilité aux changements. La plupart du temps, les fluctuations de rendement sont déterminées par la réserve d'eau initiale dans le sol disponible pendant l'hiver et par la pluviosité durant la période de croissance végétale. La variabilité du climat a une incidence maximale sur les cultures de blé dans les zones de climat continental où les précipitations fluctuent énormément. L'agriculture tropicale et subtropicale est principalement affectée par les inondations et la sécheresse. Dans les zones tropicales humides où les précipitations sont abondantes, tempêtes de pluie et vents violents causent des pertes par suite d'inondations et d'engorgement des sols. En outre, la répartition des pluies saisonnières et les variations entre les saisons limitent la production. Sorgho, millet et coton, qui résistent bien mieux à la sécheresse que les arachides et les légumineuses, peuvent être cultivés avec succès pour la production primaire.

Le climat peut engendrer des changements de grande envergure dans les forêts : la limite entre les forêts et les autres écosystèmes est déterminée par les précipitations et la transpiration, et le type de forêt par la température. À l'échelle régionale, la variabilité du climat entraîne une fluctuation des frontières entre les écosystèmes. Le climat exerce une influence indirecte à travers ses effets sur la composition des espèces, les feux de forêt, les épidémies ou l'invasion de ravageurs et autres phénomènes perturbateurs. C'est ainsi que la variabilité du climat affecte la santé des forêts, pouvant provoquer un déclin rapide durant et après des phénomènes extrêmes. L'oscillation australe est l'une des principales causes de variabilité naturelle du climat, notamment dans la zone tropicale du Pacifique et sous les basses et moyennes latitudes de l'hémisphère Sud. En raison de l'oscillation australe, la pluviosité dans ces régions est extrêmement variable; cette variabilité a des effets considérables sur la production agricole et la sylviculture. Durant la phase El Niño, les rendements agricoles sont généralement plus faibles, et la sylviculture et la pêche sont profondément perturbées. À l'inverse, il arrive que les rendements agricoles augmentent durant la phase La Niña.
Ce chapitre étudie les effets de la variabilité du climat sur les activités agricoles et forestières et expose les mesures visant à rendre les cultures moins vulnérables. On peut maximiser les résultats des activités en choisissant des zones où la productivité d'une culture agricole ou forestière sera optimale et en choisissant une culture dont le cycle de développement correspond au cycle climatique saisonnier.

Grâce à la planification agrométéorologique, il est possible de choisir le meilleur emplacement en termes de latitude, altitude et exposition. Les effets de conditions météorologiques extrêmes peuvent être modifiés si l'on choisit une bonne exposition et un site abrité. Une fois un système établi, les pratiques quotidiennes demeurent sous l'influence des conditions météorologiques. Les produits agricoles et forestiers sont souvent transportés et stockés; des conditions défavorables lors de ces opérations engendrent de lourdes pertes. Plusieurs mesures permettent de rendre les cultures moins vulnérables. Il est essentiel de choisir les activités agricoles d'une région en fonction de son climat et de sa variabilité. La sélection de variétés de cultures plus résistantes et qui s'adaptent mieux, la gestion de l'environnement (par exemple l'irrigation), la modification et la diversification des systèmes agricoles, la lutte contre les ravageurs et les maladies sont des moyens de rendre l'agriculture plus résistante à la variabilité du climat.

**CHAPITRE 5**

Les différents scénarios concernant les changements climatiques qu'entraînerait une augmentation de CO₂ envisagés lors des ateliers PNUD/OMM de Villach et Bellagio en 1987 servent de base pour l'évaluation des incidences sur l'agriculture et les forêts. Dans la plupart des cas, on s'est fondé sur le scénario moyen pour les effets au niveau régional.

Une hausse de la teneur en CO₂ serait profitable à l'agriculture de latitude froide, la production des cultures y étant limitée par la température et la brièveté de la saison de croissance. Cependant, dans les prairies méridionales, un climat marqué par des sécheresses diminuerait les rendements des cultures. Dans les zones tempérées, les effets seraient variables. Dans le sud de la Californie et les grandes plaines des États-Unis d'Amérique, l'agriculture souffrirait d'une diminution de l'humidité du sol en été. En revanche, l'est des États-Unis d'Amérique ne subirait que peu de changements. La saison de croissance se prolongerait dans les zones océaniques de l'Europe de l'Ouest, et en Europe de l'Est, les rendements de seigle et de blé augmenteraient en raison de la hausse de température. Dans les zones méditerranéennes, soit une légère modification, soit une diminution des précipitations diminuerait la productivité agricole. A moins que des pluies plus abondantes ne compensent le phénomène d'évapotranspiration dans la partie asiatique de la Fédération de Russie, il serait nécessaire d'y instaurer de vastes plans d'irrigation pour maintenir les mêmes rendements. Dans le nord de la Chine, les cultures d'hiver seraient favorisées, mais les cultures de printemps souffriraient de la sécheresse. Une hausse de température serait profitable à la production de riz dans le nord du Japon mais néfaste dans le sud. Les zones d'agriculture pastorale s'étendraient en Nouvelle-Zélande, mais diminueraient dans l'ouest de l'Australie, ainsi que les rendements de blé.

Les conséquences sur le blé et le bétail en Argentine ne sont pas connues avec précision.

Les vastes régions désertiques de la planète et les régions de mousson et de climat tropical sont situées sous de basses latitudes. Aux latitudes élevées des régions arides et semi-arides, les précipitations surviennent pendant l'hiver. Dans toutes ces régions, l'agriculture non irriguée souffrirait et les pâturages se transformereraient en terres de parcours. Les précipitations sont un phénomène estival dans les parties des déserts situées à basse latitude. Pour ces régions, les résultats des modèles sont contradictoires et les mécanismes des pluies complexes. Si le réchauffement de la planète avait pour conséquence une plus grande variabilité des précipitations, il faudrait que l'agriculture devienne moins intensive, même si la pluviété augmentait. Dans les climats de mousson, une mousson estivale plus abondante serait bénéfique à l'agriculture, surtout aux rizières d'Asie du Sud-Est. Néanmoins, les effets dépendraient dans une large mesure du rythme auquel s'opère le réchauffement. Dans les régions tropicales humides, les pluies sont généralement bénéfiques à l'agriculture. Cependant, des pluies plus abondantes rendraient les inondations plus fréquentes et entraîneraient une dégradation des sols.

Les forêts sont plus vulnérables que les cultures parce que leur écosystème est plus complexe et moins prompt à s'adapter à de nouvelles conditions. En outre, les écosystèmes forestiers génèrent leurs propres microclimats et conditions de croissance. Une hausse des températures accélérerait la photosynthèse et la croissance à la limite supérieure de la forêt en hiver. Mais on sait que même de courtes périodes de sécheresse limitent la croissance. Les forêts boréales de latitude élevée s'étendraient au nord. Les effets sur la productivité des forêts tempérées en Europe et dans le sud-est des États-Unis d'Amérique sont mal connus, mais une plus grande sécheresse en été dans le sud des États-Unis d'Amérique et dans les régions méditerranéennes provoqueraient la disparition des arbres.

Les forêts pluviales dans les régions tropicales humides et dans les parties de l'Asie sujettes à la mousson connaîtraient un cycle hydrologique accru. Les effets directs du CO₂ sur la croissance des forêts pluviales tempérées de l'hémisphère Sud seraient plus sensibles.

 Ces conclusions ne sont que des hypothèses. S'il existe dans certains cas des études très détaillées, on ne dispose dans d'autres domaines que de conclusions générales qui résultent de simulations d'un doublement de la quantité de CO₂ effectuées à partir de divers modèles de circulation générale. Dans toutes les régions, l'incidence directe d'une augmentation de la concentration de CO₂ dans l'atmosphère pourrait compenser les conséquences négatives du climat.
Ce chapitre étudie l'incidence de l'agriculture et de la sylviculture sur le climat. L'agriculture contribue à l'effet de serre. Depuis 1800, elle est l'une des causes majeures d'accroissement des gaz à effet de serre, et le demeurera à l'avenir car la demande de nourriture croît au fur et à mesure que la population augmente. Les principales sources agricoles sont, pour le méthane (CH₄), les rizières, la fermentation entérique et les excréments du bétail, et l'utilisation d'engrais azotés pour le protoxyde d'azote (N₂O). À l'heure actuelle, ces facteurs sont responsables de 15 pour cent des émissions de gaz à effet de serre. On prévoit une intensification de l'élevage et de l'utilisation d'engrais afin d'augmenter la production alimentaire, mais seulement une légère augmentation des cultures de riz. D'après les estimations, calculées à titre indicatif, la contribution des activités agricoles à l'accroissement de l'effet de serre s'est traduite par un réchauffement de 0,1–0,2 °C entre 1800 et 1990, et sera de 0,2–0,7 °C lorsque le climat parviendra à un équilibre après que la quantité de gaz à effet de serre aura doublé.

Les forêts de l'ordre d'un kilomètre carré sont suffisamment grandes pour avoir un effet sensible sur le climat local. Les forêts influent sur le climat par la nature de leur couvert, les effets aérodynamiques, la modification du cycle hydrologique et les processus de rayonnement. Le vent est physiquement ralenti dans les forêts et les clairières. Le couvert intercepte les pluies, de sorte que le sol est moins arrosé et le ruissellement réduit. Les forêts pluviales équatoriales et tropicales interceptent moins les pluies. L'albédo de la forêt étant plus faible, le surplus d'énergie est dépensé en évapotranspiration. La déforestation accroît le ruissellement de 10 à 20 % et diminue l'évapotranspiration. Les forêts tropicales constituent donc des systèmes équilibrés, du fait qu'une large proportion des pluies est le fruit de leur propre évapotranspiration. La déforestation des forêts tropicales a des effets notables sur le climat local parce qu'elle modifie les quantités d'eau disponibles, les bilans énergétiques en surface et la rétention d'eau dans le sol.

Si les températures augmentent, l'interception des pluies et l'évapotranspiration sont plus faibles, et le ruissellement augmente. La déforestation d'une vaste zone telle que l'Amazonie influerait considérablement sur le phénomène d'évapotranspiration dans la région et pourrait modifier les configurations du vent et la répartition spatiale des précipitations en Amérique du Sud.
RESUMEN DE CAPÍTULOS

CAPÍTULO 1
En este capítulo se describen la naturaleza y la variabilidad del cambio climático y se tratan las tendencias de la temperatura durante la última era glacial y el período postglacial consecutivo. Las tendencias desde los años 1850, que muestran un calentamiento global de 0,5°C se describen con mayor detalle. Cabe señalar que la Oscilación Austral representa una proporción considerable de la variabilidad anual. El impacto de la variabilidad en los ecosistemas de agricultura y silvicultura se manifiesta frecuentemente a través de fenómenos meteorológicos extremos: altas temperaturas, heladas, fuertes lluvias, sequía, nieve, temporales y ciclones tropicales, todos ellos causantes de desórdenes.

El clima y su variabilidad pueden cambiar de numerosas maneras. El clima puede cambiar progresiva o bruscamente, y los fenómenos extremos pueden reflejar dichos cambios. Sin embargo, dado que esos fenómenos son poco frecuentes, los cambios que los afectan pueden ser mucho más dramáticos. La variabilidad puede cambiar también sin alteración de las condiciones medias. Los efectos del clima y su variabilidad sobre la agricultura y la silvicultura son muy importantes pues el clima afecta a numerosos aspectos de la biología animal y de las plantas. La agricultura y la silvicultura también influyen en el clima. El capítulo concluye con la descripción del marco y del enfoque recogidos en este volumen.

CAPÍTULO 2
En este capítulo se estudian en profundidad los efectos de los elementos climáticos y la variabilidad climática en la agricultura y la silvicultura. Las plantas responden al clima diferentes formas. El CO₂ afecta directamente la fotosíntesis y la regulación de gases y del vapor del agua a través del estoma de las hojas. Aunque la evaluación de CO₂ es compleja, en general la fotosíntesis en las plantas que generan C₃ aumenta con los mayores niveles de CO₂, pero las plantas que generan C₄ responden mucho menos o en absoluto. La apertura de los estomas disminuye en la mayoría de las plantas lo que se manifiesta en menor transpiración. La temperatura óptima para la fotosíntesis y el espacio de las hojas aumentan.

A medida que la temperatura aumenta, también lo hace el ritmo de desarrollo de las plantas hasta alcanzar una temperatura óptima. Mas allá de ésta, el ritmo de desarrollo disminuye. Algunos cultivos templados necesitan de un período de bajas temperaturas para florecer. El crecimiento es más vulnerable a la temperatura, en cuanto se rebasa la temperatura umbral de crecimiento y cerca de la temperatura máxima, en que éste se detiene. Entre ambos niveles la temperatura afecta muy poco al crecimiento. Las plantas herbáceas, en comparación con las perennes leñosas, no desarrollan un verdadero letargo, pero la mayoría se endurecen con las bajas temperaturas. En general, con las altas temperaturas aumenta el ritmo de crecimiento pero disminuye su duración. Como la duración del crecimiento resulta más afectada por los aumentos de temperatura que el ritmo de crecimiento, el rendimiento disminuye usualmente con una temperatura superior a la media.

Tanto el aire seco como la baja humedad del suelo producen el cierre de los estomas de las plantas con lo que la transpiración es menor y disminuye el espacio para la expansión de las hojas. El crecimiento de la planta cesa en presencia de altos déficit de humedad en el suelo. Cuando aumentan las precipitaciones hay más días favorables al desarrollo de las plantas, y cuando disminuyen, hay menos. Por consiguiente, la productividad de las plantas depende mucho de la cantidad de lluvia. Los cambios en la variabilidad de la cantidad de lluvia pueden influir notablemente en las regiones áridas, semiaridas y subtropicales. En las regiones que soportan fuertes vientos secos, las plantas pueden sufrir daños debido a los elevadísimos niveles de evaporación.

Los ecosistemas de bosques responden en forma diferente a la agricultura, ya que comprenden varias especies y comunidades. Los cambios más importantes ocurren muy rápidamente cuando se producen fenómenos extremos después de que las presiones causadas por la variabilidad han debilitado los árboles. Debido a la presión de la humedad que se manifiesta por la sequía y las altas bajas temperaturas extremas, los bosques son más propensos a los incendios forestales, a los ataques de insectos y a las enfermedades, a los temporales de ceniciento y de viento.

La variación de CO₂ produce una respuesta mixta en los bosques. Si los aumentos registrados de CO₂ continúan, se desarrollarán ventajas competitivas entre comunidades de ecosistemas forestales. La composición básica de la comunidad constituye una respuesta a la variabilidad de la luz, pero esta variabilidad representa un efecto microclimático del mismo bosque, dada su posición latitudinal.

La temperatura determina que los ecosistemas forestales ocurran latitudinal y altitudinalmente. Dentro de esta gama de temperaturas, los fenómenos extremos causan daños en invierno e incendios forestales. Las temperaturas cálidas aumentan la tasa fotosintética de los bosques y las temperaturas frías limitan su crecimiento. La humedad determina la existencia de bosques: allí donde el clima es muy seco o se producen sequías, no pueden existir zonas boscosas. El viento es importante para la dispersión del polen y de las semillas, y para el transporte de insectos y enfermedades. Los vientos fuertes propagan los incendios forestales y causan perjuicios a los bosques.
RESUMEN DE CAPÍTULOS

Los animales responden tanto directamente como indirectamente al clima y a la variabilidad climática. Dependiendo de la actividad, las respuestas indirectas, o sea, las que se producen como consecuencia de los efectos del clima sobre otros factores que afectan a la productividad animal, pueden ser más significativas. Los animales responden directamente a los fenómenos extremos de temperatura, a las crecidas y a la sequía. Las altas temperaturas pueden ser la causa de fallas en el proceso reproductivo, y tanto la presión del calor como del frío pueden ocasionar la muerte de animales recién nacidos. Las crecidas pueden causar problemas de inanición y muerte como resultado de la inundación de los pastizales.

Los efectos indirectos sobre los animales tienen gran importancia, al cambiar la cantidad y distribución estacional de los recursos alimenticios del ganado y al modificarse la clase y grado infectivo de los insectos nocivos, las enfermedades y los parásitos. Las estaciones de crecimiento notablemente más cálidas o más frías resultan en general o en un aumento o en una disminución del alimento, así como en un cambio de su calidad. La sequía y la mayor presión de los pastizales sobre los pastos son una causa principal de bajo rendimiento y muerte de ganado. Los aumentos de temperatura y humedad suelen a producir condiciones más favorables para los insectos devastadores, enfermedades y parásitos del ganado.

Las enfermedades de las plantas y las plagas de insectos presentan respuestas indirectas al clima como consecuencia de los cambios en la ganadería, en los cultivos, en las variedades y en las prácticas culturales. Las respuestas directas son más importantes.

Los datos de Fitopatógenos y la posibilidad de volverse epidémicos es mayor cuando aumentan la temperatura y la humedad. Las condiciones más secas favorecen a algunos parámetros. Varias enfermedades se transmiten con los vectores de insectos. El clima afecta muy poco a los virus, pero sí a sus vectores. Por el contrario, afecta a cada fase del ciclo de vida fúngico, y la temperatura es importante tanto para las bacterias como para los nemátodos del suelo. La temperatura influye en los insectos y ácaros devastadores. Con el aumento de temperatura, se acelera el ritmo de desarrollo y se dan más generaciones en un mismo año.

Los modelos agrometeorológicos pueden utilizarse como instrumento para investigar los efectos de la variabilidad climática. Los análisis estadísticos de la información sobre el rendimiento constituyen una técnica, y los modelos agrometeorológicos, otra. Los modelos físico-estadísticos de estos últimos producen resultados adecuados, pero los modelos dinámicos, correctamente derivados, son más sólidos.

CAPÍTULO 3
Este capítulo proporciona algunos estudios de casos de los impactos de la variabilidad climática sobre la agricultura y la silvicultura. Los ejemplos se han tomado de cultivos en latitudes frías, templadas, subtropicales y tropicales. Los cultivos de latitudes frías ocurren en las regiones en que la temperatura es el principal factor que afecta al crecimiento y al desarrollo; las heladas tempranas y tardías limitan la duración de la estación de crecimiento. En años adversos pueden producirse importantes pérdidas de cosechas. Sin embargo, en un clima continental frío, como es el caso de las praderas canadienses, la variabilidad de las precipitaciones es la causa principal de las fluctuaciones de rendimiento. En cambio, los climas fríos más marítimos del norte de Europa están limitados por las cortas estaciones frías de crecimiento, con rendimientos reducidos en Islandia y el norte de Finlandia, que representan el más alto margen agrícola al norte cuando las temperaturas son más frías que la media, y elevados rendimientos en las estaciones cálidas.

Para los cultivos de latitudes templadas se utilizan modelos climáticos para evaluar la vulnerabilidad. En general, las fluctuaciones de rendimiento se determinan por el almacenamiento inicial de agua en el suelo durante el invierno y por las precipitaciones durante el período de crecimiento vegetativo. La variabilidad climática produce el mayor impacto sobre los cultivos de trigo en las regiones con climas continentales y grandes fluctuaciones de precipitación. La agricultura tropical y subtropical resulta principalmente afectada por la sequía y las crecidas. En las regiones tropicales húmedas no limitadas por las precipitaciones, las tormentas con lluvia y vientos fuertes provocan pérdidas de cosechas a causa de las inundaciones y de la saturación hídrica. En cambio, la distribución de lluvia estacional y su variabilidad entre estaciones limitan la producción. El cultivo del sorgo, el mijo y algodón, que son resistentes a las sequías en comparación con los cacahuetes y las frijoles, puede presentar alguna resiliencia para la producción primaria.

El clima puede forzar cambios forestales en gran escala: la lluvia y la evapotranspiración determinan los límites entre los bosques y otros ecosistemas; y la temperatura determina el tipo de bosque. A escala regional, la variabilidad del clima produce fluctuaciones en los límites entre ecosistemas. Los impactos del clima son indirectos, con efectos en la composición de las especies, incendios forestales, enfermedades y epidemias de plagas y otros trastornos. En esta forma, la variabilidad del clima disminuye la salud de los bosques, lo que puede llevar a una rápida decadencia durante los fenómenos extremos y después de ellos. La Oscilación Austral es una causa principal de la variabilidad del clima natural, especialmente en el Pacífico tropical y en las bajas y medianas latitudes del hemisferio sur. A causa de la Oscilación Austral en estas regiones existe una alta variabilidad de lluvia que tiene considerables efectos significativos para la producción agrícola y los bosques. La fase el Niño produce una disminución del rendimiento e importantes trastornos en los bosques y las pesquerías. Por el contrario, la fase la Niña puede originar aumentos del rendimiento agrícola.
CAPÍTULO 1
El propósito de este capítulo es discutir los efectos de la variabilidad del clima en las operaciones agrícolas y forestales, y las medidas para disminuir la vulnerabilidad de la agricultura. Las operaciones pueden maximizarse escogiendo las zonas que optimicen la productividad de un determinado cultivo, las prácticas agrícolas o forestales, emparejando el ciclo climático de la estación con el ciclo de vida del cultivo.

Con la planificación agrometeorológica se puede elegir el mejor sitio en términos de latitud, altitud y aspecto. Los impactos de los efectos extremos pueden modificarse al escoger la situación local y el cobijo. Una vez establecido un sistema, en las operaciones diarias siguen influyendo las condiciones meteorológicas. Los productos agrícolas y forestales se transportan y almacenan frecuentemente; las condiciones desfavorables durante este período son la causa de grandes pérdidas de productos agrícolas. La vulnerabilidad de la agricultura puede disminuirse con una serie de medidas. Lo más importante es que las actividades agrícolas correspondan al clima de una región y a su variabilidad. El cultivo de variedades de cosechas con mayor resiliencia y adaptabilidad, la gestión del medio ambiente (por ejemplo, la irrigación), la modificación y diversificación de los sistemas agrícolas, y el control de las plagas y las enfermedades, mejoran la resiliencia de la agricultura a la variabilidad climática.

CAPÍTULO 5
Los escenarios de cambio climático producido por el CO₂ en los cursos de trabajos prácticos de Villach y Bellagio (PNUMA/OMM 1987) se utilizan como base para evaluar los impactos en la agricultura y la silvicultura. En la mayoría de los casos se utilizó el escenario medio para los impactos regionales.

La agricultura en las latitudes frías se beneficiaría, ya que la temperatura y una corta estación de crecimiento limitan la producción de la cosecha. Sin embargo, en las praderas meridionales un clima más expuesto a la sequía reduciría el rendimiento de las cosechas. Las tendencias diferirían en latitudes templadas. La agricultura al sur de California y en las grandes llanuras de Estados Unidos sufrirían una reducción de la humedad del suelo en verano. Por el contrario, la parte oriental de Estados Unidos experimentaría pocos cambios. Las estaciones de cultivo se alargarían en las zonas marítimas de Europa Occidental, y el rendimiento de trigo y centeno aumentaría en Europa Oriental con un aumento de temperatura. En las regiones mediterráneas, con un pequeño cambio o una disminución de la cantidad de lluvia disminuiría la productividad agrícola. A menos que una mayor cantidad de lluvia equilibre la evaporación en las partes áridas de la Federación de Rusia, se necesitarían grandes planes de irrigación para conservar el rendimiento. En China septentrional, las cosechas de invierno se beneficiarían, pero los cultivos primaverales estarían expuestos a una presión de la sequía. Los aumentos de temperatura serían beneficiosos para la producción de arroz al norte del Japón, pero serían perjudiciales en el sur. Las zonas de pastoreo agrícola aumentarían en Nueva Zelanda pero declinarían con los rendimientos de trigo al oeste de Australia. En lo que respecta al trigo y al ganado en Argentina, los resultados no son claros.

Las bajas latitudes comprenden las grandes regiones desérticas del mundo y las regiones de climas monzónicos y tropicales. En la parte latitudinal alta de las regiones áridas y semiáridas, la lluvia es un fenómeno del invierno. En todas estas regiones, la agricultura de cultivos de secano sufriría y las tierras de pastoreo se volverían pastizales. La lluvia es un fenómeno del verano en la parte latitudinal baja de los desertos. Los resultados de los modelos son contradictorios, y los mecanismos de la lluvia son complejos. Si el calentamiento global lleva a una mayor variabilidad de la cantidad de lluvia, la agricultura tendría que ser menos intensiva, a pesar de los aumentos de lluvia. En los climas monzónicos, un verano monzónico más fuerte sería benéfico para la agricultura, especialmente en las zonas de cultivo de arroz del suroeste de Asia. Ahora bien, los impactos dependerían mucho del nivel de calentamiento. En las regiones tropicales húmedas, la cantidad de lluvia es generalmente suficiente para la agricultura, pero una mayor intensidad de las precipitaciones dará lugar a inundaciones más frecuentes y a la degradación del suelo.

Los bosques son menos adaptables que la agricultura, ya que el ecosistema es complejo y se adapta más lentamente a las nuevas condiciones. Los ecosistemas forestales generan también sus propios microclimas y condiciones de crecimiento. Los aumentos de temperatura incrementarían la fotosíntesis invierno y el crecimiento en las Líneas de árboles superiores. Sin embargo, incluso los cortos episodios de sequía limitan el crecimiento. Los bosques boreales en las altas latitudes meridionales extenderían su radio de acción hacia el norte. Las tendencias en la productividad de los bosques templados en Europa y la parte surooriental de Estados Unidos no son claras, pero un aumento de la sequía al sur de los Estados Unidos y en las regiones mediterráneas causarían la muerte de los árboles.

Los bosques lluviosos en los trópicos húmedos y en Asia monzónica experimentarían un aumento del ciclo hidrológico. Los efectos directos de CO₂ en el crecimiento de los bosques lluviosos templados en el hemisferio austral serían mayores.

Las presentes conclusiones son sólo provisionales. En algunos casos se dispone de estudios muy detallados, mientras que en otros existen únicamente algunas conclusiones generales respecto al clima, obtenidas de simulaciones de una duplicación de la cantidad de CO₂, realizadas con varios modelos de circulación general. En todas las regiones, el impacto directo de una mayor cantidad de CO₂ atmosférico podría compensar las consecuencias adversas del clima.
CAPITULO 6

En este capítulo se examina el efecto de la agricultura y la silvicultura sobre el clima. La agricultura contribuye al aumento del efecto invernadero. Ha sido una fuente importante de producción de gas de efecto invernadero desde 1800 y continuará siéndolo en el futuro debido a la creciente demanda de la población humana de una mayor producción de alimentos. Las principales fuentes agrícolas son los arrozales, la fermentación entérica y los residuos animales de las poblaciones ganaderas globales que emiten metano (CH₄), y la aplicación de fertilizantes nitrogenados al óxido nítrico (N₂O). Actualmente, esto representa un 15 por ciento de las emisiones de gases de efecto invernadero. Se proyecta que las fuentes ganaderas y fertilizantes crezcan para producir más alimentos, con incrementos modestos en la zona de arrozales. Los cálculos, que son provisionales, sitúan el aporte de las actividades agrícolas al incremento del efecto invernadero (desde 1800) en 0.1–0.2°C en 1990 y 0.2–0.7°C cuando el clima alcanza su equilibrio como resultado de la duplicación del gas de efecto invernadero.

Los bosques de una extensión aproximada de 1 km² son suficientemente vastos para causar efectos importantes en el clima a escala local. Los bosques influyen en el clima por la naturaleza de su cobertura, los efectos aerodinámicos, la modificación del ciclo hidrológico y los procesos radiativos. El viento se reduce mecánicamente en los bosques y claros. La cobertura intercepta la lluvia reduciendo el porcentaje que llega al suelo y la escorrentía. Los bosques lluviosos ecuatoriales y tropicales interceptan menos lluvia. En la medida en que el albedo de los bosques disminuye, la energía disponible para la evaporación disminuye. La deforestación aumenta la escorrentía entre un 10 y 20 por ciento, y disminuye la evaporación. Los bosques tropicales comparten un ciclo hidrológico, pero gran parte de la lluvia se genera por su propia evaporación. La deforestación de los bosques tropicales tiene importantes efectos en el clima local, por las alteraciones de la disponibilidad de agua, el balance de energía de la superficie y la retención de agua en el suelo.

Las temperaturas aumentan, la interceptación de lluvia y la evaporación disminuyen y la escorrentía crece. La deforestación de una gran parte de la selva, como la Amazonía, influiría considerablemente en la evaporación regional y podría afectar a las estructuras del viento y la distribución espacial de las lluvias en América del Sur.
КРАТКОЕ РЕЗЮМЕ

Глава 1
В этой главе описывается характер изменений и изменчивости климата. Прослеживается ход температуры за последнюю эпоху оледенения и последующий послеледниковый период. Более подробно описана температурная тенденция с 1850-х годов, которая свидетельствует о глобальном потеплении на 0,5°C. Отмечается, что южным колебаниям объясняется значительная часть межгодовой изменчивости. Воздействие изменчивости на сельскохозяйственные и лесные экосистемы часто проявляется через экстремальные метеорологические явления: высокие температуры, заморозки, сильные дожди, засуха, снег, штормы и тропические циклоны, причем все они носят разрушительный характер.

Климат и его изменчивость могут меняться различным образом. Климат может меняться постепенно или резко, и экстремальные явления могут как в зеркале отражать эти изменения. Однако, поскольку экстремальные явления редки, их влияние может быть куда более драматичными. Изменчивость может также изменяться без изменений средних значений. Влияние климата и его изменчивости на лесное и сельское хозяйство весьма существенны, поскольку климат влияет на многие аспекты биологии растений и животных. Сельское и лесное хозяйство также влияют на климат. В заключение главы описываются рамки и подход, которые применимы в данной публикации.

Глава 2
В этой главе подробно рассматривается влияние климатических элементов и изменчивости климата на сельское хозяйство и леса. Растения различным образом реагируют на климат. CO₂ непосредственно влияет на фотосинтез и регуляцию водяного пара через устья листьев. Хотя оценка CO₂ может комплексный характер, обычно фотосинтез в C3-растениях уменьшается с повышением уровня CO₂, а C4-растения реагируют гораздо меньше или совсем не реагируют. U большинства растений раскрытие устьиц уменьшается, что приводит к уменьшению транспирации. Увеличивается как оптимальная температура для фотосинтеза, так и площадь листьев.

С ростом температуры до оптимума увеличивается скорость развития растений. Следовательно, оптимальна скорость развития замедляется. Некоторым культурам умеренного пояса для цветения требуется период низких температур. Рост растений наиболее чувствителен к температуре, несколько превышающей пороговую температуру роста, а вблизи максимальной температуры рост останавливается. В промежутке этих значений температура мало влияет на рост. Правильная растения по сравнению с древесными многолетниками не претерпевают истины периода покоя и в большинстве своем закаливаются низкими температурами. Высокие температуры обычно увеличивают скорость роста, но уменьшают его продолжительность. Поскольку продолжительность роста больше повышена в связи с низкими температурами, чем скорость роста, урожайность обычно уменьшается при температурах, превышающих средние.

Сухой воздух, а также низкая влажность почвы вызывают закрытие устьиц растений, уменьшение транспирации и замедление увлажнения площади листа. Рост растений прекращается при высоких лимитирующих влажности почвы. Увлажнение осадков влияет на собой увеличение количества дней роста растений, а уменьшение осадков сокращает количество дней, в течение которых происходит рост растений. В связи с этим продуктивность растений в большей степени зависит от осадков. Изменения в изменчивости осадков могут иметь очень большое воздействие на засушливые, полузасушливые и субтропические районы. В районах с сильными сухими ветрами повреждения растений могут происходить в связи с очень высокой скоростью эвapotranspiration. В других районах сильные ветры вызывают механические повреждения.

Лесные экосистемы реагируют иначе, чем сельскохозяйственные, поскольку они включают многие виды и сообщества растений. Крупные изменения происходят очень быстро в тех случаях, когда экстремальные явления имеют место после того, как стрессы, вызываемые изменчивостью, уже ослабили деревья. Недостаток влаги в результате засухи и экстремально высоких или низких температур делает лес более повреждаемым лесными пожарами, инфекциями, вредителями и болезнями.

Изменчивость содержания CO₂ вызывает смешанную реакцию лесов. Если наблюдаемое повышение содержания CO₂ будет продолжаться, внутри лесных экосистем между сообществами будут развиваться конкурирующие благоприятные факторы. Состав основного сообщества определяется реакцией на изменчивость света, а изменчивость света оказывает микроклиматический эффект на сам лес с учетом его широтного расположения.
Формат определяет расположение лесных экосистем по широте и высоте. В пределах этого температурного диапазона экстремальные величины вызывают зимние повреждения растений и лесные пожары. Положительные температуры увеличивают скорость фотосинтеза лесов, а отрицательные температуры ограничивают рост. Существование лесов определяется наличием влаги в тех районах, где климат слишком сухой или проходит засухи, лесных угольщих не существует. Ветер играет важную роль в переносе пыльцы, семян, насекомых-вредителей и болезней. Сильные ветры переносят лесные пожары и вызывают повреждения лесов.

Животные реагируют на климат и его изменчивость как непосредственно, так и косвенно. В зависимости от активности, косвенные реакции, т.е. реакции на последствия воздействия климата на другие факторы, которые влияют на продуктивность животных, могут быть более значительными. Животные непосредственно реагируют на экстремальные температуры, наводнения и засуху. Высокие температуры могут привести к падению продуктивности, а тепловые и холодные стрессы могут вызвать гибель новорожденных животных. Наводнения вызывают голод и смерть в результате затопления пастбищных угольщих.

Косвенные воздействия на животных имеют большое значение и выражаются в изменении количества и сезонного распределения кормовых ресурсов для скота, а также в изменении типов и интенсивности насекомых, болезней и паразитов. Значительно более теплый или холодный вегетационный период обычно приводит либо к увеличению, либо к уменьшению количества корма и к изменению качества этого корма. Засуха, наряду с повышением употреблением пастбищ, является основной причиной низких урожаев и падежа скота. Увеличение температуры и влажности ведет к созданию более благоприятных условий для вредителей, болезней и паразитов домашних животных.

Болезни растений и насекомые-вредители демонстрируют косвенную реакцию на климат, вследствие изменений погодовых скота, сельскохозяйственных культур, их разновидностей и агротехнических приемов. Более важной является непосредственная реакция.

С ростом температуры и влажности увеличивается потенциальная возможность превращения болезнетворных микроорганизмов в эпидемию. Лишь немногие из болезнетворных микроорганизмов благоприятно развиваются в условиях более сухого климата. Многие болезни передаются насекомыми-переносчиками, вирусы мало подвергаются влиянию климата, но их переносчики погибают. В противоположность этому климат влияет на все фазы грибкового жизненного цикла, а температура играет важную роль как для бактерий, так и нематод почвы. Насекомые и клещевые вредители подвергаются влиянию температуры—при более высоких температурах увеличивается скорость развития, что приводит к большему количеству поколений за год.

Модели культуры как могут быть использованы как инструмент для изучения влияния изменчивости климата. Одним из методов является статистический анализ данных об урожайности, а другим — модели культуры. Из последних адекватные результаты дают физико-статистические модели, а динамические модели, если они правильно сконструированы, более надежны.

Глава 3
Эта глава содержит результаты некоторых типовых исследований воздействий изменчивости климата на лесное и сельское хозяйство. Приводятся примеры сельскохозяйственных культур, произрастающих в холодных, умеренных, субтропических и тропических широтах. Культуры холодных широт произрастают в тех регионах, где температура является основным фактором, влияющим на рост и развитие, и ограничивающим продолжительность вегетационного периода в связи с ранними и поздними заморозками. В неблагоприятные годы могут пройти и те же потери урожая. Однако в условиях континентального холодного климата, например в канадских провинциях, изменчивость урожаем является основной причиной колебаний урожая. В противоположность этому более морские холодные климаты Северной Европы, с ограниченным кратким прохладным вегетационным периодом, характеризуются уменьшением урожаев в Исландии и северной Финляндии, являющихся такими районами северной наиболее неустойчивого земледелия, при температурах ниже средних и высокими урожаями при повышенных температурах.

В отношении культур умеренных широт примеры результатов моделирования климата используются для оценки чувствительности. Вообще говоря, колебания урожайности определяются не только тепловым, но и влажным результатом. Климатическая изменчивость оказывает наивысшее воздействие на культуры пшеницы в районах с континентальным климатом и большими колебаниями в осадках. Тропическое и субтропическое сельское хозяйство подвергается главным образом влиянию паводков и засух. Во влияниях тропических районов, не страдающих от дефицита осадков, ливни и сильные ветры вызывают потери урожая в связи с затоплением и заболачиванием. В противоположность этому сезонное распределение осадков и изменчивость их выпадения между сезонами ограничивает продуктивность. Выращивание сорго, проч и хлопка, являющихся засухоустойчивыми по сравнению с земляным орехом и бобовыми, может обеспечить некоторую устойчивость первичного производства.

Климат может вызвать изменение лесов в крупных масштабах: границы между лесами и другими экосистемами определяются осадками и эвapotранспирацией, а тип леса — температурой. В региональном масштабе изменчивость климата вызывает флуктуации границ между экосистемами. Воздействия климата являются косвенными и проявляются через состав видов, лесные пожары, болезни и вирием, переносимые насекомыми, а также...
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другим физическим механизмам. Таким образом, изменчивость климата ухудшает здоровье леса, что может привести к быстрому его вымиранию во время или после экстремальных явлений. Южное коелибание является основной причиной естественной климатической изменчивости, главным образом в тропической части Луиго океана и в низких и средних широтах южного полушария. Южное коелибание вызывает в этих регионах высокую изменчивость осадков, что серьезно сказывается на сельскохозяйственном производстве и лесах. Фаза Элли-Нинь обычно связывается с низкими уровнями сельскохозяйственных культур и крупными вознаграждениями в лесном и рыбном хозяйстве. В отличие от этого фаза Ла-Нинь может вызывать увеличение урожайности сельскохозяйственных культур.

Глава 4

Цель этой главы состоит в том, чтобы описать воздействие изменчивости климата на ведение работ в области сельского и лесного хозяйства и меры по уменьшению чувствительности к нему сельского хозяйства. Эффективность работ может максимизироваться путем отбора сложных с оптимальной продуктивностью данной культуры, методов сельского и лесного хозяйства и сопоставления сезонного климатического цикла с жизненным циклом культуры.

Агрометеорологическое планирование позволяет провести наиболее разумное размещение культур с точки зрения широты, высоты и других аспектов. Воздействие экстремальных явлений может быть ослаблено путем выбора местности и защиты. После того, как система отлажена, повседневные работы все еще подвергаются воздействию метеорологических условий. Продукция сельского и лесного хозяйства часто должна транспортироваться и храниться; неблагоприятные метеорологические условия в этом период приводит к крупным потерям сельскохозяйственной продукции. Устойчивость сельского хозяйства можно сократить путем принятия мер. Сопоставление сельскохозяйственных работ с климатом региона и его изменчивостью является одной из наиболее важных мер. Выведение наиболее устойчивых и пригодных для разных сортов культур, меры по охране окружающей среды (например ирригация), изменение и разнообразие сельскохозяйственных систем и борьба с вредителями и болезнями—все это повышает устойчивость сельского хозяйства к изменчивости климата.

Глава 5

Сценарий изменения климата под влиянием СО2, разработанные на семинарах ЮНЕП/ВМО в Филадельфии и Белграде в 1987 г., используются в качестве основы для оценки воздействий на сельское хозяйство и леса. В большинстве случаев для оценки региональных воздействий использовались средние сценарии.

Сельскому хозяйству в холодных широтах изменение климата может принести пользу, поскольку произрастание культур ограничено температурой и кратким вегетационным периодом. Однако в южных широтах, где климат более павершен засухой, урожайность сельскохозяйственных культур может уменьшиться. В умеренных широтах теплее на нижних. Сельское хозяйство в Южной Калифорнии и на Великих Равнинах США будет страдать от уменьшения почвенной влаги в летний период. В противоположность этому восток США не претерпит больших изменений. Вегетационный период удалится в зонах морского климата Западной Европы, а урожай пшеницы и ячменя увеличится в Восточной Европе при увеличении температуры. В регионе Средиземного моря небольшое изменение может уменьшить северных культуры. В азиатской части Российской Федерации потребуются крупные ирригационные схемы для охранения урожаев, если эвапорация не будет сбалансирована более высоким количеством осадков. В северной части Китай изменения климата небольшие благоприятным для озимых культур, но яровые культуры будут подвергаться стрессу, вызванному засухой. Повышение температуры будет способствовать увеличению производства риса в северной Японии, но будет пагубным на юге. В Новой Зеландии увеличится площадь пастбищного сельского хозяйства, но при этом сократятся урожай пшеницы в Западной Австралии. В отношении пшеницы и крупного рогатого скота в Аргентине результаты неясны.

В южных широтах расположены крупнейшие в мире районы пустыни, а также регионы муссонально-тропического климата. В высокопродуктивных засушливых и полузасушливых регионов осадки являются зимним явлениям. Во всех этих районах будет страдать неурожайное сельское хозяйство, а пастбища и озера станут непригодны для выпаса скота. В низкозатопленных пустынь осадки выпадают главным образом летом. Результаты моделирования противоречивы, а механизмы формирования осадков сложны. Если бы глобальное потепление вело к повышению изменчивости осадков, сельское хозяйство должно было бы стать менее интенсивным, но несмотря на увеличение осадков. В муссонных климатических условиях увеличение температуры будет ухудшаться температуры и ухудшаться температуры, особенно в районах выращивания риса в Юго-Восточной Азии. Однако воздействие в большей степени будет зависеть от скорости потепления. Во всех крупных тропических областях обычно играют эффективную роль в сельском хозяйстве. Однако высокая интенсивность осадков приводит к более частым затоплениям и ледяным заносами.

Леса трудно адаптируются, чем сельское хозяйство, поскольку их экосистема сложна и медленно приспосабливается к новым условиям. Лесные экосистемы часто создают свои собственные микроклимат и условия для роста. Увеличение температуры приводит к разрушению зимнего фотосинтеза и росту верхней части древесин. Однако даже краткие эпизоды засухи ограничивают рост. Боевые леса в северных широтах увеличивают свою протяженность к северу. Тенденция продуктивности умеренных лесов в Европе и в юго-восточной части США не ясны, а увеличение летней засухи в южной части США и Средиземноморском регионе вызовет гибель деревьев.
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Тропические леса во влажных тропиках и в мусясном климате Азии подвергнутся влиянию усиленного гидрологического цикла. Большая важность приобретет непосредственное воздействие CO2 на рост влажных лесов в умеренной зоне южного полушария.

Эти выводы являются лишь предварительными. В некоторых случаях имеются более детальные исследования, хотя в других областях существуют только некоторые общий выводы об изменениях климата в результате моделирования удовлетворительного воздействия CO2, проведенных на нескольких моделях общей циркуляции. Во всех регионах непосредственное воздействие повышенного содержания атмосферного CO2 может уравновесить неблагоприятные последствия изменения климата.

Глава 6
В этой главе рассматривается воздействие сельского и лесного хозяйства на климат. Сельское хозяйство является одним из видов хозяйственной деятельности, который содействует усложнению парникового эффекта. Оно является важным источником парниковых газов, установленным еще в 1800-х годах, и будет продолжать им оставаться в связи с увеличением потребностей растущего населения в пищевых продукциях. Основными сельскохозяйственными источниками являются рисовые культуры, внутренняя ферментация и отходы лесных и лесных скота, выделяющие метан (CH₄), а также выделение закиси азота (N₂O) в результате применения нитрата озона. В настоящее время на эти источники приходится 15% выбросов парниковых газов. Предполагается, что увеличение животноводства и уборение территории будут расширяться для обеспечения роста производства продовольствия, а площади, занимаемые рисовыми полями, увеличиваются незначительно. Предварительные оценки показывают, что до расширения парниковых газов, приходящихся на сельское хозяйство с 1800-х годов, составляет на 1990 год 0,1–0,2°С и составляет 0,2–0,7°C, когда климат достигает равновесия в результате удвоения содержания парниковых газов.

Леса, занимающие порядка 1 км², уже достаточно велики для того, чтобы оказать значительное воздействие на климат в местном масштабе. Леса влияют на климат в связи с характером их покрова, аэродинамическим эффектом, изменением гидрологического цикла и радиационных процессов. Ветер механически осаждаются в лесах и лесосеках. Покров перехватывает осадки, сокращая дождь, достигающую земли, и, таким образом, сток. Экваториальные и тропические леса перехватывают меньше осадков. Поскольку альбедо леса ниже, энергия, потребляемая на эвapotranspirацию, выше. Обезлесивание повышает сток на 10–20% и снижает эвapotranspirацию. Таким образом, тропические леса представляют собой облагороженную систему, поскольку большая часть пресных осадков создается благодаря их общей эвapotranspirации. Исчезновение тропических лесов оказывает значительное воздействие на местный климат путем изменения наличия воды, приземного энергоразового баланса и удержания влаги почвой.

Температура увеличивается, перехват осадков и эвapotranspirация уменьшаются, а сток увеличивается. Исчезновение крупных лесных массивов, таких, как Амазония, будет значительно влиять на эвapotranspirацию региона и может изменить характер ветров и пространственное распределение осадков в Южной Америке.
1.1 CLIMATE CHANGE AND VARIABILITY

Climate change and variability in the past is seen in the geological climate record, with large fluctuations in global and regional climates over the past million years. These fluctuations have been between ice averages, which are periods of relatively large ice cover, extensive alpine glaciers and ice sheets, and interglacials when alpine glaciers are small and continental ice sheets confined to Greenland and Antarctica. Temperatures are substantially lower in ice ages than in interglacials. The last ice age commenced approximately 80,000 years ago and peaked around 25,000 years ago with global temperatures 5°C below present values. At that time, regional climates were substantially different. In the present interglacial, the climate has been slightly warmer than at present, with temperatures up to 1–2°C higher in some regions.

Climate trends and variability have been measured since last century (Jones et al., 1986a, 1986b), but good climate records have been kept for many regions only since about the 1850s (Figure 1.1). Shorter term temperature fluctuations over land areas differ considerably, but broad trends on a large scale show the globe has warmed by at least 0.5°C over the past 100 years.

Figure 1.1
Trends and variability in global temperatures since the 1850s. The upper graph shows northern hemisphere temperatures, the middle graph southern hemisphere temperatures and the lower graph global temperatures (From Jones, 1988)

It is certainly warmer now than at any time since climate records began. The temperature increase is common to both hemispheres, and to land and sea areas. There is noticeable short-term temperature variability, such as the northern hemisphere cooling between 1940 and 1970, which did not occur in the southern hemisphere. Since 1976, global temperatures have increased rapidly, with the 1980s being the warmest years on record.
CHAPTER 1

Regardless of time scale, all climate records demonstrate variability about the trends, such as that associated with the Southern Oscillation (see Section 3.5). About 20–30 per cent of the temperature variability about the global temperature trends, especially in the southern hemisphere, is linked to the Southern Oscillation (Jones, 1988). Such variability and change associated with global climates in the past and present will almost certainly continue in the future.

1.2 IMPORTANCE OF CLIMATE VARIABILITY

Climate extremes are of particular significance to agriculture and forests including such extreme events as high temperatures, frost, heavy rainfall, drought, snowfall and gales.

Agriculture and forestry tend to be well adjusted to the mean climatic conditions of a region, and show little sensitivity to moderate variations around those means. Outside this general band of tolerance within which agricultural and forestry ecosystems are adapted lie bands of hazard (Figure 1.2). As conditions become progressively more extreme, the ability of plants to adjust and respond without stress and damage declines, so that agriculture and forestry can be particularly vulnerable to climate variability.

High temperatures can exacerbate drought conditions, damage crops and reduce yields. Low temperatures are expressed through frosts and heavy snowfalls and the former usually curtail yields in frost-sensitive crops. However, in some temperate horticultural and arable crops low temperatures are important in promoting yield and development. Much below average temperatures, especially in spring, can cause significant losses of newborn livestock.

Heavy rainfall and floods are very costly, and any increases in flood magnitude may increase costs exponentially as areas previously considered safe require securing.

Figure 1.2
(a) Frequency distribution of a climatic element, upon which are superimposed bands of adaptation and adjustment (b). In (c), a change of mean from \( x(o) \) to \( x(1) \) increases the number of low values (e.g., rainfall) indicated by the area under the upper curve to the left of \( A(o) \) (hatched) from that under the lower curve corresponding to mean \( x(o) \). An even greater increase in the relative number of extreme events (e.g., severe droughts) is indicated by the increase in area to the left of \( B(o) \) (cross-hatched). The same frequency of recurrence shifts from values of the climatic variable of \( A(o) \) or \( B(o) \) to \( A(1) \) or \( B(1) \) respectively (After de Vries, in Kates et al., 1985)
INTRODUCTION

Changes in frequency of heavy rainfall events would also increase the occurrence of landslips and landslides. Drought directly impacts on agricultural yields by reducing the number of days available for plant growth.

High winds have a number of effects. They cause significant damage to agricultural crops and forests, through mechanical damage to plants themselves as well as to any supporting structure. Generation of storm swells and high wave heights by tropical cyclones (hurricanes) causes significant coastal erosion and inundation of low lying agricultural lands.

Finally, variability and extreme events lower the resilience of agriculture and forestry, both changing the occurrence of, and making these ecosystems more susceptible to, disease and pest outbreaks.

1.3 CHANGES IN CLIMATE AND VARIABILITY

If the climate state changes, usually characterized by a shift in means, then the frequency of formerly rare events on the side the mean has shifted might occur much more frequently. The frequency of the opposite extreme might correspondingly decrease. Thus, for example, drought occurring twice successively in one in 20-year events would normally be expected once in 400 years (Wigley, 1987). If the distribution shifts by one standard deviation (Figure 1.2), these back-to-back events could occur once in 16 years. Such rapid change in probabilities of rare events could occur for climate variability depending on the direction of change of the climate event.

Changes in variability, as a consequence of change in mean conditions, can occur in two ways. Firstly, the means can portray a steady change through time, with changes on the side of the mean also increasing steadily in frequency. The mean state can also change abruptly, in which case the frequency of extremes could also do the same.

Most of the discussion of climate change, including published research from general circulation model simulations, has focused on changes in mean conditions. Much of this work has assumed that the patterns of variability about the means do not change (e.g. Hansen et al., 1989), when discussing changes in daily maximum and minimum temperatures. Some recent work is now addressing this deficiency but conflicting results are produced by the models.

Wilson and Mitchell (1987) and Rind et al. (1989) both found that daily temperature variability tended to decrease in a CO2-warmed world. However, Mearns et al. (in press), using yet another general circulation model, found no evidence for a decrease in temperature variability. Changes in rainfall variability are even less clear, with a particular model sometimes giving different indications in different regions of the world.

Finally, climate variability can also change without a change in mean conditions. If the variability increases, recovery periods for agriculture and forestry become shorter. Increased variability may result in any damage being greater and more widespread and in increasing costs of disruption.

1.4 AGRICULTURE AND FORESTRY

The effect of climate and climate variability on agriculture and forestry is very significant. As climate affects many aspects of plant and animal biology, the effects of climatic elements and their extremes will significantly alter productivity in agriculture and forestry ecosystems, and in turn the socio-economic conditions of many societies, both developed and developing.

Climate plays a major role in determining the yield levels, year-to-year variability and regional patterns of agriculture and forestry. The Commission for Agricultural Meteorology at earlier sessions recognized the importance of this and reviewed information on climatic variability and agricultural productivity (Allsopp, 1979), and enumerated some climatic influences on crop production (CAGM/WMO, 1983; 1986).
CHAPTER 1

Agriculture and forestry also affect climate, both on the micro and local scale. Agricultural activities operate through clearing of forest and extension of available land for production, use of mineral fertilizers, land improvement and irrigation, and altering the trace gas composition of the atmosphere. Climatic effects exercised by forests can be altered by height, density and leaf area. On the microscale, forest cover has the effect of reducing wind speed within the forest itself and in clearings. On a larger scale, forest cover affects climate through the changes in the hydrological cycle. There is a growing literature on the effects of deforestation on regional climates.

1.5 FRAMEWORK OF THIS REPORT

The following chapter discusses the effects of climate and climate variability on agriculture and forests. Particular attention is given to the principles of plant and animal responses to climate as well as treatment of pests and diseases. Examples of crop-weather models are used to demonstrate their ability at simulating responses to climate. Examples of the effects of climate variability on crops from cold, temperate, subtropical and tropical latitudes are addressed in Chapter 3, together with forestry. Chapter 4 examines the response of agricultural and forestry operation to climate variability. To sustain food production, it is most important to decrease the vulnerability of agriculture to climate.

Climatic change because of the enhanced greenhouse effect would dramatically affect agricultural and forestry ecosystems. Chapter 5 uses climate scenarios to examine possible consequences of global warming on agriculture and forests. The next chapter reviews the effects of agriculture on climate through trace gas emissions, and of forests on climate from many aspects. The final chapter provides overall conclusions and a list of recommendations.
CHAPTER 2

PRINCIPLES OF THE EFFECTS OF CLIMATE VARIABILITY ON AGRICULTURE AND FORESTS

2.1 PLANT RESPONSES TO CLIMATE VARIABILITY

by M. Heikinheimo and M.J. Salinger

Plants respond to many environmental factors (e.g., carbon dioxide (CO₂), temperature, rainfall, day length). The responses summarized here include growth, development and yield. Growth is regarded as the increase in dry weight of a plant because of photosynthesis, and is a consequence mainly of ambient CO₂ concentration, light and moisture supply. Development is the progress of a plant from germination to maturity through a series of stages for an annual crop; and the annual cycle from bud initiation to maturity for a perennial crop. The rate of development in the field is generally determined by temperature, and to some extent by day length. Water supply affects both: a slight shortage accelerates development, but a major shortage will slow both growth and development. The final crop yield is the integrated result of both growth and development.

2.1.1 EFFECTS OF CARBON DIOXIDE

Carbon dioxide is not only one of the major causes of the atmospheric greenhouse effect and therefore an important regulator of the Earth's energy balance, but it is also the primary source of carbon for plant growth. Present levels of CO₂ are at 354 ppmv (in 1990) and are increasing at a rate of about 1.5 ppmv/year (0.4 per cent a year) (Pearson, 1988). The rise in the average global CO₂ concentration is smooth and continuous in comparison with climatic variables such as temperature. Assuming no reductions in the current growth of fossil fuel combustion and deforestation, the slowly changing world scenario, the rate of CO₂ increase in the near future would be about 2.5 ppmv/year so that the atmospheric CO₂ concentration would reach a level of approximately 460 ppmv by the year 2030. The preindustrial levels of CO₂ (approximately 280 ppmv) would then double by the end of the next century.

As it is clear that increasing concentrations of atmospheric CO₂ will have indirect effects on agriculture and forestry, via climate change, it is also necessary to consider to what extent the direct effects of a CO₂ rise will influence vegetation. Some estimates have indeed stated that the direct effects of CO₂ may be of the same order of magnitude as those predicted by the global circulation models for the estimated average temperature increase of a few degrees.

Atmospheric concentration of CO₂ fluctuates according to the seasonal vegetation cycle as a result of the summertime net carbon acquisition by plants. This fluctuation is greater in the northern hemisphere, which has most of the world's vegetation cover. The amplitude of the CO₂ record has been increasing over the past 25 years at a rate of 0.82 per cent a year at Mauna Loa Observatory in Hawaii (Revelle and Kohlmaier, 1986), or somewhat faster than the global mean concentration of CO₂. Part of this rise could be attributed to the response of the net primary productivity of the world's vegetation cover to CO₂, but other unknown factors could also be involved (Revelle and Kohlmaier, 1986). The contribution of different plant physiological processes to this summary feedback is still uncertain. An increase in the rate of photosynthesis combined with an overall reduction in dark respiration could account for the greater relative increase of the amplitude of the annual CO₂ cycle compared with the rise in the global mean level of atmospheric CO₂ (Gifford, 1988). Experiments, mainly carried out in controlled environment conditions, have widely demonstrated that CO₂ is a limiting factor for plant growth. Numerous studies indicate that photosynthetic rate, biomass accumulation and grain yield have in many plants been higher due to the direct effect of the CO₂ concentration increase. For example, in a survey by Kimball (1983) of more than 430 observations of the yield of 37 species, the mean yield
increase was 33 per cent for a CO₂ doubling. In a more recent survey by Cure and Acock (1986) of nine common agricultural crops, an overall increase in yield due to a doubling of atmospheric CO₂ was 41 per cent, varying from a minimum of 15 per cent in rice to a maximum increase of 209 per cent in cotton. Of the most studied crops, soybean showed a 29 per cent and wheat a 35 per cent increase in yield.

The direct effects of CO₂ on vegetation are related to two fundamental plant physiological processes, namely the photosynthetic carbon assimilation and the regulation of the gaseous exchange of CO₂ and water vapour through stomata. Photosynthesis in those plants that exhibit the common C₃ carboxylic pathway is found to respond strongly to increases in CO₂. Photosynthesis in plants of the C₄ type, mostly grown in warm and tropical climates, responds much less or not at all to elevated atmospheric CO₂, because of their internal CO₂ concentration mechanism. Of the 30 most common crop species rated by their global annual production, only maize, sorghum, cane sugar and millet, typically grown in warm climates, are C₄ species (Warrick et al., 1986). For both C₃ and C₄ species the stomatal aperture is generally decreased due to the increase in atmospheric CO₂. The effects of CO₂ increase on photosynthesis and stomatal aperture vary strongly both with time and in space. Thus it is not surprising that the results of studies of long-term and large-scale effects are often contradictory to studies of short-term and small-scale effects. It should also be mentioned that although various types of plants may respond differently to an increase of CO₂, both C₃ and C₄ plants show, at least in laboratory simulation, an increase in their water use efficiency through the reduction of stomatal aperture in the leaves. Other responses to CO₂, possibly of a secondary nature, are morphological development and dark respiration.

An assessment of the overall effect of elevated CO₂ on plant productivity is complicated because of the interaction between the CO₂ response and other environmental factors such as temperature, light and moisture. Extrapolating results obtained in controlled environments to the field involves great uncertainties, because crops naturally compete for space and nutrients and are exposed to the daily variation of the weather.

2.1.1.1 Primary responses

Photosynthesis is the process, driven by the energy from light, of the oxidation of water and reduction of CO₂ into organic compounds, such as carbohydrates. Experiments indicate that present day atmospheric CO₂ concentration levels strongly limit the rate of CO₂ fixation in photosynthesis. Particularly with those plants that exhibit the common C₃ carboxylic pathway we can expect increases in CO₂ fixation of up to 30–50 per cent from an increase to 600 ppmv of atmospheric CO₂ concentration (Tolbert and Zelitch, 1983).

With most agricultural crops, initial photosynthetic CO₂ fixation occurs via the C₃ pathway which coexists with the photorespiratory C₂ pathway. The C₃ pathway, or the Calvin cycle, is the primary pathway for net CO₂ fixation, where an enzyme called ribulose 1,5 biphosphate carboxylase/oxygenase (RuBP) initially fixes CO₂ to form a three carbon product, 3P glyceral. RuBP also catalyses the oxidative photosynthetic C₂ cycle, a process called photorespiration, which releases recently fixed CO₂ by oxidation of sugars.

Of the many enzymes involved in the C₃ cycle, only RuBP is thought to be affected by CO₂. RuBP fixes CO₂ at a turnover rate of about 0.5 mole CO₂/sec/mole. With more CO₂ in the air, the carboxylation reaction would occur faster per unit time and per unit leaf area, resulting in increased CO₂ fixation. Most of the potential capacity of RuBP is either unused or partially active as an oxygenase. Limitations to CO₂ fixation by both CO₂ concentration and by RuBP availability have been observed. More research is required to reveal particularly the long-term responses of RuBP activation, and its role as a limiting enzyme for CO₂ fixation under CO₂ enriched climates.

In C₃ species, the photorespiration rate compensates the photosynthetic CO₂ fixation at about 50 ppmv at 25°C. For C₄ species, in contrast, photorespiration is practically nil.

Photosynthesis in C₃ species is inhibited by atmospheric oxygen concentrations by about 30–50 per cent at 340 ppmv, but when the CO₂ level is raised
to 600 ppmv, oxygen inhibition decreases to about 20–30 per cent (Ku et al., 1977). Atmospheric oxygen can therefore be considered as an inhibitor to photosynthesis, but an increase in ambient CO₂ will improve the competitive advantage of CO₂ molecules over oxygen molecules at the active sites of RuBP (Warrick et al., 1986).

Photosynthesis in C₄ plants is already CO₂-saturated at the present levels of ambient CO₂. This is because, in the C₄ pathway, CO₂ is trapped efficiently and stored into a carboxyl group of four carbon acids before it is reduced further by the common C₃ pathway. The primary carboxylase in C₄ species is phosphoenolpyruvate (PEP), which has a higher affinity for CO₂ than RuBP has. The enzyme is close to CO₂ saturation at present atmospheric CO₂ concentrations. Plants exhibiting the C₄ cycle are more efficient in their use of CO₂ and for an equivalent rate of CO₂ uptake, they also have a better water and nitrogen use efficiency than C₃ species.

The simultaneous uptake of CO₂ in photosynthesis and release of CO₂ in photorespiration form the so called carbon exchange rate (CER) which has been used as a measure of the photosynthetic activity of a plant. The net CO₂ fixation can be affected by elevated atmospheric concentrations of CO₂ in at least four ways (Sharkey, 1985):

1. The rate of CO₂ fixation is increased;
2. The number of oxygenations in the photorespiration cycle is reduced;
3. The number of CO₂ molecules released in photorespiration is reduced;
4. Some of the chemical energy becomes available for further fixation in carboxylation.

In a review by Cure and Acock (1986), using nine agricultural crops, the average increase in CER produced by a doubling of atmospheric CO₂ was initially 52 per cent but decreased to 29 per cent after plants had acclimatized for at least a week. Corn and sorghum, which are C₄ species, showed some initial response to increases in CO₂, but in the long term CER returned to near the value initially found at low CO₂ concentration.

The rate of photosynthesis is almost a linear function of internal CO₂ concentration at low concentrations, where the capacity for carboxylation limits net CO₂ uptake. At internal CO₂ concentrations above 220–240 ppmv (corresponding to about a 340 ppmv ambient CO₂ concentration) electron transport in the C₃ cycle becomes a limiting factor, causing reduction in the RuBP regeneration (Farquhar and von Caemmerer, 1982). This results in the saturation of the photosynthetic rate. Pearcy and Björkman (1983) have made the interpretation that if intercellular CO₂ concentration rises with ambient CO₂ concentration, the response in many C₃ species shifts from a region where electron transport and carboxylation capacities are in balance, to a region where electron transport is the more rate-limiting process.

The flow of carbon through the photosynthetic carbon reduction in light and the respiratory pathways in the dark finally leads to formation of starch and sucrose. A negative effect of more CO₂, suggested by Tolbert and Zelitch (1983), may be to stimulate sucrose synthesis to a point where sucrose production is in excess of the ability of the plant to transport it, or the sinks to use it. This would lead to various feedback mechanisms such as increased starch accumulation, which may cause reduction of the rate of photosynthesis.

In making quantitative estimates of the impact of CO₂ increase on plant growth, as Warrick et al. (1986) have pointed out, because of the non-linearity of the photosynthetic response to CO₂, one must carefully make note of the CO₂ reference level used in CO₂ enrichment studies.

2.1.1.1.2 Stomata

The stomatal pores in the epidermis function as a common bidirectional pathway for CO₂ and water vapour. Plants open the stomatal pores to allow ambient CO₂ to diffuse into the intercellular space of the leaf, but at the same time water vapour is lost into the atmosphere through transpiration. Stomatal pores form a major external regulatory mechanism for the physical flow of CO₂ into a plant. Stomata respond to light intensity and its spectral composition, CO₂ content and vapour pressure deficit in the air, and water availability in the soil. Signals controlling the stomatal guard cells are transferred mainly in the form of plant hormones such as cytokinins, abscisic acid and auxins. The degree of stomatal opening can be considered as a compromise in the balance between limitation of water loss and admission of CO₂.
CHAPTER 2

Some evidence indicates that the functioning of stomata could be part of the plant's strategy to optimize growth with a target rate of soil water depletion (Gifford, 1988). The response of stomata to environmental factors was reviewed recently in Zeiger et al. (1987).

The magnitude of stomatal closure with increasing concentrations of CO₂ is found to vary somewhat depending on species and the degree of environmental stimulation by other factors. Based on 80 observations from various experiments, Morison (1987) concluded that for a doubling of CO₂ concentration from 330 to 660 ppmv, stomatal aperture is reduced on the average by 40 per cent. No significant difference was seen between C₃ and C₄ species in their stomatal response to high CO₂. One coniferous species (Picea sitchensis) was not included in the comparison since it showed no response to increases in CO₂. Other sources also indicate that the stomata of many tropical plant species and coniferous trees possibly respond weakly to increases in CO₂.

Variability in the response of stomata to CO₂ is caused by species differences in the responses of photosynthetic assimilation to CO₂ (Goudriaan and Unssworth, 1988) and is also dependent on the interaction between other environmental factors such as light, temperature, and available moisture. In most C₃ and C₄ species investigated so far, stomatal conductance changes in response to a change in ambient CO₂ (Ca) in such a way that the ratio of intercellular CO₂ (Ci) to Ca remains more or less constant (Farquhar et al., 1978). When the Ca levels are raised, stomata in C₃ species will usually close somewhat, affecting transpiration, but the ratio Ca/Ci is not significantly changed.

The closing effect caused by increases in leaf internal CO₂ (Ci) has been found to be least at low light intensities (quantum flux density 0–250 E/m²/s) compared with high light intensities (Wong et al., 1978), but Morison (1987) has argued that as low light is often correlated with low temperatures and low vapour pressure deficit, the effects of stomata could be more important in these conditions, typical of early morning and evening. Lowering of ambient CO₂ can lead to stomatal opening even in darkness, but the width of stomatal apertures is never as great in the dark as in the light.

If the plants are water stressed, the stomata in most plants tend to respond more strongly to increased Ca, and Ci will remain nearly constant (Goudriaan and van Laar, 1978). With this response, transpiration is strongly reduced. When the water supply is ample, some species may show a less pronounced stomatal response (Farquhar et al., 1978), experiencing only a small decrease in transpiration but a greater increase in net CO₂ uptake and photosynthesis. The mechanism by which the concentration of CO₂ determines whether stomata tend to open is still largely an unresolved question. Stomata tend to respond to changes in intercellular CO₂ concentration, but how this information is transferred to the guard cells is unknown.

2.1.1.3 Dark respiration

The slow breakdown of stored carbohydrate occurring in the dark provides energy and building material for growth and for maintenance of the existing tissue. Dark respiratory processes consume oxygen, while CO₂ is simultaneously released to the atmosphere. Very little is known of the direct effects of atmospheric CO₂ fertilization on dark respiration.

As the net primary production is enhanced by more CO₂ in the air, it would be logical to assume increases in combustion and turnover of biomass as well. Direct measurements under CO₂-enriched air have contradicted this assumption, showing rather a slight suppression of dark respiration, for example in wheat (Gifford et al., 1985). In addition, measurements in the Arctic have indicated no respiratory response by the tussock tundra vegetation (Oechel and Riechers, 1986).

2.1.1.4 Morphological development

Observed changes in plant morphological development under increased CO₂ include alterations in the partition of dry matter into roots and shoot, expansion of leaf area, earlier or delayed flowering and a possible effect on the stomatal density of leaves.

Goudriaan and de Ruiter (1983) found an average of 15 per cent increase in leaf area with a doubling of CO₂ for lucerne, field bean and poplar (C₃ species). As
photosynthesis in C₄ plants is practically insensitive to increases in CO₂, it is interesting to note that C₄ plants also tend to increase their leaf area. Table 2.1 gives an example by Morison and Gifford (1984), where the efficiency of conversion of light to plant structural dry matter did not change with an increased concentration of CO₂.

The relatively large decreases of root to shoot ratio (see Table 2.1), especially for maize and sorghum, demonstrate the ability of C₄ species to optimize growth with the minimum expense of water. Higher production may then be attributed to more efficient light interception by larger leaves than to an increase in photosynthesis under elevated CO₂ (Warrick et al., 1986).

<table>
<thead>
<tr>
<th>CO₂ (ppmv)</th>
<th>E (gMJ⁻¹)</th>
<th>Leaf area/plant (cm²)</th>
<th>Root/shoot ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>340</td>
<td>680</td>
<td>340</td>
</tr>
<tr>
<td>Maize</td>
<td>3.1</td>
<td>3.0</td>
<td>648</td>
</tr>
<tr>
<td>Sorghum</td>
<td>3.0</td>
<td>3.1</td>
<td>568</td>
</tr>
<tr>
<td>Amaranth</td>
<td>4.9</td>
<td>4.9</td>
<td>417</td>
</tr>
</tbody>
</table>

**TABLE 2.1**

The effect of continuous CO₂ enrichment to 680 ppmv during vegetative growth of the C₄ species Zea mays, Sorghum bicolor, and Amaranthus edulis on the efficiency of conversion of intercepted radiation to plant dry matter (E), leaf area and root/shoot ratio (Morison and Gifford, 1984)

Although plant dry matter and crop yields are reported to increase with increasing atmospheric CO₂, little effect by CO₂ is found on percentage dry weight, i.e. on the relative amount of water and solutes in the plant tissue (Idso et al., 1988). In some instances, however, especially for lucerne, faba bean and poplar (Goudriaan and de Ruiter, 1983) and for cotton (Idso et al., 1988), higher CO₂ levels have led to starch accumulation in leaves.

In poplar, Goudriaan and de Ruiter (1983) found stronger root growth under high CO₂ concentrations, probably associated with reduced nutrient supply to the leaves, resulting in an increased leaf abscission.

Tolbert and Zelitch (1983) have indicated that high CO₂ concentrations may prolong the photosynthetically active period of leaves, thus delaying senescence. This may not necessarily lead to higher productivity, since the growth cycle of annual crops may be extended into an unfavourable season or the fruit development may be interfered with.

Sionit et al. (1981) report that increased CO₂ is associated with some acceleration of flowering in wheat, and Goudriaan and de Ruiter (1983) found a doubling of CO₂ accelerated flowering in faba bean, wheat and lucerne by two or three days. No effect was seen on maize, but a slowing effect was observed in sorghum without a change in dry weight growth (Marc and Gifford, 1984). This retardation was related to the pace of subsequent development of the floral apex rather than to floral initiation.

Other anatomical adaption to rising CO₂ may also appear. Recently Woodward (1987) reported a 40 per cent decrease in the frequency of stomata in the leaves of eight temperate arboreal species from the preindustrial time to the present. During this time, a period of about 200 years, the CO₂ concentration has increased globally by about 60 ppmv. This response was repeated experimentally in a growth room. No increase in stomatal number was, however, detected when CO₂ was raised further from present day levels. Implications of this response, for example to plant water use or regional evapotranspiration, are not yet clear (Gifford, 1988).

2.1.1.2

Interaction with other environmental factors

Most of the studies of the direct influences of CO₂ on plants have been carried out in controlled environments without the natural variation of and species competition for light, water and nutrients. Even under a shortage of these necessary elements, the response of plants to elevated CO₂ has been positive, but relatively less than under optimal conditions. As an exception, under water-limited conditions, the relative enhancement of growth has been even greater compared with the corresponding increase in optimal growth.

2.1.1.2.1

Moisture

Both C₃ and C₄ species respond to rising CO₂ in such a way that the ratio of CO₂ taken up in photosynthesis to the water lost in transpiration, or the so called water use efficiency (WUE) increases. WUE may also be defined as the ratio of biomass gained to the amount of water lost over a period of time (Pearcy and Björkman, 1983).
In C₃ species, the response of net photosynthetic CO₂ uptake to higher CO₂ is based both on photosynthetic and stomatal effects, but for C₄ species mainly on stomatal regulation. For example, with a doubling of CO₂, photosynthesis in two C₃ species (Nerium Oleander and Gossypium Hirsutum) was stimulated by 50 per cent and stomatal conductance reduced by 22 per cent (Dowton et al., 1980).

In another similar experiment for maize (C₄ species), photosynthesis was stimulated by 23 per cent but stomatal conductance was reduced by 33 per cent (Wong, 1979). For both experiments WUE nearly doubled but because of the greater stomatal response the C₄ species became more competitive with respect to water.

Predictions based on responses to increased CO₂ at single leaf and plant level indicate that in arid- and semi-arid regions where water available for plants is already restricted, increases in CO₂ concentration, under an otherwise constant environment, should lead to improvements in productivity (Pearcy and Björkman, 1983; Penning de Vries et al., 1987).

According to growth room experiments, the doubling of atmospheric CO₂ will reduce stomatal aperture of most agricultural plants by about 40 per cent, and thereby the water use efficiency of these plants will be increased (with both C₃ and C₄ species) (Morison, 1987). However, transpiration from most agricultural plants is not expected to decrease correspondingly. There are at least two reasons for this: first, agricultural plant stands are aerodynamically rather smooth and most crops have relatively large leaves, which means that the boundary layer around stomata is relatively well developed. As the water vapour diffusion through stomata is initially decreased there is less evaporative cooling and the air is dryer around the leaves, resulting in increased potential for evaporation. In other words, for plants exhibiting a relatively thick boundary layer, the driving force behind transpiration, namely the vapour pressure difference between the leaf and the air, will become stronger with the response of plants to higher CO₂ of partially closing their stomata. Second, as mentioned above, plants tend to increase their leaf area under CO₂ enriched conditions.

When considering the possible combined impacts of rising CO₂ and associated climate warming on photosynthesis, two opposing effects are involved. Higher CO₂ stimulates photosynthesis in C₃ plants, but higher temperatures result in higher dissolved oxygen compared with CO₂ and thus favour photorespiration over primary photosynthesis (Tolbert and Zelitch, 1983). On the other hand, at elevated CO₂ concentrations the inhibition of photosynthesis by photorespiration is reduced (Ku et al., 1977). In C₃ species the overall response of CO₂ uptake to increasing CO₂ in C₃ species is least at low temperatures, and increases continuously towards higher temperatures (Pearcy and Björkman, 1983) (see Figure 2.1).

C₄ species lack the inhibition of net CO₂ uptake by photorespiration, and photosynthetic rates and temperature optima are higher than those of C₃ plants at

![Figure 2.1](image_url)

The effect of temperature on the ratio of CO₂ uptake at 300 ppm to that at 1000 ppm in Larrea divaricata (C₃) and Atriplex glabriscula (C₃) (Aifer Berry and Raison, 1981)
normal CO₂ concentrations. Because photosynthesis in C₃ plants benefits from elevated CO₂, the temperature response curves of maximum photosynthesis at elevated CO₂ conditions for both C₃ and C₄ species become more similar (see Figure 2.2).

For a doubling of CO₂ the optimum temperature for photosynthesis increases in general by about 4–6°C (Acock and Allen, 1985). These results suggest that C₃ species could, under otherwise optimal conditions, improve their competition with C₄ species in warm climates when atmospheric CO₂ is increased. Long-term experiments under conditions of transient changes in temperature and CO₂ are still needed to confirm this conclusion.

Low-light intensity does not prevent the positive effect of increased CO₂ on plant growth and yield (Warrick et al., 1986). The relative enhancement of wheat growth has been even greater in light-limiting conditions than at high light intensities (Gifford, 1979). However, the maximum absolute increase in photosynthesis occurs at light intensities that are saturating for photosynthesis (Pearcy and Björkman, 1983).

![Figure 2.2](image)

2.1.1.2.3 Nutrients

Under conditions of nitrogen deficiency, enhancement of growth due to CO₂ enrichment has been detected with perennial rye grass, wheat and soybean (Sionit et al., 1983; Goudriaan and de Ruiter, 1983). Goudriaan and de Ruiter (1983) found no response under phosphorus deficiency.

Despite the fact that in general the utilization efficiency of nutrients is improved with increasing CO₂ in the air (Warrick et al., 1986), it is still likely that rates of fertilizer application will need to be increased to take full advantage of a future CO₂ enriched-atmosphere. Nodulated legumes such as soybeans or peas are an exception, since with these plants high CO₂ leads to greater biological nitrogen fixation (Penning de Vries et al., 1987) so that legumes may become more important in the future especially if the cost of fertilizer is high (Baker and Enroch, 1983).

More experimental work is required to quantify the interactions between high CO₂ levels, assimilation rate and nutrient stress. Under field conditions, where
CHAPTER 2

nutrient supply is often limiting, the direct effect of CO₂ and temperature may be small but the indirect effect of increased CO₂ through improved water use efficiency may be positive and stabilizing.

2.1.3 Suggested future research

To be able to predict how plants in conditions of high CO₂ will react to field environments with stresses varying in type, intensity and timing throughout the season, we need more information on the mechanisms that control organ initiation and abortion, and dry matter partitioning. We also need to know the minimum mineral nutrition requirements for organ growth. This and other information about plant processes can be assembled and synthesized in the form of dynamic simulation models to evaluate the cumulative effects of an enriched CO₂ atmosphere on the whole of plant growth and development (Baker and Enoch, 1983).

These models, which should contain enough detail to analyze plant responses through several life cycles, should be used to critically analyze the effects of CO₂ on plant establishment, growth, reproduction and survival. Long-term studies in representative ecosystems are required to validate the models and detect possible CO₂ effects on plant communities.

2.1.2 LIGHT

2.1.2.1 Leaf photosynthesis

The rate at which green plants grow is limited by the rate at which they can assimilate CO₂ from the atmosphere for reduction to carbohydrate. All the external energy needed for this process is supplied by light which is absorbed by molecules of the pigment chlorophyll. As far as weather is concerned, the photosynthesis rate of a leaf can be limited either by irradiance, or by CO₂ concentration, or a combination of these factors.

In a very weak light the photosynthesis is strictly proportional to the irradiance. However, above a certain irradiance there is no increase in photosynthetic rate. This maximum photosynthetic rate depends on the type of leaf and the stage of crop development. Monteith (1981) noted that the maximum photosynthetic rates of flag leaves of wheat are attained with irradiance of 190 W m⁻², about a quarter of the maximum irradiance from bright sunlight in midsummer in England.

2.1.2.2 Crop photosynthesis

Because in most crop canopies, leaves are arranged in some systematic way, sunlight attenuates as it passes down through the foliage. The mean irradiance then usually decreases exponentially from the top of the crop canopy. When the crop canopy is dense enough to absorb all incident light, crop photosynthesis is at a maximum which will be determined by the amount of irradiance intercepted over the day. The amount of crop photosynthesis is then a function of irradiance intercepted by the leaves over the entire growing season.

2.1.2.3 Photosynthetically active radiation

The plant responds to photosynthetically active radiation (PAR) which is approximately 50 per cent of the visible spectrum. Thus the amount of PAR intercepted by a crop over its life or annual cycle ultimately determines the yield. The balance of PAR in daylight does change with cloudiness. Measurements by McCree (1967) show that the proportion of PAR increased from 48 per cent in clear sky conditions to 65 per cent with increased cloud. This increase is caused by the absorption of infrared radiation by water vapour. The highest PAR proportions occur at the lowest irradiance levels.

With climate trends and variability, the changes in light and how they affect particularly growth rates and yields will be dependent on changes in cloudiness amounts. With clearer skies, there is more irradiance but the proportion of PAR drops. The increase in PAR then will be slightly below the percentage increase in irradiance. Cloudier skies will give a decrease in irradiance but the accompanying decrease in PAR will be less than the percentage decrease in irradiance.

2.1.3 TEMPERATURE

Temperature is a primary climatic factor influencing the distribution of natural vegetation and setting latitudinal and altitudinal limits to agriculture. Within a certain crop range, air and soil temperatures have a major role in determining the rate of development of plants through their various stages from sowing to maturity. Temperature also directly influences the rates of such metabolic processes as
photosynthesis and dark respiration which contribute to growth. The thermal regimes outside the growing season are also important since many plants need to experience a period of cool temperatures for the stimulation of seed germination and flowering.

The effects of temperature on plant biology are basically distinguished at three levels (Berry and Raison, 1981):

1. The level of molecular reactions, which affect the chemical structure of substances and the rate of chemical transformations;
2. The level of physiological processes such as photosynthesis and respiration, which are much more complicated than the pure chemical reactions because of the thermodynamic characteristics of proteins and membranes;
3. The level of the ecosystem where the selection of species and varieties is set by the local climate constraints.

The temperature dependence of many of the chemical and metabolic processes is rather well established; however, the overall effect of temperature on plants is complex, because plants have the capability of acclimating to new thermal regimes at the level of physiological processes. Temperature also affects these processes indirectly via other environmental factors. For example, temperature regulates such processes as the water and nutrient uptake by roots, the atmospheric demand for evapotranspiration, and the plant's response to rising atmospheric CO₂. At the ecosystem level, species competition and distribution of diseases and pests are also strongly affected by temperature. Because of the complications, the temperature responses of plants are often analysed by experiment, and the results are specific both for the crops studied and the environment in which they were grown.

Here the principles of the various direct effects of temperature on crops, mainly at the level of physiological processes, are discussed.

### 2.1.3.1 Plant development

Plant development, or the rate of successive appearance of individual vegetative and reproductive plant organs, is possible above a threshold (or base) temperature which for most cool temperate crop plants is found between 0 and 4°C, and for tropical plants near 10°C. The development rate increases with increasing temperature up to about 20–25°C for temperate crops. Beyond this optimum temperature, enzyme denaturation becomes so strong that development rates are reduced. The upper temperature limit for the development of temperate crops is near 35°C. For species grown in warm and hot climates, the optimum and maximum temperatures are about 10°C higher (Monteith, 1981).

Plant development is also dependent on day length, although the intensity of the daylight (irradiance) is of minor importance (Keulen and Seligman, 1987). A slight shortage of water may accelerate development, but a major shortage will slow down both growth and development (Monteith, 1981). Development may also be slowed by low nutrient level in the soil, or when there is competition for space.

Experimental data for most species suggest a linear relationship between the rate of development (expressed in units of day⁻¹) and temperature (Angus et al., 1981; Keulen and Seligman, 1987) (see Figure 2.3 for wheat). For these crops the concept of effective temperature sum, or ETS, can be used to describe processes such as germination, leaf initiation, organ expansion, vegetative development or grain filling. Data for crop development and cumulative temperature are obtained relatively easily, and methods for simulating crop development by using cumulative temperature sums are applied widely (Robertson, 1983). Such models have proved to be fairly reliable for a given variety, and deviations from observed values have coefficients of variation ranging from 4–9 per cent (Nuttson, 1955).

As a caution, the cumulative temperature requirements of crops for different stages of development are crop and variety specific, and may vary depending on soil fertility level, plant population density, photoperiod, soil type and its water-holding characteristics (Eide, 1977). In assessing climate impacts on crop development it is thus important to take note of the crop variety used and the conditions under which the cumulative temperatures were obtained. Error may also be introduced when estimating early plant development rates, because temperature near the soil surface may differ significantly from the screen level temperature normally used to calculate ETS. In addition, some plants may begin development but then be retarded by a
Figure 2.3
The relation between temperature and development of spring wheat in the (a) pre-anthesis phase and (b) post-anthesis phase according to various sources (from Keulen and Seligman, 1987)

cool period before resuming development again. ETS operates only in one direction, ignoring these types of feedback effects, and thus errors may be introduced in estimates of development.

It is important to make distinction between determinate and indeterminate crops in the discussion of temperature effects on plants. Determinate crops (such as cereals) develop according to prescribed phenological stages, whereas indeterminate crops (such as root crops like potatoes, sugar beet and grasses) have no such restrictions and continue to grow throughout the growing season.

2.1.3.1.1 Germination

The prime requisite for the seed to break its dormant state is availability of water. Given sufficient moisture, the time between sowing and the emergence of arable crops is predominantly dependent on temperature. Too low or too high a temperature may adversely affect seed germination, resulting in leakage of endogenous sugars and amino acids out of the seed (Berry and Raison, 1981) and depletion of the reserves available for subsequent growth. Leakage of solutes may also lead to a fungal attack on the seed (Simon, 1974).

Another common prerequisite for germination is a period of cold temperatures, usually in the range 0–5°C, experienced for some months before germination. This process, called stratification, is common in temperate latitude species. In other plants, particularly those of arid regions, germination is initiated by a period of wet weather when the seeds are flooded with water.

2.1.3.1.2 Flowering

Initiation of floral buds can be triggered by many different environmental signals depending on plant species; of these, the most important ones are temperature and changes in photoperiod. Many autumn sown crops, such as rye and winter wheat, and many temperate zone perennial species require a period of cool or cold temperatures before they can flower, a process called vernalization. Chilling requirements have been determined particularly for horticultural crops. For example, in New Zealand, kiwi fruit require about 600 chill units (a chill unit, CU, equals one hour’s exposure at 7°C) for successful flower bud initiation. Apples require about 1200 CU, peaches from 900 to 1500, depending on variety, and blackcurrants 2000 CU. Salinger (1988) calculated that a warming of climate by about 2°C in New Zealand would shift the climate boundary (in terms of growing season length
and chilling requirement) of potential horticultural crops such as kiwi fruit and wine grapes approximately 4° latitude poleward.

Extreme temperatures can affect the components of sex expression of flowers. In general, high temperatures within the range of normal growth promote maleness, while low temperatures favour femaleness. Most examples have been reported on tropical species exposed for short periods to chilling temperatures (Berry and Raison, 1981). For example, if the floral differentiation of dwarf Cavendish bananas occurs at temperatures below 12°C, the female flowers lack one or more carpellary leaves, and the resulting fruit is unacceptable on the commercial market. The flowers of peppers may be injured when exposed to chilling temperatures below 8°C. Adversely high temperatures coinciding with a dry period during early summer have been found to cause malformation of anthers and pistils in barley.

Temperatures well below the optimum (about 15–19°C) at the meiotic stage of pollen mother cells cause sterility in rice (Yoshida, 1972). Low temperatures can, on the other hand, be favourable for the formation of yield. Controlled environment studies have indicated that relatively low temperatures have increased the size of inflorescence, number of spikelets, number of florets per spikelet and grain yield of perennial rye grass, wheat, and barley (Yoshida, 1972).

2.1.3.1.3 Development periods

As noted above, warm temperatures within the range where development can occur accelerate development, while cool temperatures lengthen the time that a plant needs to proceed from one stage to another. Accelerated development tends to be beneficial for crop plants during germination and early vegetative growth, when plants need to increase their leaf area quickly for light interception, and when the uncovered soil is subject to drying directly by evaporation (Monteith, 1981). Generally, however, slow development is favourable for the formation of yield, provided the growing season is long enough to allow the grains or fruit to mature. In cereal crops, for example, low temperatures favour the duration of tillering. This is prolonged as other powerful sinks for the translocation of assimilates develop slowly (Keulen and Seligman, 1987).

Low temperatures also favour the formation of yield during the post-anthesis phase, provided environmental factors are otherwise suitable. For example, the effect of temperature on the overall maturation time of spring wheat in the Saskatchewan area in Canada (Williams et al., 1988) is as follows: decreasing temperature (relative to the 1951–80 average) increased the length of time needed to reach maturation by about 5–6 days/°C. On the other hand, an incremental increase in temperature by 1, 2 or 3°C reduced the time of maturation on average by four, seven or nine days respectively. Increasing temperature had the tendency to reduce both the interannual and regional variation of the maturation time of crops. For an incremental increase of temperature by 1, 2 or 3°C, the average regional variation of spring wheat maturation in Saskatchewan dropped by nine, six or five days respectively. On the other hand, for a decrease in temperature the regional variation increased.

2.1.3.1.4 Overwintering

Temperature effects on wintering crops outside the growing season are pronounced in climates where a considerable period (several months) of snow cover exists, but the daily temperature frequently fluctuates above and below zero. Depending on snow cover, winter temperatures may have direct and indirect impacts on the productivity of many wintering crops. During snow-free periods, severe cold can directly kill the plants. When snow covers the ground, a thaw followed by sub-zero temperatures may cause formation of an ice layer at the ground surface. A persisting ice crust for about two to three months in late winter can cause damage or total kill to wintering grasses and cereals (Berghorsson et al., 1988; Kettunen et al., 1988).

Berghorsson et al. (1988) report a dominant role of winter temperatures over summer temperatures on hay growth in Iceland. Varying degrees of winter damage or total kill of grasses frequently occur due to the direct and indirect effects of winter temperatures mentioned above. In this way it is possible to predict summer hay yield in Iceland in the early spring on the basis of winter temperature alone, provided the level of fertilizer application is known.
In cold climates, snow usually protects crops from extreme cold and prevents the soil from freezing to great depths. In some years much snow early in the season may leave soil unfrozen, allowing low temperature parasitic fungi to grow under the snow and to kill the overwintering plants (Kettunen et al., 1988). In the then Leningrad region more than 10 percent of the winter rye sown has been lost in some years because of rotting of the crop under the snow (Pitovranov et al., 1988).

2.1.3.2 Growth

A distinction must be made between plant development and plant growth. Plant growth is the accumulation of photosynthetic products into plant structural matter, and is expressed in terms of an increase in dry weight of the plant or as an increase in size of individual plant organs. Temperature is an important factor affecting the capacity of growing points to generate new growth, but a more limiting factor is the availability of substrates for growing cells (Berry and Raison, 1981).

The dependence of growth on temperature is characterized by a bell-shaped curve with specific minimum, optimum and maximum temperatures (Figure 2.4). At the lowest temperatures permitting growth, temperature limitation is very strong; for example, observed Q10 values of 10 have been detected for the primary leaf of barley (Smillie, 1976). At temperatures near the optimum, light growth rate is not strongly dependent on temperature (Q10 is less than 1.5), but when temperatures increase beyond the optimum, growth rates fall very steeply up to the maximum temperature where growth stops.

Growth is the end result of many parallel and channeled physiological processes which individually respond to temperature. Of these processes, the responses to temperature of photosynthesis, respiration and translocation of assimilates are discussed here in some detail.

Figure 2.4 (left)
An idealized relationship between plant growth rate and temperature

Figure 2.5 (right)
Light response curves of CO₂ assimilation of maize leaves measured at different temperatures

2.1.3.2.1 Photosynthesis

The light response curves of photosynthesis generally show a truncation which is related to ambient temperature: the light intensity to saturate CO₂ uptake is lower at low temperatures than at higher temperatures (Figure 2.5). The quantum yield, which is the slope of the light response curve at light limiting intensities, is unaffected by temperature in C₄ species, but with C₃ species it is somewhat reduced as temperature increases (see Figure 2.6). The temperature dependence of the quantum yield is attributed to a stimulation of photorespiration by increasing temperature (Ehleringer and Björkman, 1977).

Typical response curves of maximum photosynthesis rate with temperature are shown in Figure 2.7A, for light intensities sufficiently high to saturate CO₂ uptake at all temperatures. In Figure 2.7B, the light response curves of photosynthesis are compared between plants, grouped according to their optimum temperature range. A sensitive index of the thermal response of photosynthesis is the temperature optimum seen on these curves. Species adapted to warm climates such as corn, sorghum, cotton and soybeans exhibit higher temperature optima for photosynthesis than species adapted to cool climates such as potatoes, crop cereals and peas. Correspondingly, C₄
Figure 2.6
The effect of temperature on one quantum yield for light limited photosynthesis by leaves of C₃ and C₄ plants (From Berry and Raison, 1981)

Figure 2.7
Typical response curves of leaf photosynthesis: (A) temperature dependence of the maximum photosynthesis rate; (B) light response curves of photosynthesis of plant groups I, II, III and IV pm = maximum leaf photosynthesis rate at light saturation (for explanation of groups see Table 2.2)

species generally have higher temperature optima than C₃ species. The latter difference in particular is attributed to the existence of a stimulatory effect of temperature on photosynthesis and a consequential inhibition of photosynthesis in C₃ species. Observations of the sensitivity of temperature optima for many species indicate a change of about 1°C for each 3°C change in the growth temperature, indicating only a partial compensation for changes in the growth temperature (Berry and Björkman, 1980).

Monette (1981) has estimated that for plant leaves of temperate crop species at light saturation, the maximum photosynthetic rate may increase by a few percent per °C. This estimate assumed that the maximum photosynthetic rate is approximately inversely proportional to the leaf mesophyll resistance at full sunlight and that the mesophyll resistance will decrease somewhat with increasing temperature. An increase in temperature from 14°C to 15°C would increase the

<table>
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<th>TABLE 2.2</th>
<th>A tentative classification of plants according to their optimum temperature range</th>
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<td>Group photos</td>
<td>I C₃ low</td>
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<tr>
<td>wheat</td>
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<td>potato</td>
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<td>5–30°C</td>
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maximum photosynthetic rate by 7 per cent, equivalent to a maximum increase in the daily assimilation of carbohydrates of about 2 per cent. Under low temperature conditions, however, the relative sensitivity is much greater. For example, the corresponding maximum increase of assimilation is about 7 per cent when the temperature is raised from 4–5°C.

2.1.3.2.2 Respiration

Dark respiration rates are reported to increase almost exponentially with increasing temperature. It is suspected that only the maintenance part of dark respiration in higher plants contributes markedly to this dependence, and that the major part of respiration, associated with growth, is independent of temperature. The Q10 value for maintenance respiration is near 2.

The capacity of respiration, the temperature optimum for respiration and the temperature tolerance for respiration in general seem to be related to the thermal environment in which plants are grown. Relatively large differences in these characteristics may occur within plants of the same species adapted or acclimated to contrasting temperatures (Berry and Raison, 1981).

2.1.3.2.3 Translocation of carbohydrates and nutrients

Many experiments have shown that translocation of carbohydrate and inorganic nutrients is dependent on temperature (Yoshida, 1972). In general, the rate of translocation is similar to that for the change in viscosity of phloem exudate (Giaquinta and Geiger, 1973). With many tropical species a sharp decrease in the rate of translocation is observed at about 10°C, while temperate species are usually unaffected or become inhibited only at temperatures near 0°C (Giaquinta and Geiger, 1973). The rate of transfer of nitrogen from the leaves to the grain and the uptake rate of nitrogen by the seeds is dependent on temperature with a Q10 value around 2 (Vos, 1981).

2.1.3.3 Exposure to cold

Herbaceous plants, in contrast to woody perennials, do not develop a true dormancy during the autumn, and their tissues maintain a growth capability throughout the winter season. Non-acclimated herbaceous plants can tolerate only a few degrees of frost, but in species capable of acclimation above ground, tissues hardened to cold can survive -30 to -35°C.

Hardening to cold occurs when a plant is exposed for a period of time to cool temperatures. Kacperska (1985) described a three stage process based on experiments with winter rape. Low temperatures of about 2–5°C induce the first stage, during which plants are hardened to temperatures just below the initial low temperature. The occurrence of temperatures a few degrees below zero triggers a second stage for the development of maximum frost tolerance. The third phase depends on the occurrence of prolonged frosts which induce dehydration of cells.

Similar patterns of hardening with successive non-freezing and sub-freezing conditions have been detected with alfalfa, red clover, sweet clover, cabbage and winter wheat (Kacperska, 1985).

2.1.3.4 Soil temperature

The temperature of the soil medium is known to affect the uptake of water by the plant root system. Two processes are involved. The conductance of roots may change, due to the change in structure of cell membranes with temperature. On the other hand, increasing temperature decreases the viscosity of water, thus improving the availability of water for the roots. Kuiper (1964) has shown for beans that with temperatures below 15°C both of these effects are important, with a Q10 value of about 4. For temperatures above 15°C only the effect of viscosity is important.

In severe winter climates, snow cover usually protects the soil from freezing down to temperatures that are detrimental to overwintering plants. However, in some years exceptionally low soil temperatures of around -11 to -13°C at the rooting depth have caused damage to winter rye (Pitovranov et al., 1988).

The soil surface temperature is strongly dependent on the vegetation cover and moisture in the uppermost soil layer. Dry soil and sparse vegetation result in higher soil surface temperatures and enhanced heating of the air during the daytime, and lower temperatures during the night-time. More extreme microclimates are expected to form in areas where the vegetation cover is removed.
The interaction of soil temperature and nutrient supply may in extreme cases affect the root-to-shoot biomass of plants (Berry and Raison, 1981). When the nutrient status is high, the root system is rather insensitive to temperature. However, in regions with lower nutrient availability and lower temperatures, root-to-shoot ratios tend to be higher. Subtropical plants may have a minimum root-to-shoot ratio at around 35°C, while for temperate plants Davidson (1969) has proposed an optimum temperature in the range 20–30°C at which the ratio is at its minimum.

2.1.3.5 Implications for crop yields

To summarize the numerous studies that have attempted to relate temperature to yields, generally higher temperatures increase growth rate but decrease growth duration. Yoshida (1972) has noted that since overall growth is the product of growth rate and growth duration, and since growth duration is more affected by temperature than growth rate, above normal temperatures during plant development usually result in decreased yields. This effect is well demonstrated by the yield data for wheat and barley in England compiled by Monteith (1981). The annual yields of spring wheat and barley were regressed with the May–August mean temperature with a temperature coefficient of about -6 per cent K⁻¹ at 14°C for both crops. Similar coefficients were also found by Bryson (1978) for cereal crops in the United States.

Also Williams et al. (1988) and Pitovranov et al. (1988) have reported that a relatively cool season in mid-continental climates in Saskatchewan and in the Volgograd region of the then USSR (approximately 50°N) coincide with high yields while, on the other hand, above normal temperatures coincide with low yields. In these more continental mid-latitude climates, however, it is likely that the temperature effect on yields is due to the coupling of moisture availability and growing season temperature rather than merely the temperature effect on the duration of growth. High temperatures usually coincide with dry weather, high transpiration demand and moisture stress, while cool temperatures coincide with moist weather and low transpiration demand.

Increased growth rates may in some drought prone regions promote higher yields. In the rainy season in the dry tropical regions of India, temperature increases led to decreased yield through drought stress, but in the short, post-rainy season, increased temperatures promoted enhanced yields. This was because increased growth rates limited the crop’s exposure to detrimental moisture deficits.

In the high latitude marginal zone, agricultural production in many locations is limited predominantly by low temperature and associated short growing season. For example, spring wheat yields in the Perm region of the former USSR (approximately 60°N) are reduced by below average temperatures (Pitovranov et al., 1988). Higher yields and better grain quality during relatively warm seasons are, in the cold marginal regions, explained, at least partly, by the accelerated development of crops which allows larger portions of the sown area to be safely harvested.

2.1.4 Effects of moisture

The supply of water for plants is a key environmental factor regulating crop yields and the success of agriculture in most parts of the world. A shortage of water can in some locations be overcome by irrigation, but large agricultural regions will remain under the climatic control of soil water availability through precipitation and evaporation.

This control is strongest in the low latitude and temperate zones, where the timing of agricultural operations is set by the seasonal distribution of precipitation rather than by the seasonal temperature cycle. Where high evaporative demand in the summer is poorly compensated by precipitation and where winters are not too cold, as in the Mediterranean region, the winter rainfall maximum can be exploited to cultivate crops that can be harvested in the spring.

A warming of the winter climate may open up possibilities, for example, in the bringing into cultivation of overwintering cereals. This has already been demonstrated in the globally important wheat production areas of the Canadian province of Saskatchewan, where, during the 1980s, winters have been sufficiently mild to allow cultivation of winter wheat instead of spring wheat (Williams et al., 1988).

Of great concern are the consequences of the possible increasing compositions of radiatively active greenhouse gases on agricultural production in the
CHAPTER 2

world’s main grain production regions in the North American midwest and central Russian Federation. Any increase in evaporation demand connected with the proposed increases in temperature, changes in rainfall variability or decrease in precipitation would lead to a large reduction in crop yields and have far reaching consequences on global food markets.

Examples from the past, such as the dust bowl era of the 1930s in the North American midwest, serve as an indicative reminder of the power that climate has through its control of available water.

2.1.4.1
Responses at plant level

2.1.4.1.1
Plant water use and stomatal conductance

The major moisture perturbations affecting water use by plants are changes in ambient air humidity or changes in availability of soil water for plant roots (Schulze et al., 1987). Dry air or drought in the soil both cause stomatal closure and hence some reduction in leaf transpiration, but the nature of these two responses is quite different, as outlined below.

Signals transmitting the message of moisture availability appear as changes in the epidermal turgor pressure in the leaf tissue and as hormones, such as cytokinin and abscisic acid, sent by the root tips directly to the stomatal guard cell. Other hormones transported from the roots or synthesized in the leaves, such as auxins (Davies and Mansfield, 1987), may also be involved.

The response of stomatal closure to an increase in evaporational demand, with ample water supply from the soil, is found to be reversible (Schulze et al., 1987), i.e. plants are able to recover quickly from stress induced by atmospheric humidity. The stomata will also close as the soil dries. Dry soil causes a reduction in the speed of water flow through the xylem cells, and as a consequence some turgor is lost and recovery from drought is relatively slow.

2.1.4.1.2
Growth and development

The shortage of water for growth and development is first manifested in a partial closure of stomatal pores and loss of leaf water potential, which results in a slowing of cell division and expansion. A growing cell must maintain a high turgor potential to force an immature cell wall to stretch out and expand. Under limiting soil water conditions, leaf area development is therefore slowed down. When the soil moisture deficit rises above a critical level, which is dependent on the plant's rooting depth and the soil's physical characteristics, plant growth ceases totally and green leaves wilt. A prolonged drought will finally result in a senescence and dropping of leaves. All these responses are plant ration strategies to minimize water use.

2.1.4.2
Prospects for regional productivity

2.1.4.2.1
Effect of moisture on trends in productivity

Despite the advances in technology which have led to significant increases in crop yields, water availability is the main climatic factor affecting crop productivity in arid and semi-arid regions.

Based on a global analysis of wheat yields with ten years of data, a slowing down of wheat yield growth occurred particularly in regions where production is controlled by water supply. The decreasing positive trend of wheat yields was typical for regions of rainfed agriculture where annual potential evapotranspiration exceeded annual precipitation by an amount of 200 mm or more. Of the globally important wheat producing areas, those found exhibiting a negative contribution of climate technology interaction into wheat yield growth were the Canadian and American prairies, the south eastern portion steppe of the Russian Federation and the Australian subhumid regions, regardless of their apparent differences in absolute amount of annual precipitation or soil fertility.

2.1.4.2.2
Effect of rainfall variability

Water resources for crop production are often analysed in terms of the annual and seasonal frequency distributions of precipitation. Changes in these distributions induced by changes in climate could significantly alter agricultural practice in terms of the need for irrigation and the timing of crop cultivation. Since climatic precipitation patterns vary greatly even on a local scale, it has been very difficult to give realistic assessments for possible future changes induced by an increase of radiatively active gases in the atmosphere. Most analyses so far are based mainly on the sensitivity of agroecosystems to scenario-type perturbations in rainfall time distributions.
An analysis by Salinger (1988) applied rainfall anomalies of 10 per cent from the baseline in a temperate latitude climate, and performed water balance calculations on the assumption that evapotranspiration rates remained unchanged. Areas that received 10 per cent more precipitation gained 4–15 extra days for plant growth. Conversely, areas that received 10 per cent less rainfall lost 12–17 days because of drought. The corresponding changes in irrigation requirements to compensate for loss in rainwater were 60–70 mm.

The same analysis showed that for regions characterized by high annual and/or seasonal variability, a anomaly in the mean annual rainfall of 5–10 per cent would have a more dramatic impact on the effective growing period than for regions of low variability. Many desert areas, the Mediterranean regions, monsoon and sub-tropical climates have a high amount of annual or seasonal variability of rainfall. In these regions a change in rainfall variability could be more important than a change in the mean amount over the year. As an example, rainfall changes of 80–100 mm are not important with respect to the detected annual or seasonal variability of 300 mm. In regions of less variable rainfall, a change in the seasonal or annual mean precipitation would, however, be more significant in terms of a change in the risk of extreme events such as drought. This is demonstrated, for example, by considering the probability distribution function of rainfall (Wigley, 1985). For England and Wales, with an annual mean rainfall of about 920 mm, a 100 mm reduction (which corresponds to about 0.9 standard deviation of the mean) in precipitation would cause a one in a 100 year drought to occur 7.5 times more frequently and changes in the probability of two successive extremes would be even larger (Wigley, 1985).

2.1.4.3 Modelling the effect of drought on crops

Plants use stomata as a bidirectional pathway for the uptake of CO₂ for photosynthesis and for the release of water vapour as transpiration. In climates where crop production is mainly limited by water availability, crop yields are well correlated with the amount of water actually used by the crops. This finding has opened modelling opportunities for assessing the relationship of climate change and crop production in a fairly straightforward and simple manner using readily available climate data and information about the soil characteristics. Consistent results have been obtained when the crop transpiration is scaled with the mean vapour pressure deficit of the growing season (Bierhuisen and Slatyer, 1965). An example of this approach is shown in Figure 2.8 from Day (1986).

A useful measure of the impact of drought is the time during which plants undergo water stress and therefore slow down their growth. The higher the number of days when plants are exposed to drought, the more time is lost for growth. The formulations such as those by Monteith (1981) can yield useful estimates of the deficits of growth affected predominantly by limitation of soil water availability during the growing period.

Figure 2.8
The relationship between dry matter production and the ratio of water use to mean saturation vapour pressure deficit for several drought treatments in 1976 (o) and 1979 (s) (From Day, 1986)
2.1.5 Wind

Wind affects plant production in two ways: by physical damage because of strong winds and gales, and by its effects on soil moisture because of evapotranspiration.

2.1.5.1 Physical effects

Gale and storm force winds cause mechanical damage to plants which may damage plants to such an extent that plants need to be replaced, or that the present season's crop is uneconomic. Horticultural and arable crops are the most sensitive to wind damage, particularly the former. In regions with frequent strong and gale force winds, such as New Zealand (McAneney et al., 1990), shelter is essential to grow fruit crops. In these areas, any change in both the frequency and direction of strong and gale force winds will affect crop production, unless the shelter is changed to provide effective wind protection.

2.1.5.2 Soil moisture

Wind variation can also affect soil moisture depletion by its effect on evapotranspiration rates. However, this occurs only in areas where the air is not close to saturation for water vapour. Clothier et al. (1982) note that in maritime areas, evapotranspiration is mainly a consequence of net radiation and temperature. In such localities, variations in wind will not affect evapotranspiration, which is a function of the equilibrium evaporation rate of Penman (1948). This term is dominated by net radiation, temperature and saturation vapour pressure.

However, in areas which receive dry winds, Penman's second term (the turbulent transfer of heat and water vapour) becomes important in evapotranspiration. Dry winds are characterized by low relative humidities and high temperatures near the surface, and by wind velocities which sometimes reach great intensity. This causes high potential evapotranspiration leading to disturbances in plant water balance and to a possible damage of plant organs. The harmful action of the dry wind on plants is intensified when wind velocity increases. Potential evapotranspiration rates can reach 8 mm per day in temperate areas with very strong, dry winds. If the soil moisture deficit is low (plant water status is high), leaves will lose their turgor during daylight hours. With high soil moisture deficit (low plant water status), plants wilt when the dry wind commences and do not regain their turgor during the night. When soil moisture is maintained at a high level by irrigation, damage to plants by dry winds does not occur. Any changes in occurrence of dry winds will be most important should the climate change.

2.2 FOREST RESPONSES TO CLIMATE VARIABILITY

by W.T. Sommers

Forest ecosystems are characterized by time scales over which considerable climate variability is known to occur. Therefore, the establishment and evolution of forest ecosystems, their status, and the life cycle of many individual ecosystem components intrinsically represent successful adaptation to local and regional climate and to the variability of that climate. Components of those ecosystems composed mainly of long-lived individuals, trees for example, demonstrate such adaptation in individual members as well as in the overall population. Components of short-lived individual members, such as insects, demonstrate it through population dynamics. While a full representation of forest ecosystem responses to climate variability should include responses of wildlife, vegetation, soils, water, air, pathogens and several other factors and their interactions, it is necessary here to focus on trees as the primary representative component of forest ecosystems and, where necessary, to refer to other components for illustrative purposes.

Disturbance phenomena should also be considered when characterizing forest ecosystem responses to climate variability. While forest ecosystems evolve slowly, major changes occur very rapidly in such catastrophic events as forest fires, insect and disease outbreaks, wind storms (such as hurricanes), and ice storms. When these disturbance phenomena take place, wholesale ecosystem changes occur at the minor catchment to landscape scales in periods ranging from a few hours to a few years. These disturbance events often result after multiple stresses have seriously weakened trees. Climate variability in the form of moisture stress (drought) and temperature
stress (extreme cold or heat at the wrong time) is included in a list of primary stressors. Thus, forest ecosystems respond to climate variability through both long-term stress and disturbance phenomena.

Finally, it should be considered that these responses are most often manifested in those parts of forest ecosystems that are closest to the margins of age and distribution for the particular ecosystem. Put simply, old, decadent tree stands and tree stands growing at the margins of species adaptability are most likely to succumb to stress, pathogen attack, forest fires, and physical damage from wind and ice. This dynamic is important to an understanding of responses to climate variability and to potential climate change. These introductory comments set the context for placing the following subsections on carbon dioxide, light, temperature, wind, and moisture, as well as for the discussion on the examples of climate variability on forestry given in Section 3.1 of this report.

2.2.1 Carbon Dioxide

Metabolism of CO$_2$ is essential to tree ring growth and carbon composes about 50 per cent of the dry weight of trees (Houghton et al., 1983). Various factors lead to a ratio of from 10 to 20 for converting tree volume to carbon content. The atmosphere contains about 700 x 10$^{15}$ g of carbon as CO$_2$, global vegetation about 800 x 10$^{15}$ g of reduced carbon, and soil organic matter between 1000 x 10$^{15}$ g and 3000 x 10$^{15}$ g of carbon. Forests occupy about one third of the area of global terrestrial ecosystems and are estimated to hold 60-90 per cent of the total terrestrial carbon pool (Smith, 1981). Net primary production of carbon from metabolism of atmospheric CO$_2$ is estimated to be of the order of 36 x 10$^{15}$ g/yr. Forest ecosystems are thus dependent on atmospheric CO$_2$ for existence and growth, they are a primary factor in the flux of carbon between the atmosphere and the biosphere, and a principal carbon storage agent in trees and soils.

Carbon dioxide concentration in the atmosphere is about 0.034 per cent. Atmospheric CO$_2$ variability can be summarized as follows. Average global values approach 350 ppmv (parts per million volume). Annual average concentrations at high northern latitudes are about 3-4 ppmv greater than annual average southern hemisphere values. Annual CO$_2$ cycles show a large seasonal variation in the northern hemisphere, which is strongly linked to the seasonality of land-based vegetative processes, with spring maxima and late summer minima. The amplitude of the seasonal signal ranges from 16 ppmv at high northern latitudes to the 0 to 5 ppmv range in equatorial regions. The amplitude of the seasonal signal in mid- to high southern latitudes is 0.5-1.5 ppmv. There is little diurnal variation. The overriding factor in CO$_2$ variation is the change in measured average annual values from the 260-280 ppmv range in the late 19th century to today's values. There is some evidence that the current average difference of 3 ppmv between the northern and southern hemispheres did not exist earlier in this century (Fraser et al., 1986).

Plants, including forest trees, convert atmospheric CO$_2$ to carbon by photosynthesis. Leaves take up CO$_2$ from the atmosphere by gaseous diffusion. Within the leaf, chloroplasts, carbohydrates, amino acids, proteins, and adenosine triphosphate (ATP) are synthesized by photosynthesis. Photosynthesis depends on light and CO$_2$ availability, and is temperature dependent. Inward diffusion of CO$_2$ is closely related to outward diffusion of water vapour. Diffusion of CO$_2$ into a leaf is expressed by Fick's Law,

\[ P = \frac{(C_a-C_c)}{R} \]

where \( P \) is the photosynthetic rate and \( C_a \) and \( C_c \) are the CO$_2$ concentrations in the air and chloroplasts respectively, and \( R \) is the leaf resistance to CO$_2$ diffusion. \( R \) is a function of the leaf boundary layer, stomata, intercellular air spaces, cell walls, and cytoplasm (Gates, 1980). Climate affects photosynthetic rates through ambient CO$_2$ concentration (\( C_a \)), solar radiation, moisture, temperature, and nutrient availability. Metabolic function in the chloroplasts regulates \( C_c \) and conversion of \( C_c \) to transport and conversion to reduced carbon in the woody material of trees. This results in varying degrees of photosynthetic rates for different species, clonal differences in species, and between ecotypes of seedlings (Smith, 1981).
CHAPTER 2

Photosynthetic rates are generally greater for deciduous trees than for conifers on a leaf weight basis, but conifers in turn are photosynthetically active for longer periods, particularly in high latitudes.

Variability of CO₂ does not translate linearly to photosynthetic variability because of associated variability of light, moisture and nutrients, and because of the inherent makeup of the plant material in question. Variability in ambient CO₂ thus leads to varying responses in forest ecosystem components. If that ambient variability were to become large, or if observed changes in ambient CO₂ were to become sufficiently large, competitive advantages would be likely to develop between forest ecosystem components as a response result.

2.2.2 LIGHT

Availability of light is the second major external factor (after CO₂ concentration) that determines photosynthetic rate. On a global scale, light availability is primarily of latitude and secondarily a function of cloud cover. Ecosystem composition in terms of predominant, co-dominant and other species reflects adaptive response to light availability among other environmental factors.

In terms of light variability, the most important responses are associated with microclimatic effects within the forest ecosystem. The forest ecosystem thus becomes internally regulating through the relative availability of light reaching the various leaf surfaces of component members of the ecosystem. A critical stage in forest evolution, from establishment to maturity and decadence, is the point where canopy closure takes place. Canopy closure acts to limit or eliminate growth of subcanopy and forest floor species by limiting light availability. Prior to canopy closure, sufficient light reaches subcanopy trees and the forest floor to allow for sufficient photosynthesis by non-dominant species. The interaction with wildlife is important here since closed canopy forest ecosystems seldom permit enough light to penetrate and adequately support optimal vegetative growth for browsing animals such as deer. Thus, the basic composition of forest ecosystems responds to light variability, but that variability is primarily a microclimatic effect of the forest ecosystem itself, given its latitudinal placement.

2.2.3 TEMPERATURE

Temperature is a main determinant of forest ecosystem placement. A global mapping of average temperatures and ranges of temperature would roughly map forest type distributions. Temperature variability causes forest ecosystem responses through effects on photosynthesis, growth and water loss. These physiological responses, along with other temperature effects such as winter injury damage, produce stresses in trees that can lead to insect and disease attacks, forest fires, and other disturbance phenomena.

Photosynthesis depends on temperature in a manner similar to many chemical reactions (Gates, 1980). Photosynthetic rate increases with temperature to a certain point and then begins to decrease. The maximum rate of photosynthesis, PM, as a function of light, L, and temperature, T, is

\[
P_M(L,T) = \frac{P_{MLT} G(T)}{1 + (K_L/L)}
\]

where \( P_{MLT} \) is the value of PM for optimum temperature, light and CO₂ saturation, \( G(T) \) is a skewed bell-shaped temperature curve, \( L \) is light intensity where photosynthesis is half of that for light and CO₂ saturation. The maximum rate of photosynthesis for a given light intensity, is therefore temperature driven. There is a range of temperatures below which and above which a given plant's photosynthetic rate is negligible. Temperature is thus seen to cause a direct photosynthetic response.

Tree growth responds to temperature variability in various other ways. Cold temperatures tend to produce a more definitive limit to growth than warm temperatures because of the freezing point of water. As with photosynthesis, growth increases with temperature up to a certain optimum and then decreases rapidly. Temperature affects the ability of tree roots to absorb moisture, with very little moisture movement occurring when the soil is frozen. Tree growth responds to temperature variability in different ways according to species. Radial growth of pines
in Finland was affected by growing season temperatures and height growth by previous season temperatures. Spruce growth was more affected by early summer temperatures and pine growth by late summer temperatures.

Forest species damage, dieback and decline have been related to temperature variability. Higher than normal soil temperatures are thought to damage root mycorrhizae that are needed to fix nitrogen for tree growth. Cold damage to trees occurs most frequently in spring and fall, with late spring frosts being cited as the most frequent cause of damage. Temperature variability that causes severe (in magnitude and/or timing) cold can result in damage to tree cells through cavitation. But temperature variability in the form of unusual winter warmth can cause premature bud breakage and consequent damage when colder temperatures return. Frozen soil can combine with wind to result in tree damage by desiccation.

2.2.4 Moisture

Whereas temperature is a main determinant of forest placement, moisture is the main determinant of forest existence. The division between forest and non-forest lands closely follows mean annual precipitation patterns, except in the northern boreal forest ecotone. Moisture in forest ecosystems should be considered in terms of precipitation, evaporation, transpiration and soil moisture. Moisture variability is of major importance in terms of long-term forest health and as it contributes to increased or decreased probability of catastrophic disturbances.

While variability in the form of increased moisture can occasionally cause some disease problems, most negative forest responses to moisture variability arise from moisture deficit situations. Water forms a continuum in trees from the soil, through roots, stems, trunks and leaves to the atmosphere. Water is a vital part of photosynthesis and is needed in the exchange of CO₂ with the atmosphere. Variability in the supply of moisture thus translates very directly into variability in the basic life and growth process of forests.

Water evaporates from the surface of leaves in much the same manner that it evaporates from the surface of a lake or any other flat body of water. Evaporation takes place when there is a differential in water vapour pressure between the atmosphere and the surface, and there is energy available. The energy usually derives from wind and solar radiation. Total heat loss from a surface consists of that lost through convection and that lost as latent heat through evaporation. The ratio between convective and latent heat loss is known as the Bowen ratio. The basic expression for evaporation may be written:

\[ E = (e_s - e_a) f(V) \]

where \( E \) is the evaporation, \( e_s \) and \( e_a \) are the surface and atmospheric water vapour pressures, and \( f(V) \) is a wind speed function (Gates, 1980).

Plant transpiration is a basic function of photosynthesis. Diffusion of atmospheric CO₂ into the chloroplasts of leaves requires the exchange of water vapour to the atmosphere. Water is transported from the soil through tree roots, xylem, mesophyll, stomata and leaf boundary layer to the atmosphere. Considering the variability of precipitation, it is seen that forest soils must act as reservoirs and moisture supply regulators for trees.

As water flows upward through the roots to the atmosphere, it meets internal resistance at all points. The direction of net water movement is determined by the energy status of water in the plant cells. Air inside plant leaves is usually at or near saturation, except under conditions of severe drought, so the atmospheric relative humidity of the air has an enormous effect on the water potential at the atmosphere leaf interface. Variability of atmospheric moisture, as reflected in the relative humidity, and in the longer term by precipitation, thus causes major responses in forest transpiration and photosynthesis.

At larger scales, the variability of moisture results in long-term forest ecosystem responses in terms of tree species, other vegetation, soils, wildlife, and almost all other components. Forest ecosystems range from those which characterize Mediterranean regions where precipitation typically falls in only a few months of the year, to temperate rain forests where precipitation falls throughout the year and is
maintained in rich, thick soils. The Mediterranean ecosystems are characterized by vegetation that limits warm season transpiration and can survive frequent fires. Moist forests on the other hand are able to survive modest droughts through their soil reservoirs but can sustain severe damage when fires move through in response to more severe drought conditions. In sum, forests respond to moisture variability in ways that affect the productivity, health and diversity of almost all ecosystem components, and to a degree much greater than variability in any other atmospheric parameter.

### 2.2.5 Wind

Wind plays a principal role in the life cycle of forest ecosystems. It serves to carry pollen, disperse seeds, transport insects and diseases, drive forest fires, and causes damage through breakage and blowdown. Forest structure interacts with wind to determine wind distribution within a forest and the stress individual trees receive from the wind. Large differences in wind speed profiles relate to canopy structure and density, with higher in-forest wind speeds associated with more open canopies (Fritchen, 1985). Large openings in forests result in stronger winds at the forest edge along the downwind side of the opening. With deciduous forests, the effect of wind varies significantly depending on the presence or absence of leaves.

Many species of forest insects depend on wind within the forest for transport to new host trees. Dispersal of fungi within the forests is heavily dependent on, and related to, wind variability. There are complex dynamic interactions between wind and trees that can add to the damage caused by wind (Ammann, 1985). Wind variability in the form of speed, gusts or directions of a climatologically unusual nature causes vibrational frequencies in trees that can lead to excessive breakage or uprooting. Wind variability in the form of major disturbance phenomena associated with tornadoes, thunderstorm downbursts or cyclonic storms such as hurricanes can cause significant amounts of forest damage and blowdown that are related directly to canopy structure.

Another major category of forest response to wind variability involves the fluxes of heat, momentum, gases and particles between the forest and the atmosphere. These fluxes primarily involve transfers between the atmosphere and forest canopy. Atmospheric concentration of the flux variable, the wind and the roughness of the forest canopy are the three main constituents involved with forest atmosphere fluxes. The flux may be considered to be the product of a depositional velocity and the gradient of concentration of the variable in question. Momentum flux is the most basic example of the response of forests to wind variability, and knowledge of momentum flux forms the basis of other flux calculations. Proper computation of the momentum flux involves measurement of the turbulent wind field in the region of canopy atmosphere interaction. In reality it is extremely difficult to measure that turbulent field, especially in light winds, and we do not have a sound conceptual description of subcanopy flow fields (Hicks, 1985). A great volume of micrometeorological study has gone into determination of atmospheric forest fluxes, and significant progress has been made in determining the parameters for the processes involved. In sum, fluxes of all variables between forests and the atmosphere are enhanced by increased wind variability.

Forest fires represent one of the most critical considerations of the response of forests to wind variability. When catastrophic forest fires occur, in all places in the world, stronger than normal wind conditions are usually present. Forest fires may be affected by ambient wind variability in a small area, or at times be influenced by ambient wind variability over areas of thousands of hectares. Fires often grow large enough for fire-induced convective winds to become a major factor in wind variability. When dry forest conditions, high temperatures, low humidity and ignition sources, such as from lightning, combine with strong and variable winds on a regional scale, fire complexes result. Most historic forest fires worldwide were actually fire complexes where more than one individual fire was involved. Under the most severe wind conditions, large fires can merge with other large fires and result in million hectare conflagrations. Fortunately only a very small percentage (less than 2 per cent) of forest fires ever reach conflagration size (Pyne, 1982). Strong winds can drive forest fires forward at rates of spread approaching 2–3 m/s. In addition, these strong and variable winds can lift burning embers and send them kilometres ahead of the main fire to start new fires, a mechanism known as spotting. These types of catastrophic fires are usually not controlled until the wind decreases or the fire runs out of forest to burn.
2.3 ANIMAL RESPONSES TO CLIMATE VARIABILITY
by S.B.B. O'tengi

Global climatic variabilities and anomalies are determinants in the planning and execution of agricultural activities, including livestock. The period from late 1984 to early 1986 displayed high global climatic variability and significant anomalies in rainfall and temperature parameters (WMO, 1987). Figure 2.9 shows the spatial distribution of patches of wet and dry conditions associated with El Niño—Southern Oscillation (ENSO). An El Niño phase ended early in 1988, to be overtaken by the La Niña phase (see Section 3.5).

![Figure 2.9](image)

Major temperature and precipitation anomalies and events in 1988 (WMO, 1989)

Animal production on a global scale responds to such climatic variability as regional droughts, or floods, associated with phenomena like El Niño (Nicholls, 1985; Wood and Lovett, 1974). These regional phenomena therefore indirectly affect primary production and the type of management decisions needed to plan the use of rangelands.

In the tropics, rainfall can be a limiting factor to production especially in desert-prone regions including arid and semi-arid areas. Here the high variability in rainfall areas affects primary production which in turn influences animal production. In regions with two rainfall peaks, rainfall reliabilities decrease in dry areas and dry seasons (O’tengi, 1982; Ogallo, 1981; Nieuwolt, 1974). In some parts of the tropics, dry seasons may be hot or cool. The hot dry seasons are associated with high daytime temperatures, while low temperatures characterize the cool season.
In the temperate regions, summers are normally hot and winters very cold (Parry et al., 1988), with temperature being the main limiting factor in raising livestock.

In the Sahel, north of the Sahara, and in the Middle East, arid grazing areas have been overused. The perennial grazing vegetation is slowly disappearing. Restoring good vegetation capable of supporting a healthy animal life and better domestic stock is a difficult process. In such areas the aim is to establish edible shrubs with higher production and greater potential than a mere grass sod on which animal life can depend. Hence intensive forage management is necessary. During early stages of establishing such shrubs (especially for browsers) one has to provide the seedlings with protection from harsh environmental conditions. Planting in a pit to provide protection from dust storms and sunstoke is one example (Orev, 1986).

Loss of weight in transhumant animals reduces their market value (Orev, 1986). In Kenya it has been found that after a major drought that might claim some 25 per cent of the herd, the surviving animals develop resistance to major diseases (Kangara, personal communication).

World distribution of livestock reflects frequent weather vagaries, level of development of the owners and their taboos, customs and religions. Most parts of Africa suffer from droughts; nevertheless for 11.5 per cent of the world’s population, Africa has 11 per cent of the world’s cattle population and 17 per cent of the small ruminants (Janke et al., 1987). The developing world which normally experiences the world’s harshest drought conditions is able to support 70 per cent of the world’s small ruminants.

### Table 2.3

The role of small ruminants in agricultural production systems (Peters, 1988)

<table>
<thead>
<tr>
<th>Climatic zone</th>
<th>Land utilization system</th>
<th>Farming system</th>
<th>Animal species</th>
<th>Utilization of small ruminants</th>
<th>Functions of small ruminant farming</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Subsistence function</td>
<td>Asset function</td>
</tr>
<tr>
<td>Arid</td>
<td>Pastoral Range livestock systems</td>
<td>Traditional pastoralism</td>
<td>Camel, goat, sheep</td>
<td>Milk, skins fleece, meat</td>
<td>xxx</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ranching</td>
<td>Sheep, goat, sheep</td>
<td>Wool, pelt</td>
<td>Mohair, skins</td>
</tr>
<tr>
<td>Semi-arid</td>
<td>Pastoral Range livestock systems</td>
<td>Agropastoralism</td>
<td>Cattle, goat, sheep</td>
<td>Meat, milk</td>
<td>skins</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Ranching</td>
<td>Cattle, goat, sheep</td>
<td>Meat, skins</td>
<td>-</td>
</tr>
<tr>
<td>Semi-humid</td>
<td>Crop-livestock production systems</td>
<td>Small holder mixed farming</td>
<td>Cattle, sheep, goat, (cattle)</td>
<td>Meat, milk</td>
<td>x</td>
</tr>
<tr>
<td>Humid</td>
<td>Shifting cultivation</td>
<td>Small holder crop-farming</td>
<td>Cattle, sheep, goat, (cattle)</td>
<td>Meat</td>
<td>(x)</td>
</tr>
<tr>
<td></td>
<td>Permanent crop production systems</td>
<td>Large plantations</td>
<td>Sheep, goat</td>
<td>Meat</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Small holder plantations</td>
<td>Goat, sheep</td>
<td>Meat</td>
<td>-</td>
</tr>
<tr>
<td>Tropical highlands</td>
<td>Crop-livestock production systems</td>
<td>Small holder mixed farming</td>
<td>Cattle, sheep</td>
<td>Meat, wool</td>
<td>(x)</td>
</tr>
<tr>
<td></td>
<td>Range livestock systems</td>
<td>Traditional husbandry</td>
<td>Sheep, goat, camelid</td>
<td>Wool, meat, milk</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Ranching</td>
<td>Sheep</td>
<td>Wool, meat</td>
<td>-</td>
<td>x</td>
</tr>
<tr>
<td>Winter rain areas</td>
<td>Crop-livestock production systems</td>
<td>Small holder mixed farming</td>
<td>Goat, sheep</td>
<td>Milk, meat</td>
<td>skins, fibres</td>
</tr>
<tr>
<td></td>
<td>Range livestock systems</td>
<td>Transhumant husbandry</td>
<td>Sheep, goat, cattle</td>
<td>Milk, meat</td>
<td>skins, fibres</td>
</tr>
<tr>
<td></td>
<td>Ranching</td>
<td>Goat</td>
<td>Mohair</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

1 Extent: x small, xx moderate, xxx large, (x) sporadic
2 Fibre = coarse wool, long hair, mohair.
bovines and buffaloes, providing 29 per cent of the meat and 23 per cent of the milk. The developing countries also have 64 per cent of the small ruminant population and produce 54 per cent of the meat (Janke et al., 1987). India has 27.4 per cent of the sheep, with 20 per cent in Oceania (Peters, 1988). Sheep rearing increased in the Sahel as a result ofbuilding up the herd after the drought of the early 1970s. In East Africa, particularly Somalia and northern Kenya, goats are of increasing importance, with early maturing sheep and goats better able to cope with the sharp seasonal vegetation periodicity. Small ruminants therefore guarantee human survival in adverse environmental conditions.

2.3.1 Direct effects of climatic variability

2.3.1.1 Animal adaptability

Climatic variability and socio-economic circumstances affect the transfer of specialized animal production technologies from developed to developing countries. Exotic breeds lead to neglect of indigenous breeds and feed resources that are highly vulnerable to the tropical weather vagaries and hence high production costs (Preston and Leng, 1987). The introduction of exotic breeds removes the multipurpose nature of traditional livestock systems that include draught power, milk and meat, wool and hides, eggs, money when sold alive, especially following a crop failure, and manure to serve as fuel to be used in the home or sold or bartered or used as fertilizer.

The draught animal has received little attention from researchers, except recently when attempts have been made to define the connection between work and nutrition (Mohamed-Saleem and von Kaufman, 1989).

In drought-prone regions, such as the Sahel, small ruminants are preferable to cattle. They have lower absolute nutrient requirements, a better selective grazing ability (being browsers) and a broader fodder consumption spectrum (Peters, 1988). Their adaptability is connected to body size, reproduction pattern, local pathogens, feed quality and local microclimate.

<table>
<thead>
<tr>
<th>Region</th>
<th>Sheep</th>
<th></th>
<th></th>
<th>Goat</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>abs. (m.)</td>
<td>Change in sheep nos. 1974-84 (%)</td>
<td>% in each region</td>
<td>abs. (m.)</td>
<td>Change in sheep nos. 1974-84 (%)</td>
<td>% in each region</td>
</tr>
<tr>
<td>Europe</td>
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<td>+10.0</td>
<td>12.8</td>
<td>12.5</td>
<td>+8.0</td>
<td>2.7</td>
</tr>
<tr>
<td>Former USSR</td>
<td>145.3</td>
<td>+1.5</td>
<td>12.8</td>
<td>6.5</td>
<td>+11.3</td>
<td>1.4</td>
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<td>12.2</td>
<td>-7.9</td>
<td>7.8</td>
<td>8.8</td>
<td>-9.0</td>
<td>1.9</td>
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<td>7.8</td>
<td>12.5</td>
<td>+10.9</td>
<td>2.7</td>
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<tr>
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<td>84.0</td>
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<td>2.1</td>
<td>11.0</td>
<td>+14.7</td>
<td>2.4</td>
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<tr>
<td>South America (tropical)</td>
<td>23.4</td>
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<td>3.4</td>
<td>11.5</td>
<td>-9.5</td>
<td>2.5</td>
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<tr>
<td>North Africa</td>
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<td>3.6</td>
<td>35.5</td>
<td>+21.3</td>
<td>7.7</td>
</tr>
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<td>Sahel</td>
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<td>3.6</td>
<td>35.5</td>
<td>+21.3</td>
<td>7.7</td>
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<tr>
<td>West/Central Africa</td>
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<td>2.0</td>
<td>36.0</td>
<td>+3.6</td>
<td>7.8</td>
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<td>East Africa</td>
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<td>+13.6</td>
<td>4.1</td>
<td>52.4</td>
<td>+17.2</td>
<td>11.4</td>
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<tr>
<td>Southern Africa</td>
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<td>+3.0</td>
<td>3.6</td>
<td>15.5</td>
<td>+7.3</td>
<td>3.4</td>
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<tr>
<td>Near East</td>
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<td>+19.0</td>
<td>11.8</td>
<td>45.6</td>
<td>+5.2</td>
<td>9.9</td>
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<tr>
<td>Indian Subcontinent</td>
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<td>+4.8</td>
<td>6.2</td>
<td>125.7</td>
<td>+21.9</td>
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<td>China/Mongolia</td>
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<td>72.8</td>
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<td>0.0</td>
<td>0.7</td>
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</tr>
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<td>South-East Asia</td>
<td>4.9</td>
<td>+47.0</td>
<td>0.3</td>
<td>10.4</td>
<td>+13.7</td>
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<td>+2.6</td>
<td>18.3</td>
<td>5.0</td>
<td>28.8</td>
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<tr>
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<td>1139.5</td>
<td>+8.1</td>
<td>100.0</td>
<td>459.6</td>
<td>+10.3</td>
<td>100.0</td>
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<tr>
<td>Developed countries</td>
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<td>+4.8</td>
<td>47.8</td>
<td>26.9</td>
<td>+9.7</td>
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<tr>
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<td>+11.2</td>
<td>52.2</td>
<td>432.7</td>
<td>+10.4</td>
<td>94.1</td>
</tr>
</tbody>
</table>

2.3.1.2 Temperature regulation

(1) Temperature regulation

Animals maintain an optimum body temperature at 37°C. Above 37°C, body muscle is damaged and below it, functions decrease and may cease altogether at very low temperatures. Thermoregulation ensures that body temperature does not vary much from 37°C.

Animals can regulate their body temperature in the following ways:

- Hibernation, e.g. toads;
- Panting, e.g. dogs;
- Sweating, e.g. horses;
- Shivering, e.g. cows;
- Nose leaking, e.g. cows;
CHAPTER 2

- Big ears, e.g. elephants;
- Shedding hair in summer and gaining it in winter, e.g. sheep;
- Passing out very concentrated urine, e.g. camel;
- Passing out faeces with low water content, e.g. camel.

When considering geographical distribution of areas suitable for animal production, temperature is seen as the most important bioclimatic factor, as adverse temperatures result in direct stress to the animal (Preston and Leng, 1987).

(2) Heat stress

Most heat in ruminants is produced through fermentative digestion and by metabolism, especially on diets high in fibres (Preston and Leng, 1987). This is advantageous in cold conditions since it permits cows to live comfortably without extra feed. As ambient temperature approaches body temperature it becomes increasingly difficult for the animal to lose the heat that it produces. However, the dairy animal continues to produce milk by drawing on its body reserves.

In such situations, and in hot dry climates the microclimate can be modified by sprinkling the cows with water and by using shades to keep them cool. Situations such as this are found in the tropics at elevations of 500–1000 m where night temperatures fall to 20°C or less (Preston, 1987).

Cold stress might cause death in neonatal animals (wind chill factor). The wind chill forecasting scheme for lambs, such as the one operated by the UK Meteorological Office and Agricultural and Advisory Service (Strarr, 1981), can save young animals from wind chill stress.

<table>
<thead>
<tr>
<th>Total Region/Country</th>
<th>Thousand heads</th>
<th>Share in</th>
<th>1,000 TLU</th>
<th>Total TLU %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Camel</td>
<td>Castle</td>
<td>Sheep</td>
<td>Goats</td>
</tr>
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<td>Western Africa</td>
<td>2,048</td>
<td>37,635</td>
<td>40,272</td>
<td>56,468</td>
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<td>Sahel</td>
<td>2,027</td>
<td>19,589</td>
<td>20,178</td>
<td>23,259</td>
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<td>Nigeria</td>
<td>18</td>
<td>12,169</td>
<td>13,160</td>
<td>26,320</td>
</tr>
<tr>
<td>Other</td>
<td>–</td>
<td>5,877</td>
<td>6,934</td>
<td>6,901</td>
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<td>Central Africa</td>
<td>–</td>
<td>7,982</td>
<td>3,564</td>
<td>6,888</td>
</tr>
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<td>Zaire</td>
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<td>1,400</td>
<td>700</td>
<td>2,930</td>
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<td>Other</td>
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<td>2,974</td>
<td>3,958</td>
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<td>67,939</td>
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<td>30,000</td>
<td>23,000</td>
<td>17,000</td>
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<td>33,504</td>
<td>24,339</td>
<td>37,039</td>
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<td>9,009</td>
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<td>Total</td>
<td>12,320</td>
<td>161,135</td>
<td>121,388</td>
<td>142,711</td>
</tr>
</tbody>
</table>

2.3.1.3 Some climatic stress indices are described below:

Stress indices

(1) Wind chill factor K (Spile and Passel, 1945)

This factor occurs when there is a danger of exposure to freezing temperatures. It does not depend on evaporation but depends on environmental cooling power. It has units of WM⁻² and is given by

\[ K = 1.63 \text{ (IOU}1/2 - U + 10.45)(33 - T_a) \]

where \( T_a \) is air temperature in °C, and U is windspeed in ms⁻¹.

(2) Wet bulb globe temperature, WBGT

This index indicates heat stress of livestock due to solar radiation load. It is given by

\[ WBGT = 0.7 T_w + 0.2 T_d + 0.1 T_a \]

where \( T_w \) is wet bulb temperature; \( T_d \) is shaded dry bulb temperature, and \( T_a \) is standard black globe temperature.
(3) Temperature—humidity index, THI

This index is related to milk production for lactating cows. THI has units of temperature. It is given by

\[ \text{THI} = T_a + 0.36T_{dp} + 41.2 \]

where \( T_a \) is air temperature, and \( T_{dp} \) is dewpoint temperature.

Monthly mean THI values can be used to compare the stress of areas which might display diverse mean temperature and humidity ranges.

(4) Poultry climatic variability model

Climatic elements of importance to poultry performance include temperature, evaporation (respired water use and heat loss), advection (flow of sensible heat to surroundings) and relative humidity (Charles and Wathes, 1979).

The above parameters together with stocking density, effective surface area and average thickness of feathers influence performance and fecundity in poultry. Evaporative heat loss is calculated from:

\[ E = LE \times W/24 \times 3600 \]

where \( E \) is evaporation cooling \( \text{JS}^{-1} \); \( LE \) is latent heat of water taken as 580 cal g\(^{-1}\) = 2428 g\(^{-1}\), and \( W \) is water use (gd\(^{-1}\) bird\(^{-1}\)).

Flow of sensible heat to the surrounding air is given by:

\[ H_s = T_c \times (T_b - T_e) \times A/X \text{ Js}^{-1} \]

where \( H_s \) is sensible heat transfer \((\text{Js}^{-1} \text{ bird}^{-1})\); \( T_c \) is apparent thermal conductivity of feathers taken as \( 5.7 \times 10^{-5} \) cal cm\(^{-1}\) s\(^{-1}\) \text{ {C} K}^{-1} \) equivalent to \( 2.38 \times 10^{-4} \) J cm\(^{-1}\) s\(^{-1}\) K\(^{-1}\); \( T_b \) is body temperature; \( T_e \) is ambient temperature; \( A \) is surface area (cm\(^2\)), and \( X \) is thickness of feather layer (cm).

If heat production exceeds the rate at which it is dissipated to the surroundings, body temperature starts to rise and heat stress increases. The expression becomes:

\[ T_c = T_b - (H_s \times X)/(T_c \times A) \]

The recommended maximum ventilation rate is 28 m\(^3\) s\(^{-1}\) per 10 000 birds. House temperature is estimated from \( T_r = H_s/(1200 \times Q + U \times A) \)

where \( T_r \) is temperature rise outside air (\text{C}); \( H_s \) is sensible heat output \((W \text{ bird}^{-1})\); \( Q \) is ventilation rate \((m^3 \text{ s}^{-1} \text{ bird}^{-1})\); \( U \) is average thermal conductance of roof and walls per bird taken as 0.5 WM\(^{-2}\) °C\(^{-1}\), and \( A \) is exposed area of roof and walls per bird.

The temperature will start to rise when the outside air temperature exceeds about 25°C for a 2 kg bird and 28°C for a 1.5 kg bird and the birds become stressed.

2.3.2 INDIRECT EFFECTS OF CLIMATIC VARIABILITY

2.3.2.1 Animal diseases

Rapid changes in temperature and relative humidity will impose strong stresses rendering the animal (host) more susceptible to pathogenic attack (Webster, 1981). Drought causes extreme hardship to animals, especially in those African countries in the Sahel and bordering regions. Too much rain also causes floods resulting in a number of diseases associated with wet and muddy conditions. Lack of good quality forage results in metabolic disorders.

In chickens the above conditions interfere with healthy feathering and intact skin, exposing the birds to disease-causing agents (pathogens) (Kenya Farmer, 1989).

The impact of climatic variability on animal diseases is generally to increase their virulence, since extremes of weather reduce the animals' active immunity to disease.

"Sway back" a nervous disorder of newborn lambs, and hypo-magnesaemia, both nutritional deficiency diseases, are highly influenced by weather anomalies and hence climate variability, with rainfall and temperature anomalies exacerbating their virulence (WMO, 1988).
"Limbenneck" or "western duck sickness", a disease which attacks poultry, is more frequent with extremes of rainfall since the causative bacteria thrive in the mud under and around ponds or lakes with little oxygen. (WMO, 1988; Kenya Farmer, 1989).

The effect of climate and its variability including extremes of temperature on animal diseases are fully covered in WMO Technical Notes 190 and 191 (WMO, 1988; 1989). However liver fluke and parasitic gastroenteritis in cattle are discussed here in some detail.

(1) Liver fluke (Fascioliasis)

Liver fluke and other helminthological diseases intensify their virulence depending on the temperature and humidity values that exceed the normal comfort range (Ollerenshaw and Rowlands, 1959). Summer rainfall enhances the development and hatching of fluke eggs and subsequent infection of the snail. Climatic factor $M_e$ estimates the severity of the summer (or winter) incidence given by

$$M_e = N(R - P + 5)$$

where $N$ is the number of rainy days; $R$ is total monthly rainfall, and $P$ is potential transpiration.

Factor $N(R - P + 5)$ identifies intensity of the wet conditions. High values of $N$ or $(R - P)$ give a large $M_e$ index reflecting wet conditions for parasitic activity. The constant 5 ensures $M_e$ is always positive.

Where the egg and snail stages are exposed to fluctuating temperatures from one stage in the liver fluke life cycle to the next, this becomes

$$\frac{d}{DT} = \frac{a}{\text{Do}_{e^{T_{1}}}^{a1i} + \text{Do}_{e^{T_{2}}}^{a2i} + \text{Do}_{e^{T_{n}}}^{an} > 1}}$$

where $\frac{a}{\text{DT}} = \frac{a}{\text{Do}_{e^{T}}}^{aT}$, $a = \frac{\max(T - T)}{\max.T - \min.T}$, and $e$ is exponential part.

For a stage experiencing different constant temperatures $T_1, T_2, T_3, ...$ on days 1, 2, 3, ... development will be completed on day $n$, when the sum of the development fractions for the $n$ days exceeds 1. If the stage requires temperature $T$, then the development time is a function of that temperature (WMO, 1978; Getzinby et al., 1979).

Fascioliasis is a parasitic disease that attacks ruminants, causing major economic losses. In Africa, fascioliasis poses a serious problem in the humid and sub-humid zones (Traore, 1989). In the arid and semi-arid lands (ASAL) climatic conditions have been less favourable for its incidence. However, the incursion of human population from high potential energy and food production, thereby increasing the number of potential snail habitats and the danger of liver fluke infestation. Fascioliasis was found to pose the highest danger to sheep followed by goats, and the least to cattle in the Niono rice scheme in central Mali (Traore, 1989). The specific infestation index (SII), calculated to characterize the degree of infestation (Vassiliades, 1970), was between 1 and 5, or between 20 and 100 eggs per gram of faeces examined.

Infestation is higher in the dry season than in the rainy season (Table 2.6), and is higher with greater rainfall variability.

<table>
<thead>
<tr>
<th>SEASON</th>
<th>Animal species</th>
<th>Number of animals</th>
<th>Per cent positive</th>
<th>SII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>Cattle</td>
<td>80</td>
<td>18.0</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>Sheep</td>
<td>27</td>
<td>22.2</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>Goats</td>
<td>80</td>
<td>6.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Rainy</td>
<td>Cattle</td>
<td>55</td>
<td>10.9</td>
<td>1.3</td>
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<tr>
<td></td>
<td>Sheep</td>
<td>55</td>
<td>10.0</td>
<td>5.0</td>
</tr>
<tr>
<td></td>
<td>Goats</td>
<td>65</td>
<td>3.1</td>
<td>1.0</td>
</tr>
</tbody>
</table>
(2) Parasitic gastroenteric in cattle
A prediction model similar to that adopted for fascioliasis was developed for bovine oesertagiasy by Gettiney et al. (1979) and Gibson (1978). This uses maximum and minimum temperatures. They give the relationship:

\[ D(T) = D_0 e^{aT} \]

Terms are similar to those for fascioliasis. The proportion of the day for which development takes place, \( a \), is calculated using a temperature threshold \( T_r \), equal to 5°C.

2.3.2.2 Disease insect vectors
Strong winds transport insect vectors from one area to another thus acting as the likely vehicle for epidemics of African horse sickness (Sellers et al., 1977) and rift valley fever (Pedgley, 1982). The disease risks are therefore spread to countries outside endemic areas. Some common tropical insect vectors and reservoirs of major livestock diseases are:

- Tsetse fly (Glossina sp) highland species, riverine species and savanna species;
- ticks (Rhipicephalus sp), etc. (ICIPE, 1986, 1987, 1988).

2.3.2.2.1 Tsetse and livestock trypanosomiasis
According to FAO (1978), much of the land infested by tsetse has relatively high agricultural potential. This can be seen in Figure 2.10 where the areas in Africa inhabited by tsetse coincide with those suitable for cassava, sorghum and maize.

Figure 2.10
Area of tsetse distribution and suitable agroecological zones for three major crops
Tsetse-borne trypanosomiasis ( nagana in livestock; sleeping sickness in man) constrains livestock production in the humid and subhumid zones of sub-Saharan Africa. Apart from the N'Dama and West Africa shorthorn cattle breeds, and the sheep and goats of the Djallonke dwarf breeds from West Africa (Gambia), the majority of animal breeds are infected by trypanosomiasis (ILCA, 1988).

Heavy tick infestations and the diseases they cause combine to reduce the productivity and usefulness of the livestock population in ranch animals and in nomadic, transhuming and sedentary animals. For instance, in east and central Africa, east coast fever severely inhibits the improvement of cattle production (Preston and Leng, 1987; ICIPE, 1988), and throughout the tropical world, three other major tick-borne diseases and several minor ones pose further severe constraints on the development of the livestock industry and can cause heavy mortality, particularly in cattle.

Climatic influences on spatial variability of ticks has not been studied as yet. However, the host-environment-disease relationship, calls into play both direct and indirect stress on livestock.

Livestock feed resources come from naturally growing and cultivated forages and other feeds, including pastures and fodder (both natural and cultivated), hay or grass silage, concentrates, and mineral feeds. These provide carbohydrates, proteins and other nutrients. Temporal and spatial variability of climate thus controls the quality and quantity of these animal feeds. Drought leads to both low quality and low quantity of fodder and pasture (Preston and Leng, 1987). Raising livestock, therefore, consists of planning and management of these resources to maximize production (ILCA, 1987).

Ground hay is stored and fed to oxen, horses and donkeys during the dry season in Gambia (O N’jai et al., personal communication).

In some sub-humid to humid regions farmers use crop residues, concentrates, mineral licks, natural forage and browse, and tree fodder as feed classes. Manure is highly valued in mixed farming systems where there is an interaction between crop and livestock production, the use of draught animals, manure and crop residues, which are used as a dry season feed, with animals grazing crop fields after harvest.

After harvest, N’jai contended that management and feeding of cereal stovers (maize, rice, wheat, etc.) can alleviate dry season feeding of draught animals and small ruminants. Sorghum has also been found a suitable forage for livestock in Somalia and other parts of the world (Shirwa et al., 1988; Mohamed Saleem and von Kaufmann, 1988). Table 2.7 names some of the dry-season feeds for draught animals.

Previous research on Merz sheep in Ethiopia reveals that leaves from the fodder tree Sesbania sesban and from lucerne are excellent supplements to straw-based diets in sheep fattening systems (ILCA, 1987; WMO, 1986).

In dryland farming of the tropics, the tendency is to satisfy water use efficiency by breeding forage that survives on limited soil moisture. Rainfall variability from one year to the next makes it difficult to be consistent in fodder/pasture production (Stewart, 1980) hence there is a need to change the morphology of fodder and pasture feeds in arid and semi-arid (ASAL) areas by reducing the surface area available for evaporation.

Intensive poultry production in Africa, for instance, hardly differs from that in North America or Europe, despite the vast differences in climate and socio-economic values (Preston, 1987). In dry seasons/dry areas the quality of feeds and biomass of those feeds decreases with increasing climatic variability parameters.

Agroforestry with livestock components can be either silvopastoralism (livestock/pasture + trees) or agro-silvopastoralism (crops + trees + livestock/pasture) (Nair, 1987; Winterbottom and Hazlewood, 1987; Joffre et al., 1988; Lundgren and Rain Tree, 1983). The agroforestry approach of incorporating trees and shrubs in land, use planning can solve the problem of declining fertility and increasing desertification of farming and pastoral systems. Such an agroforestry system has the potential to produce food and fodder as well as fuel and timber.
<table>
<thead>
<tr>
<th>Village</th>
<th>Sorghum stalks</th>
<th>Rice straw</th>
<th>Grass hay</th>
<th>Ground bush</th>
<th>Cypres hay</th>
<th>Aphysorpus hay</th>
<th>Sorghum grain</th>
<th>Cotton seed</th>
<th>Alfalfa africana</th>
<th>Pterocarpus eminens</th>
<th>Daniella oliveri</th>
<th>Comon salt</th>
<th>Xane</th>
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<tbody>
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<td>x</td>
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**TABLE 2.7**

Dry season feeds for draught animals, Niger States, Nigeria (Mohamed-Saleem and von Kaufmann, 1989)

A combination of agroforestry and improved livestock grazing practices protects and even restores soil fertility. Establishment of windbreaks and shelter belts, the planting of individual trees on cropland, the use of trees and shrubs in pastures and the establishment of fodder banks (mixed trees and grasses surrounded by fencing) constitute a sustainable agroforestry complex.

Trees and shrubs that can stand insufficient moisture can be established in arid and semi-arid lands (ASAL). Where rainfall becomes variable in time and space, tree establishment becomes delayed, resulting in less accumulation of dry matter over time, and fodder quality deteriorates (Amara and Mansuray, 1989).

### 2.3.4 Natural pasture production in rangelands

Three animal husbandry systems—nomadism, transhumance and sedentary animal husbandry—are practised in rangelands (Wallen and Gwynne, 1978).

These are based on three criteria: the system of rangeland exploitation, rangeland localization and human life-style (de Ridder et al., 1982; Figure 2.11).

Forage availability determines the productivity of an animal husbandry system, and depends on the biomass produced per season, its quality during the season and the length of the growing period. Growth occurs in the rainy season which, in the Sahel, decreases in length from south to north. The period is longer for perennial plants than for animals. The quality of the biomass depends on its age and quantity, and tends to decline at the end of the growing period, attaining its lowest value in a dry season (de Ridder et al., 1982; Rosema, 1986a, b). Biomass development in the Savanna region depends, therefore, on the vegetation composition, surviving seeds in a dry season and the photosynthetic rate.
The monitoring and estimation of the composition and productivity of the vegetation cover (primary production) that forms forage for livestock in the Savanna is done through aerial photography, conventional estimation, hand-held radiometer data and satellite remote sensing methods.

Studying rainfall distribution, its timing and duration, and associated vegetation green-up and senescence can lead to the detection of grazing patches in rangelands. This process, when supported by map ground truthing, can therefore act as an early warning system to detect areas of deteriorating vegetation which might be a danger to livestock (Henricksen and Durkin, 1986; O'tengi, 1986; Curran, 1985; Justice et al., 1986a, b).
2.4 PLANT DISEASE AND INSECT PEST RESPONSES TO CLIMATE VARIABILITY
by H. Lappalainen and M. Heikinheimo

In this section, general principles of the effects of different climate elements on plant diseases and insect pests are discussed. It is recognized that the responses of diseases and pests to climate are both direct and indirect. Indirect responses may be mediated via the changes in crops, cultivars and cultural practices, as well as changes in the natural fauna and flora as a result of changes in regional climates. For example, a climate change may allow the introduction of new crop species and cultivars of existing crops, thus changing the resource base for diseases and pests. Since there are no reliable predictions of possible future changes in cropping and cultural practices, it is too early to make firm assessments of the overall effects of climate change on plant diseases and pests.

The direct responses of plant diseases and pests to climate and weather are here expressed in a general form without specifying particular regional features or systematically scanning through the different disease or pest types. The discussion of plant diseases is divided into groups of pathogens including viruses, fungi, nematodes and bacteria. Insect pests are discussed by examples of responses mainly to temperature, precipitation and wind.

In contrast to the relatively small number of studies on the relationship of climate change to plant diseases and pests, there have been many efforts to collect meteorological and biological data for use in specific short-term predictive systems for plant diseases and pests. Predictions are usually based on the observed and expected duration of certain combinations of meteorological factors, mainly temperature and moisture. For those diseases that are weather sensitive, early warning of disease outbreak and development is possible based on observed daily meteorological data and numerical weather forecasts. For more information see for example WMO documents on potato blight (Bourke, 1955; Bajic, 1988), desert locusts (Rainey and Aspliden, 1963), apple scab (WMO, 1963), wheat rust (WMO, 1969), the Colorado potato beetle (Hurst, 1975), parasite animal diseases (Gibson, 1978), the cotton leaf worm and the pink bollworm (Omar, 1980) and airborne organisms in general (Pedgley, 1980).

2.4.1 PLANT PATHOGENS

Plant diseases are caused by different pathogens in groups of viruses, fungi, nematodes, bacteria and mycoplasma-like organisms.

In principle, diseases caused by these biotic pathogens are limited to those areas where the environment is simultaneously favourable, for a sufficient time period, for the host, for the pathogen itself, and for any necessary vector. Weltzien (1978) has proposed that only environmental factors can explain the distribution patterns of diseases, and that disease distribution will vary as the environment varies. Disease development will stop as soon as the environment becomes limiting for one or more of these organisms. Meteorological conditions influence not only the development of an epidemic over a single growing season, but also the survival of the pathogen until the next season (Coakley, 1986).

Most diseases will have a greater potential to become epidemic under warmer and moister conditions. Plant pathogens generally tend to require warm temperatures and prolonged leaf wetness in order to develop. Only a few pathogens are favoured by dry or cooler conditions (Deckert et al., 1985).

The rate of disease development is governed by the most limiting factor. Meteorological conditions influence every sequence of epidemic release, transport of pathogenic agents, retention, infection and incubation (Rapilly, 1983). In temperate and moist tropical climates, temperature is the most important regulating factor, whereas rainfall is vitally important in arid climates (Broadbent, 1967). Either temperature or moisture can be decisive in the contamination, development and spread of a pest or a disease. If one is continuously favourable, the other becomes limiting. If both fluctuate, they must be favourable at critical times. If both are continuously favourable, the pest or disease infestation or infection becomes serious (Sarker, 1988).
CHAPTER 2

Many disease pathogens are transmitted by animal vectors, usually insects. The seasonal cycles of insects vary with climate, and also from year to year with weather. The effect of climate upon the activity of vectors can influence the rate of infection and the size of the infected area. The factors involved here are principally wind, precipitation and temperature.

2.4.1.1 Viruses

Viruses may be described as infective, intracellular agents of minute size. They consist of particles of nucleic acid, and in order to multiply the virus must be inside an appropriate living cell. Some of the common disease viruses are tobacco mosaic virus, barley yellow dwarf virus, maize dwarf mosaic virus, maize streak virus, rice hoja blanca virus, sugarbeet yellowing virus, lettuce mosaic virus, potato virus Y (PVY), potato leaf roll and mop top. Some viruses are restricted to a single or a few plant species, others are widely distributed in several genera.

Climate elements have little direct impact on viruses. Instead, their effect on virus epidemics is a complex result of vector and pathogen interactions. The severity of an epidemic depends upon the variability and density of the vector, virus and host plant populations (Knöke and Louie, 1981).

Viruses are transmitted by seed, vegetative propagation, sap-transmission (infected sap), nematodes, fungi, mites and insects (Collingwood et al., 1988). Insects (aphids) and nematodes are the most important vectors for almost all the widely distributed viruses (Broadbent, 1967). The requirements for a long-range spread of virus diseases are a source of the virus and a suitable mobile vector, retention of the virus throughout flight, a suitable target and appropriate wind (including direction, duration, speed), temperature and humidity conditions (Thresh, 1983). Weather influences the spread of a virus not only through the vectors but also through the host plant. Fast growing plants in a favourable environment are more susceptible to insect colonization or to virus infection than slowly growing plants under limiting environmental conditions (Broadbent, 1967). Temperature can influence either the vector or the pathogen. Aphids are the single most important virus vectors. Their overall effectiveness as vectors is based on their ability to reproduce rapidly and produce winged adults at certain stages of the life-cycle (Thresh, 1983). The optimum temperature for aphid reproduction is about 26°C. Under optimal environmental conditions for the host, aphids multiply faster in warm continental climates than in cool maritime ones and during warm dry summers than during cool wet ones. Not only is the life cycle of aphids shortened as the temperature rises, but their activity increases. Temperature extremes can be important in limiting virus vector spread. For example, hot weather may inhibit infection of the vector (Broadbent, 1967). Leafhopper, white fly, nematode and mite transmitted viruses are likely to be favoured by warmer climates.

Moisture has mainly a secondary effect on virus diseases, influencing the plant and the vector activity rather than the pathogen itself (Fry, 1982). Virus particles are sensitive to drying out, possibly brought about by some change in the protein coating around the nucleic acid core (Pedgley, 1982). It has also been noted that water stress has a tendency to promote virus diseases on pasture crops (Beresford and Fullerton, 1989).

Variability in the weather can lead to extreme fluctuations in vector populations, or to their periodic extinction. In such circumstances there are obvious advantages for viruses, vectors and immunologically distinct strains in having the ability to disperse far and colonize fresh habitats. The epidemiological characteristics of the insect-borne viruses of plants are likely to have more common features than is currently appreciated (Thresh, 1983).

2.4.1.2 Fungi

The majority of phytopathogenic fungi are multicellular, immobile organisms, whose cells possess a rigid wall. Unlike plants, they are completely devoid of chlorophyll, a condition in which they need a supply of organic carbon compounds for their basic nutrient requirements. Phytopathogenic fungi, the most outstanding group of plant pathogens, cause various spot, stripe, rust, smut, wilt, rot, blight and mildew diseases of crop plants.

Climate factors can affect every phase of the fungus life cycle: sporulation, dispersal, retention, germination, infection and survival between growing seasons.
Changes in the range of environmental factors are important when the effect of climate on the different phases is assessed. One of the most studied fungus pathogens *Phytophthora infestans* (Mont) de Bary, which causes potato blight, serves as an example. The spores are formed in a saturated atmosphere (relative humidity more than 91 per cent) in a temperature range of 3–26°C. Immature spores are very sensitive to dry conditions, whereas liberated spores are killed by solar radiation. Free water or dew on the leaves is necessary for the germination of the spores. Direct germination can occur over the temperature range of 9–26°C. The infection process requires temperatures from 10–25°C. The incubation phase is also dependent on temperature (Bajic, 1988).

Moisture is the prime environmental factor affecting sporulation. The production of spores and their release is often brought about by a change from wet to dry conditions (Butler, 1988). In many ascomycetes the perithecia on the plant or in plant debris begin to shoot ascospores only when the substrate has been thoroughly wetted by a precipitation of at least 0.5 mm (Butler, 1988; Zadoks and Schein, 1979). Many basidiomycetes sporulate only when the air is nearly saturated with water vapour. Some peronosporaceous fungi exploit rapid changes in water vapour pressure for the release of spores (Zadoks and Schein, 1979).

The long distance dispersal of diseased plants has contributed to the spread of certain plant diseases, as also has the use of infected seed. Many fungal spores are small, light and can be carried hundreds of kilometres by the wind (Pedgley, 1986). The fate of the individual spore is of little interest and attention must focus on the fate of spore clouds. Because we know little of regional climate change, the long distance dispersal of spores, which depends on synoptic scale air circulation, is difficult to predict. On a smaller scale, fungal disease can spread within irrigation water or by rain, or by insects, flies, beetles or moths (Collingwood *et al*., 1988; Pedgley, 1980). For instance, in a field ecosystem, plant pathogens disperse by splashing. The theoretical analysis of the dispersal of rain splash droplets given by Walklate *et al*., (1989) provides a basis for understanding the rainfall characteristics that affect the vertical transport of splash droplets. In the future, possible changes in rainfall intensity could affect the dispersal of fungal pathogens. Heavy rainfall increases splash dispersal, and floods promote the long distance dispersal of fungal diseases.

The germination of fungal spores is normally initiated under conditions of wet weather. Immersion in water on the leaf blades is normally required, but several fungi are also hygroscopic to high water vapour contents of the air. For example, conidiospores of powdery mildews are often inhibited by free water on the leaf, but humid air will trigger germination (Ford, 1982).

The infection phase also tends to be triggered by periods of wet weather. For instance among trees, cool and moist springs are ideal for infection by fungal spores causing anthracnose disease in weeping willow (*Salix babylonica*), London plane (*Platanus* *hybrida*), walnut (*Juglans* *regia*) and poplar (*Populus* *spp*.) (Ford, 1982). Temperature, wetness and humidity are the primary factors in the incubation phase. Moderate temperatures, prolonged wetness on the leaves (rainfall or dew) and high relative humidity are ideal for the development of most fungal leaf diseases (Renfro, 1986).

In contrast to other groups of fungi, powdery mildews do not depend on the existence of free water on the leaves, either for germination or for infection. Diseases mediated by the powdery mildews would not generally be enhanced by a wetter climate (Beresford and Fullerton, 1989).

Warmer temperatures shorten the generation time of fungal and bacterial pathogens and therefore generally increase the rate at which epidemics develop, provided water is not limiting. Fungal pathogens and their hosts often show a high degree of co-adaptation to the environment, particularly with respect to the temperature requirements for the completion of the disease cycles (Beresford and Fullerton, 1989). Some fungi, for instance *Puccinia striiformis* (yellow rust), do not thrive at high temperatures and may be absent from tropical or semitropical regions (Collingwood *et al*., 1988; Mulder and Booth, 1971).

The development of downy mildew of tobacco, caused by *Peronospora tabacina*, in the south of the USA is closely associated with winter temperature, in
particular for January. If the January temperature is above normal and close to the optimum required for the pathogen to infest the crop (16.5°C), the disease appears very early in the season, developing at high rates. However, the development of the mildew is also related to the temperatures during the growing season. Lower January temperatures result in a later crop infestation by the downy mildew, and less crop damage, although during the growing season the conditions may well be favourable for the disease outbreak (Volvach, 1986). Low temperature fungi are a threat to overwintering cereal crops in climates with a considerable duration and depth of snow cover. During winters when snow has accumulated early in the season, the soil may be left unfrozen, allowing the parasitic fungi to grow under the snow and kill the overwintering plants. In regions of less snow cover, winter frosts can reduce the amount of overwintering disease by killing the pathogen, or the host on which it persists. Some fungal pathogens have overwintering structures which require winter chilling to complete their development, or to break dormancy (Beresford and Fullerton, 1989).

2.4.1.3 Bacteria

Bacterial diseases of plants are transmitted by humans, insects, rain and wind. Species from the genera *Pseudomonas*, *Xanthomonas* and *Streptomyces* cause losses in vegetable growing. In present climates, plant pathogenic bacteria cause diseases mainly in subtropical areas, because they need high temperatures and moisture, so they are not such important plant pathogens as fungi and nematoda. In the future, possible climate warming may also increase the severity of bacterial diseases.

Temperature is the main environmental factor governing bacterial life. Growth as well as other biological events such as fruiting, sporulation, spore germination, mobility and survival are tightly related to temperature, or its variability. Because different bacteria tolerate different temperature extremes and have diverse temperature optima for growth, it is impossible to develop generalizations pertaining to all diseases induced by bacteria (Fry, 1982). While studying responses of microorganisms to temperature, it is often difficult to assess whether temperature has a direct effect on the processes studied, or whether its role is an indirect one; temperature can alter other physiochemical characteristics of the environment (Arango, 1981).

As an example, the bacterial wilt of maize, found in North America, hibernates in flea beetles (*Chaetocnema* spp), with these beetles dying in great numbers in cold winters. Thus, on the occurrence of a mild winter the bacterial wilt of maize is a rapidly developing disease, whereas a cold winter reduces the outbreak severity. If, under the conditions of Illinois, the accumulated mean daily temperature for December through to the end of February is above 32°C, then the bacterial wilt of maize will most probably infest the crop. If the same accumulated temperature is above 37.8°C, the disease outbreak will be disastrous (Volvach, 1986).

Moisture is a controlling factor in the epidemiology of diseases induced by bacteria. Most plant pathogen bacteria do not produce spores and are unable to survive periods of low moisture (Fry, 1982). For instance, cassava bacterial blight (CBB) epidemic is caused by the bacterium *Xanthomonas campestris* pv *manihotis* which is a host specific to cassava (*Manihot esculenta* Crantz). CBB shows its characteristic symptoms and maximum intensity during the rainy seasons when conditions are ideal for its rapid development and spread (Theberge, 1986).

Effects of elevated atmospheric CO₂ on the growth and community composition of plant pathogenic bacteria may be important, because bacteria can survive from season to season by living in decaying plant tissues. Hence, the return of plant residues to the soil may increase the population of pathogens as well as the number of useful organisms (Lamborg et al., 1983).

2.4.1.4 Nematoda

Soil nematodes are aerobic, very small, worm-like creatures that inhabit the system of interconnected spaces between soil particles. Plant parasitic nematodes, in the current context, are nematodes that feed on the roots, stems, leaves or seeds of higher plants. They may function as ectoparasites, remaining physically outside the plant while feeding, or endoparasites, moving into the plant tissues during feeding, or they may occupy some intermediate physical location and associated appellation
(Ferris, 1986). The amount of damage to root systems caused by root endoparasitic nematodes is far more than the damage caused by ectoparasites. Plant parasitic eutonematodes are important vectors of several plant viruses (Fry, 1982).

Nematodes near the soil surface are subjected to extremes of temperature and moisture variations, during which they are either inactive or die, whereas those inhabiting the deeper layers are protected from these extremes but are subject to periods of anoxia. Climate factors such as temperature, rain and moisture have major effects on nematode population diversity. These effects may be mediated indirectly via the soil or via effects on host plants. Survival capabilities of nematodes to adverse environmental conditions appear in the form of hypobiosis or reduced metabolism as a result of dehydration (Ferris, 1986).

Temperature is a key factor in the development, movement and activity of endo- and ectoparasitic species. Low, optimal and high temperatures for nematodes in general are considered to be 5–15, 15–30, and 30–40°C respectively (Wallace, 1963). For instance, a soil temperature of 18°C, with an optimum of 26–28°C is highly conducive to the development of the genus Meloidogyne, the root knot endonematodes (Collingwood et al., 1988). Accumulated degree days can also be used in estimating the development and activity of Meloidogyne. For instance, Lahtinen et al. (1989) found that for the population of Meloidogyne hapla, the thermal time requirement above the base 8.25°C for development from juvenile to the first juvenile of the second generation was about 553 degree days. Even though active nematodes are severely affected by extreme temperatures, dormant stages may survive them. For instance, eggs in cysts of endoparasitic Heterodera sp may survive temperatures of -40 to -80°C (Wallace, 1963).

Nematode populations increase most rapidly at intermediate moisture levels close to field capacity, because their eggs do not hatch in dry soils. Field studies show correlations between population trends and accumulated rainfall. Different species of nematodes respond differently to rainfall patterns in different soils (Vrain, 1986). Variations in soil moisture are also likely to affect nematode activity. The active, invasive stages of free-living species are dependent on moisture for movement. The water film on the soil particles must be sufficient for movement, with mobility and activity greatest when the soil is drained after rainfall. Most nematodes are sensitive to anaerobic conditions, so that they may not survive such conditions in soils flooded for a long period (Fry, 1982). Even moderate rainfall, evenly distributed in time, is more favourable than large amounts of rain that fall infrequently. In a warmer and moister climate, nematode populations can be assumed to increase, with climate change also functioning indirectly via the host plant.

2.4.1.5 Conclusions

Following Beresford and Fullerton (1989), some generalizations about the impact of climate change on plant diseases can already be made. For most plant pathogens, the potential to become epidemic increases with a warmer and moister climate. Of the various plant pathogens, fungal and bacterial diseases in particular spread under a wetter climate. Changes in plant disease severity will occur simultaneously with changes in climate and associated cropping patterns and practices. In climate impact assessments, consideration must be made simultaneously on the links between agronomy, plant breeding, entomology (for vector-transmitted viruses) and agricultural chemicals.

Assuming future global climate warming, the potential for an inadvertent introduction of new diseases will tend to increase, particularly in temperate and northern latitudes, where the already existing diseases would also continue to increase in severity.

2.4.2 Insect pests

Insects represent the most numerous class in the animal kingdom. An adaptability to a wide range of environmental conditions, and a prodigious power of reproduction are the two outstanding characteristics of this group. Insect pests can affect both the quality and quantity of crop yields, causing, for example, deformations, or disturbances in development. By sucking out sap they are able to transmit plant diseases, particularly viruses, and cause deformations, discolorations, leaf rolling, etc. They are often pests of specific crops, and their development is
2.4.2.1 Responses to temperature and rain

Insects are essentially ectothermic organisms, with their physiological processes displaying a high degree of sensitivity to ambient temperatures. Insect populations generally increase with higher temperature and humidity. The general effect of a dictated climate warming would be to increase the developmental rates of insect and mite pests, leading to more generations per year. As a result, higher pest populations would appear and problems with pest management would worsen. The regions concurrently suited to the development of pests would move poleward without a reduction of populations in areas now affected, unless a natural enemy limited the pest population (Kimball, 1985). Reduction in the pest populations could be expected if temperatures extended more frequently into the lethal range for a particular pest, or if winter chilling, for example, became more frequent in regions of reduced snow cover.

In a situation where a natural enemy is present, biological control would be more or less effective in warmer temperatures, depending on the optimum temperatures for a particular pest and its related natural enemy (Hill and Dymock, 1989). Some insects become inactive at higher temperatures, and some are inhibited by wetter conditions (Decker et al., 1985).

Desert locusts (Schistocera gregaria), for example, are resistant to low temperatures, but adults buried in snow or exposed to prolonged frost may die. Near the upper limit of their temperature range, hoppers, which are the wingless young stages, have been seen to die during the heat of the day if they are unable to find shade or move off the hot ground, particularly if the humidity is low. Excessive heat is probably sometimes the cause of death in very large numbers of newly hatched hoppers. Insufficient moisture in the soil will prevent eggs from developing and hatching successfully, and reduce the extent of food plants for the young hoppers. Too much rain can kill eggs by exposing them on the surface of the soil, washing them out of the ground or causing them to rot (Steebman, 1988).

It is difficult to distinguish the effects of rains from those of temperature. For example, fewer winged aphids develop during cool wet weather and as the rain hinders aphid flight, fewer new colonies are formed. On the other hand, warm and dry weather will favour development of winged forms. Heavy rain mechanically washes many insects off plants, after which they may die. In dry climates, however, a wet period will favour the rapid growth of both wild and cultivated plants, and of the insects that feed on them (Sarker, 1988).

2.4.2.2 Responses to CO₂

The effect of elevated atmospheric CO₂ concentration on insects is likely to be indirect rather than direct. The scale of absolute increase is relatively small for affecting insect activity directly. Rather, insect pests are expected to closely follow the development and adaption of plants to higher CO₂. For example, if more nectar is produced in flowers because of the increased carbohydrate supply associated with a high CO₂ level, pollinators will probably respond with increasing populations and
pollinating activity (Kimball, 1985). There has also been discussion as to whether plants grown under CO₂-enriched air are likely to be more or less vulnerable to insect attacks. Lincoln et al. (1984) found that the soybean looper larvae fed more on leaves grown under higher CO₂ concentrations. These leaves had a greater C:N ratio, so that the larvae had to eat more to obtain the same amount of required nutrition. On the other hand, no differences were found among population numbers of white flies trapped and counted in open top field enrichment chambers, in which cotton was exposed to various CO₂ concentrations (Butler et al., 1985). As a result of increases in CO₂ concentration, some plants will probably become more or less vulnerable to particular insects, whereas other host pest relationships may not be significantly changed (Kimball, 1985).

2.4.2.3 Migration

Migration by flight takes place in a succession of stages: take-off, displacement and landing. Each of these is affected by the weather, particularly by temperature, light and wind. It is usually young adults that migrate, before reproduction becomes important in their life cycle. Apart from weather changes, other triggers causing insects to take off are smells from a host or mate. For some species, take-off becomes more likely as relative humidity falls, while for others relative humidity must rise. Too much or too little rain may also trigger take-off (Pidgeley, 1980).

Observations by radar have provided increasing evidence of mass flights by species other than grasshoppers and locusts, including, for example, moths and aphids (Berg, 1985; Drake and Farrow, 1988).

Strong flyers such as locusts frequently travel in swarms with winds and storm fronts to areas likely to receive rainfall and provide suitable habitats for their progeny (Rainey, 1951; Clark, 1969). The activity of desert locusts is affected by air temperature and sunshine. Long continuous flight usually takes place only above 23°C. The presence of rain and cold air generally reduces flying activity. In sunshine, long-lasting continuous flight is possible when the air temperature is above 14°C, but flight activity ceases when the air becomes hotter than 40°C. Locusts take off and land under moderately windy weather. Under strong wind conditions they shelter behind rocks or vegetation. Swarms of locusts travel consistently downwind until they eventually arrive at a low-level wind convergence region. Swarms move between seasonal breeding areas with the winds, and there are certain areas within each country where swarms and breeding can be expected at particular seasons. The locusts live in a generally dry environment, where the average rainfall is low and sporadic, and is usually limited to a particular season of the year. Locusts need moist soil for egg laying and egg development, and hoppers need fresh vegetation on which to feed; therefore they are only abundant during the spring rainfall in north Africa, the Middle East, southern Iran and Pakistan (Steebman, 1988).

Lightweight insects and ballooning species do not have strong directed flight, and are likely to be blown to distant places where their hosts may or may not be present (Johnson, 1954). Migrant African armyworm moths, (Spodoptera exempta), for example, invade Zimbabwe farm land from the moist grasslands of Mozambique by travelling on winds directed to temporary convergence zones (Rose and Law, 1976; Blair et al., 1980). These insects are also raised to high altitudes in regions of frequent strong convective air current, such as those found in tropical thunderstorms or during the passage of a cold front (Tomlinson, 1973). The intertropical convergence zone is known to play an important role in the long-term transport of many tropical insect pests (Bowden and Gibbs, 1973).

Aphids, which are not only the vectors of virus diseases but are also primary pests, are not strong fliers and generally cannot achieve speeds greater than 2.5 km per hour (Kring, 1972). Consequently, they do not take off in winds higher than 5–6 km per hour (Sarker, 1988). While strong winds generally deter take-off, aphids that are ready to fly will be less affected. For example, the occurrence of aphid migration across the Baltic Sea in Europe not only depends on the proper wind direction but also on the location of the source of flying aphids. The size of this source of aphids depends on the prevailing and preceding weather, the number of parasites and predators, the time of the year, etc. The very complicated web of
interactions makes correlations between the number of aphids flying across the Baltic Sea and the separate factors unrealistic, and no such attempt has been made (Wiktelius, 1984).

Newly emerged winged insects need a certain amount of heat before their flight activity is triggered. Because of the daily temperature cycle, the time needed to achieve this heat also varies with time of day. If the day is too warm, the rate at which aphids become ready to fly is also slowed down and so the afternoon peak may be lost. With *Aphis fabae*, for example, the range of temperatures for take off is from 9–28°C (Pedegley, 1980). Convergence and atmospheric circulation in the higher troposphere have appeared important in the long distance dispersal of aphids.

As a proof of this, aphids have been found trapped at an altitude of 1000–2000 m and hundreds of kilometres from their nearest host (Kring, 1972).

2.4.2.4 Conclusions

The general effect of a dictated climate warming on insect pests, under otherwise favourable conditions, would be to increase their developmental rates, leading to more generations per year. Theoretically, pest populations would increase and greater problems with pest management would develop.

Many indirect effects influence the distribution of pest populations, further complicating the climate impact assessment of insect pests. For example, in situations where a natural enemy is present, biological control may be more or less effective in warmer temperatures, depending on the optimum temperatures for the particular pest and natural enemy concerned. Changes in distribution of host plants and insect enemies will have a major indirect effect on insect biology. The timing of the development of both the insect pest and the host plant is important. The potential for damage is greatest when the damaging phase of the pest and the vulnerable phase of the host plant coincide.

Under a warmer climate the geographic range of some insect pests currently limited by temperatures may also be increased. Climate warming is likely to increase the risk of establishment of tropical and subtropical pests in northern temperate regions. Counteractions in the form of intensified quarantine procedures and strategies may become necessary.

2.5 CLIMATIC VARIABILITY AND CROP-WEATHER MODELS

by O.D Sirotenko

2.5.1 TECHNIQUES BASED ON STATISTICAL ANALYSIS OF LONG-RANGE YIELD DATA

Factors that influence yield over time are usually divided into two groups: the first is related to the change of cultural practices and management, while the second depends on the annual fluctuations of meteorological conditions.

Cultural practices cannot change rapidly and, as a result, the first component is presented in the form of a smooth curve, i.e. trend. Usually the trend is described by a linear or quadratic function of time. If so, the general variation of the yield "s²" can be presented as a sum of two terms, one characterizing agricultural practices "s²n", and the other one reflecting the fluctuation of weather conditions "s²m":

\[ s^2 = s^2_n + s^2_m \]  

(1)

Using this assumption, the variation (V_m) is calculated using the following formula:

\[ V_m^2 = \frac{\sum_{i=1}^{n} (Y_i - \bar{Y})^2 - \sum_{i=1}^{n} (\hat{Y}_i - \bar{Y})^2}{n - 1} \]  

(2)

where: Y_i is the yield of the i-th year, i = 1, 2,...,n; \( \bar{Y} \) is the mean yield for the given row of years; \( \hat{Y}_i \) is the yield of the i-th year calculated by the equation or trend, and n is the number of years.

To evaluate the climatic fluctuation (C_m), the mean yield for the given row of years along with the corresponding coefficient of variation (V_m) is used.
The results of this technique are applied in Section 3.2 to evaluate the climatic component of grain crop yield on the territory of the former USSR (by regions) and on the territory of Europe and North America (by countries). Coefficients of variation (in per cent) are presented, which characterize the yield variation of spring and winter wheat (Pasov, 1986):

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<tbody>
<tr>
<td>Former USSR</td>
<td>21</td>
<td>14</td>
</tr>
<tr>
<td>USA</td>
<td>14</td>
<td>7</td>
</tr>
</tbody>
</table>

These data show that the stability of winter wheat yield is 1.5 or 2 times higher than the corresponding index for spring wheat, while wheat yield stability in the USA is 1.5 or 2 times higher than in the former USSR. The former is explained by the biological properties of spring and winter wheat, the latter by the climatic conditions of the USA and former USSR.

From this technique, rows of climate dependent yields in the form of fluctuations from the trend are obtained.

\[
\hat{Y}_i = Y_i - \hat{Y}_i
\]

(4)

where: \( \hat{Y}_i \) is the climate dependent yield; \( Y_i \) is the actual yield, and \( \hat{Y}_i \) is the yield by the trend.

This technique is used by Ulanova (1984), where trends are extracted and the analysis of fluctuations from the trend line are given. In particular, those years from the past 35 years which were anomalous in the then USSR are identified from the point of view of agrometeorological conditions so that the increase of yield fluctuations over time can be examined.

The technique used in this section can also be applied to analyse rows of climate dependent components of yield to calculate normalized correlation matrices for the corresponding systems of random values.

\[
\begin{pmatrix}
1 & r_{12} & \ldots & r_{1n} \\
(1 & r_{23} & \ldots & r_{2n} \\
& \ldots & \ldots & \ldots \\
& & & \ldots & 1
\end{pmatrix}
\]

(5)

where: \( r_{ij} \) is the coefficient of correlation between the \( i \)th and \( j \)th rows of yields.

Section 3.1 reviews the multiple examples of the use of this technique. Anderson (1984) deals with the problem of the global synchronism of wheat yield, which shows the existence of a high level of coincidence of yield variation for basic grain producing areas in the northern hemisphere.

To study the structure of correlation matrices of yields (Equation 5), several approaches are used. One of the most simple approaches is to map the correlation isolines for the meteorological components of yield. Pasov (1986) shows a map for the yield of spring wheat for the territory of the former USSR centred in the Dneproropetrovsk region.

More complicated is the technique of analysing and calculating eigenvectors of the correlation matrix of the yield (Equation 5).

This approach is widely used for the analysis of meteorological fields (Meshcherskaia \textit{et al.}, 1970) and for forecasting (Sirotenko, 1971). The symmetric correlation matrix of the \( n \)th order after solving the complete problem of eigenvalues, the eigennumbers \( 1_1, 1_2, \ldots, 1_n \) are calculated along with the corresponding system of orthogonal functions \( u_1, u_2, u_n \) that possess some interesting qualities. Among the vectors \( u_1, u_2, u_n \) several (usually from one to three) are chosen with the maximum eigennumbers and are mapped.
CHAPTER 2

The study of the geographical distribution of the components of the first eigenvectors reveals the basic features of the fields under study. In some cases the fields can be related to patterns of general atmospheric circulation. This technique is used in Paasiv (1966) for the analysis of mean regional spring wheat yield.

To investigate the correlation matrices of the meteorological component of the yield, the Monte Carlo technique is very effective. Here the population of temporal rows of yield are viewed upon as a multi-dimensional distribution. The hypothesis of multi-dimensional normality is supplied as usual. The multi-dimensional normal distribution is known to be determined completely by the vector of mathematical equations \( \mathbf{y}^* = (y_1, y_2, ..., y_n) \) and correlation matrix:

\[
\begin{pmatrix}
(y_1^2 & m_{11} & \cdots & m_{1n}) \\
(m_{11} & V_1^2 & \cdots & m_{1n}) \\
& (m_{21} & V_2^2 & \cdots & m_{2n})
\end{pmatrix}
\]

\[ (m_{ij}) = \begin{pmatrix} m_{11} & m_{12} & \cdots & m_{1n} \\ m_{21} & m_{22} & \cdots & m_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ m_{n1} & m_{n2} & \cdots & m_{nn} \end{pmatrix} \]  

(6)

where: \( \mathbf{y}^* \) is the operation of transposition; \( m_{ij} \) is \( r_{ij} V_i V_j \), and \( V_i \) and \( V_j \) are the standard deviations.

The normally distributed vector \( \mathbf{V} \) that is required can be obtained as a result of linear transformation of the vector \( \mathbf{n}^* = (n_1, n_2, ..., n_n) \), components of which are the normally distributed values in the standardized scale,

\[ Y = \mathbf{An} = \bar{y} \]  

(7)

where:

\( \mathbf{A} \) is the triangular matrix

\[
\begin{pmatrix}
(a_{11} & 0 & \cdots & 0) \\
(a_{21} & a_{22} & \cdots & 0) \\
& (a_{31} & a_{32} & \cdots & a_{3n})
\end{pmatrix}
\]

(8)

determined from the condition:

\[ \mathbf{A^*A} = (m_{ij}) \]

The technique is easily computed using standard software.

Using the above technique, the yield rows with any record length (for example 500 years) corresponding to the given correlation matrix and the vector of mean values can be obtained. Yields for one year for \( n \) geographical regions are characterized for the 500 years. Potentialities of such data use are numerous enough. This can be used to assess very diverse situations, such as possible combinations of different levels of yields (the positive or negative anomaly in all places, or a combination of high yields in some regions and low yields in others, etc.).

There are some drawbacks to the approach described, such as the imperfection of the technique of trend separation and the drawback in the concept itself, i.e. separation of the two components of yield, the technological and meteorological ones.

It is not always accurate to assume that cultural practices, such as fertilization, treatment, varieties used, etc., do not change sharply from year to year. For example, the annual increase in rates of mineral fertilizer dressing in the USSR in 1961–65 was 3.25 kg/ha of arable land; in 1966–70 it amounted to 3.7 kg/ha, while in the following five year period it increased sharply up to 6.1 kg/ha. In 1976–80 it decreased to 1.6 kg/ha and then increased again to 6.7 kg/ha (Zagaitov, 1984).

It is also assumed that there is no trend in the meteorological component of the yield. The evidence available does not confirm this theory as there are, for example, many examples of a significant trend in precipitation, and the trend of \( \text{CO}_2 \) concentration in the Earth's atmosphere is particularly important because of its direct influence on plant productivity.
The technique of trend separation can be improved using the assumptions of Mershulun et al., (1983) which uses data on trends of economic indices. The trends of wheat yields for the USSR and USA for the period from 1945–77 were calculated as functions of the rate of mineral dressing, number of combined harvesters and tractors used, and electric energy used per hectare of arable land.

2.5.2 TECHNIQUES BASED ON CROP-WEATHER RELATIONSHIPS

The results of the investigation of the crop-weather system serve as the basis for better understanding of the relationships between climatic conditions and agricultural crop production. All the indices used for climate evaluation within the terms of the approach discussed are separated into two types, i.e. direct and derived indices. As per modern terminology, the direct indices are the models of the production process in the agroecosystem. Indirect indices are separate meteorological characteristics, or their simple functions, i.e. sums of temperature above a given threshold, sums of precipitation, sums of the air humidity deficit, ratio of precipitation to air temperature, balance of radiation to evaporation, etc. The main advantage of the indirect agroclimatic indices is their simplicity and availability. The main deficiency is that they are not connected directly with the growth and development of plants and the existence of such a relationship must be established with each dataset.

The direct indices, i.e. the crop-weather relationship models in their essence, are divided into three types (Sirotenko, 1981):

(a) Empirical-statistical;
(b) Physico-statistical;
(c) Dynamic models.

The work of Fisher in the field of finding empirical-statistical relationships for the yield calculations is considered to be basic by many researchers. As a result of processing numerous data on yield and meteorological observations, a number of regressions are derived. These form the basis of the system of the agrometeorological services to agriculture performance in a number of countries. The empirical-statistical models are very diverse in the factors used, and within the frames of a regression equation (usually a linear one). Diversity of soil and climatic conditions and agrotechnical peculiarities of crop growing are not reflected in any form in these equations. Each such relationship applies only to the local area where the factors accounted for in the model were measured. The regression analysis is not suited for a mathematical description of a crop-weather system which is multi-dimensional and nonlinear. More detailed approaches to this technique are available in literature (e.g. Sirotenko, 1971; 1981). Recently, new techniques have been used to build empirical-statistical models by regresional analysis, i.e. robust, ridge regression, etc.

Physico-statistical models of crop-weather relationships appeared as a solution to the mathematical difficulties in describing such a system. Such schemes were offered by Konstantinov et al. (1981), Dmitrenko (1973) and Baier (1973). Though different in form, these have the general tendency to use the theoretical information on the mechanics of the processes described. By way of example, the scheme by Baier is discussed. The basic equation of his model is:

\[ Y = \sum_{i=0}^{m} V_i \cdot V_2 \cdot V_3 \]  

(9)

where \( Y \) is the yield, and \( t \) is the biometeorological time by Robertson (1983), changing from \( t = 0 \) up to \( t = m \) (for the date of sowing \( t = 0 \), for the date of emergence \( t = 1 \), for tillering \( t = 2 \), etc.).

\( V_1, V_2, V_3 \), are the functions of meteorological variables, each of them has the form of:

\[ V = A_0 + A_1x + A_2x^2 \]  

(10)

where \( A_0, A_1, A_2 \), are the polynomial of the fourth degree from \( t \), and \( x \) presents in \( V_1, V_2, V_3 \), the daily values of solar radiation, minimum air temperature and the ratio of the actual evaporation to potential evaporation.
CHAPTER 2

The model parameters are evaluated using the data on spring wheat yield in Canada.

The model developed by Baier explains about 80 per cent of yield variation. It is a good example of the case whereby simple means robust models can be derived. The regressive model accounting for the same amount of information contains several hundreds of parameters for evaluation. A more robust model to describe the impact of hydrometeorological conditions is to use the dynamic models oriented on a description of the processes. So far, 50 dynamic models with different degrees of complexity have been developed. They simulate the development of practically all economically valuable agricultural crops (Sirotenko, 1981; Penning de Vries and van Laar, 1986; Whisler, 1986).

By way of example, the structure of a dynamic model of moderate complexity, developed by Sirotenko (1981) and Gringof and Sirotenko (1987) is discussed. The model comprises the closed system of differential equations, describing the phytomass dynamics, soil moisture (by 10 cm layers up to a depth of 150 cm) and the content of the available mineral soil nitrogen.

\[ \begin{align*}
\dot{m}_p &= G_p \cdot D_p \cdot Q_p \cdot P_p \\
W_i &= q_{i-1} \cdot q_i \cdot TR_i \cdot V_i E \\
N_i &= H_k \cdot d_k U_N - h_k + V_{k-1} - V_k \cdot A_k
\end{align*} \]  

(11)

**Figure 2.12**

Diagram of the model algorithm

... Nitrogen consumption by roots
where ($\bullet$) is the symbol denoting the derivative; $m_i$ is the mass of the $p^{th}$ organ of plant (leaves, stems, roots, grain hulls and grains are separated); $G_p$, $D_p$, $q_p$, and $P_p$ are rates of growth, respiration, destruction and death of tissues, correspondingly; $W_i$ is the moisture storage in the $i^{th}$ layer; $q_{i-1}$, $q_i$ is the flows of water through the upper and lower boundaries of the $i^{th}$ soil layer, correspondingly; $T_R$ is the water loss on transpiration from the $i^{th}$ soil layer; $E$ is the evaporation from soil; $N_k$ is the content of the available mineral nitrogen for the $i^{th}$ soil layer; $H_k$ and $h_k$ are the rates of mineralization and denitrification; $V_{k,1}$ and $V_k$ are the flows of mineral nitrogen with water through the upper and lower boundaries of the $k^{th}$ soil layer; $A_k$ is the nitrogen uptake by plants from the $k^{th}$ layer, and $d_k$ and $d_k'$ are the logical variables.

The diagram of the model algorithm is shown in Figure 2.12. In this model, growth is the process of structural mass building from the CO$_2$ fund ($m_c$) and is formed from the products of nitrogen consumption by roots photosynthesis (F) and the destruction of ageing plant structures (q). The daily photosynthesis of the agroecosystem depends on the intensity of photosynthetic radiation (PAR), 1, stomatal resistance (1/ct), temperature (QF), day length ($t$) and leaf area index (LG).

The model is run at a one day step. The model parameters have been identified for many grain and vegetable crops. The model uses standard meteorological information: mean air temperature (T), hours of sunshine (S), mean daily air humidity deficit (d) and daily amount of precipitation (R).

A comprehensive treatment of the modern state and trends of dynamic model development is given in Sirotenko (1981), Penning de Vries and van Laar (1986), Robertson (1983) and Plasier (1986). The last achievements in this field are presented in the review by Whisler (1986), where the characteristics of 30 dynamic models including the main crops are described (see Table 2.8).

### TABLE 2.8
Some process-level crop simulation efforts

<table>
<thead>
<tr>
<th>Research group</th>
<th>Institutions</th>
<th>Model name</th>
<th>Species</th>
<th>Process treated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Allen, J. and J.H. Smajper</td>
<td>University of Florida</td>
<td>CITRUSIM</td>
<td>Citrus</td>
<td>Photosynthesis</td>
</tr>
<tr>
<td>Angius, J.F., and H.G. Zandtma</td>
<td>CSIRO (Australia) and International Rice Research Institute</td>
<td>IRRIMOD</td>
<td>Rice</td>
<td>Growth, phasic development, soil water flow, soil nitrogen, transpiration, and evaporation</td>
</tr>
<tr>
<td>Arkin, O.F., J.T. Richie and R.L. Vanderlip</td>
<td>Texas A. &amp; M.U., USDA/SEA, and Kansas State University</td>
<td>SORG</td>
<td>Sorghum bicolor</td>
<td>Photosynthesis, respiration, transpiration, and evaporation</td>
</tr>
<tr>
<td>Brown, L.G., J.D. Heskerth, J.W. Jones and F.D. Whisler</td>
<td>Mississippi State University</td>
<td>COTCROT</td>
<td>Cotton</td>
<td>Photosynthesis, respiration, transpiration, runoff, drainage, nitrogen uptake, denitrification, leaching, organogenesis, partitioning and growth</td>
</tr>
<tr>
<td>Childs, S.W., J.R. Gilley and W.E. Splinter</td>
<td>University of Nebraska</td>
<td>Unknown</td>
<td>Corn</td>
<td>Photosynthesis, respiration, transpiration, growth, soil evaporation, and soil water flows</td>
</tr>
<tr>
<td>Curry, R.B., G.E. Meyer, J.O. Streeter and H.L. Medenski</td>
<td>Ohio Agriculture Research and Development Center</td>
<td>SOYMOD OARDC</td>
<td>Soybean</td>
<td>Photosynthesis, respiration, translocation and evaporation</td>
</tr>
<tr>
<td>Duncan, W.G.</td>
<td>University of Florida and University of Kentucky</td>
<td>SIMAIZ</td>
<td>Corn</td>
<td>Photosynthesis processes involved in setting seed number and seed size</td>
</tr>
<tr>
<td>Duncan, W.G.</td>
<td>University of Florida and University of Kentucky</td>
<td>MIMSOYZ</td>
<td>Soybean</td>
<td>Photosynthesis, nitrogen fixation, assimilate redistribution, processes for setting seed number and seed size</td>
</tr>
<tr>
<td>Duncan, W.G.</td>
<td>University of Florida and University of Kentucky</td>
<td>PEANUTZ</td>
<td>Peanuts</td>
<td>Photosynthesis, nitrogen fixation, processes for setting seed number and seed size</td>
</tr>
<tr>
<td>Research group</td>
<td>Institutions</td>
<td>Model name</td>
<td>Species</td>
<td>Process treated</td>
</tr>
<tr>
<td>----------------</td>
<td>--------------</td>
<td>------------</td>
<td>---------</td>
<td>-----------------</td>
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<tr>
<td>Fick, G.V.</td>
<td>Cornell University</td>
<td>ALSIM</td>
<td>Alfalfa</td>
<td>Photosynthesis defined as crop growth rate, and partitioning</td>
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<tr>
<td>Holt D.A., G.E. Miles, R.J. Bala, M.M. Schreiber, D.T. Doughtery, and R.M. Peart</td>
<td>Purdue University and USDA/SEA</td>
<td>SIMED</td>
<td>Alfalfa</td>
<td>Photosynthesis, respiration, growth, translocation and soil moisture uptake</td>
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<tr>
<td>Jones, C.A., and R.T. Ritchie</td>
<td>USDA/SEA (Texas) and IFDC, Alabama</td>
<td>CERESMAIZE</td>
<td>Corn</td>
<td>Photosynthesis, development, morphogenesis, growth, biomass accumulation and partitioning, soil water balance and plant-soil nitrogen status</td>
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<tr>
<td>Kercher, J.R.</td>
<td>Lawrence Livermore Laboratory</td>
<td>GROVI</td>
<td>General</td>
<td>Photosynthesis, transpiration, translocation</td>
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<td>van Keulen, H.</td>
<td>Netherlands Agricultural University (Wageningen)</td>
<td>GRORYZA</td>
<td>Rice</td>
<td>Gross assimilation and respiration</td>
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<tr>
<td>van Keulen, H.</td>
<td>Netherlands Agricultural University (Wageningen)</td>
<td>ARIDCROP</td>
<td>Natural vegetation in semiarid regions</td>
<td>Photosynthesis, respiration, transpiration, and water uptake</td>
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<tr>
<td>Lambert, J.L., D.N. Baker, and J.M. Mc Kinion</td>
<td>Clemson University and USDA/SEA (Mississippi)</td>
<td>RHIZOS</td>
<td>Soil</td>
<td>Infiltration, uptake, capillary redistribution, ET, nitrogen transformation, and fertilizer applications</td>
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<tr>
<td>Loomis, R.S. and E. Ng</td>
<td>Univ. of California-Davis</td>
<td>POTATO</td>
<td>Potato</td>
<td>Photosynthesis, respiration, transpiration, water uptake, growth, development and senescence</td>
</tr>
<tr>
<td>Loomis, R.S., J.L. Wilson, D.W. Rains, and D.W. Grimes</td>
<td>Univ. of California-Davis</td>
<td>COTCRO</td>
<td>Cotton</td>
<td>Photosynthesis, respiration, transpiration, water uptake, growth, development, flowering, fruit development, senescence, and heat flux</td>
</tr>
<tr>
<td>Loomis, R.S., G.W. Fick, W.A. Williams, W.H. Hunt, and E. Ng</td>
<td>Univ. of California-Davis</td>
<td>SUBORO</td>
<td>Sugar beet</td>
<td>Photosynthesis, respiration, transpiration, water uptake, plant development, and senescence</td>
</tr>
<tr>
<td>Masioli, A.</td>
<td>The Hebrew University of Jerusalem</td>
<td>ELCOMOD</td>
<td>Cotton (Acala)</td>
<td>Photosynthesis, respiration, growth, morphogenesis, ET, nitrogen uptake, and gravitational soil wetting</td>
</tr>
<tr>
<td>Mc Menamy, J.A. &amp; J.C. O’toole</td>
<td>International Rice Research Institute</td>
<td>RICEMOD</td>
<td>Rice</td>
<td>Photosynthesis, respiration, growth</td>
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<tr>
<td>Ortwick, P.L., M.N. Schreiber, and D.A. Holt</td>
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<td>SETSIM</td>
<td>Setaria</td>
<td>Carbon flow, photosynthesis, respiration, growth and translocation</td>
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<td>Ritchie, J.T. and S. Otter</td>
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<td>CERESWHEAT</td>
<td>Wheat</td>
<td>Photosynthesis, development, morphogenesis, growth biomass accumulation and partitioning, soil water balance, plant nitrogen status</td>
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<td>Weir, A.U., P.L. Bragg, J.R. Porter, and J.H. Rayner</td>
<td>Rothamsted Experimental Station, Letcombe Laboratory, University of Bristol</td>
<td>ARCWHATI</td>
<td>Wheat</td>
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<tr>
<td>de Wit, C.T. et al.</td>
<td>Netherlands Agricultural University (Wageningen)</td>
<td>PHOTON and BACROS</td>
<td>Any crop</td>
<td>Photosynthesis, respiration, transpiration, reserve utilization, water uptake, and stomatal control</td>
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<td>Wilkerson, G.O., J.W. Jones, K.J. Ingram and J.W. Mishoe</td>
<td>University of Florida</td>
<td>SOYORO</td>
<td>Soybean</td>
<td>Photosynthesis, respiration, growth, senescence, phenology, infiltration, drainage, transpiration</td>
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</tbody>
</table>
CHAPTER 3
IMPARTS OF CLIMATE VARIABILITY ON AGRICULTURE
AND FORESTRY

3.1 COLD LATITUDE CROPS
by M. Heikinheimo

3.1.1 The concept of cold marginality

The aim of this section is to consider examples of the observed impact of climate on agriculture in regions where the seasonal temperature cycle permits a growing season just long and warm enough for successful agriculture to be practised. Regions where thermal resources are the primary factor limiting the cultivation and growth of crops are typically in high latitudes (or at high altitudes), while moisture is more important in lower latitudes.

For Europe, locations north of latitude 55°N are considered. For North America, a case study of climatic impacts on the wheat production in the northern border of the wheat belt region is viewed.

Other agroclimatic constraints may often be coupled with or be a cause of cool climate. The length of the growing season, for example, is strongly affected by the occurrence of spring and autumn frosts, but is also dependent on the moisture conditions; soil which is cool and too moist in the spring, as well as heavy autumn rains, often further shorten the time for growth of crops.

Drought may also be a limiting factor in cold climate regions, such as the coastal areas of the Baltic Sea in northern Europe. Here, early summer is often very dry and the summer precipitation maximum occurs late in the growing season. Drought and low temperatures in winter may both be limiting factors for agriculture in some continental regions such as the high latitude border of the North American wheat belt.

The impact of short-term climatic fluctuations is of extreme importance in the agricultural border regions. Inter-annual variability in climate causes variations in crop yields and, where the average climate is marginally favourable for a particular crop, substantial losses can be expected in adverse years. Thus it is not surprising that in general the variability of crop yields increases towards the climatological cold margin. An agroclimatological margin may also be identified according to the geographical gradients in climate variability. For example, the variability in rice yields in Japan increases markedly as the inter-annual standard deviation of the July–August temperature increases above 1°C (Yoshino et al., 1988).

The cold marginal regions are also characterized by steep mean gradients of the agroclimatic (or terrain slope direction) potential in a more or less north-south direction, resulting in cultivation zones for a specific type of agricultural practice. For example, zones for the cultivation of bread grain, forage grain, and grasses (Solantie, 1986), or fruit trees and woody ornamental plants (Solantie, 1986) have been identified for Finland. The primary climatic factors determining the northern boundaries of these zones were the length of the growing season, the cumulative temperature during the growing season and the time between early and late frosts. Latitudinal limits defining the zones vary geographically because they depend, for example on the culture, the economy, the availability of suitable soil and the local climate of the region.

3.1.2 Concepts and methods of climate impact analysis

Climate impacts on managed ecosystems such as agriculture involve a complex network of interactions between the physical environment, plant physiological processes and human decision making. The list of possible impacts to be analysed is long. A climate change will change the agroclimatic potential of a region, and will produce geographical shifts in the potential, varying according to the type of climate considered. A climate change will be felt both as a change in the long-term means of climatic elements and as changes in the frequencies of short-term climatic events. Climatic impacts may appear as alterations in the level and quality of crop yield, and the farmer may respond by changing the selection of crop species and crop varieties within a region.
Such a response in agriculture is possible in one or two years, but much longer time periods are needed to see change in natural ecosystems or in forestry. Adoption of new (or abandonment of old) cultivation practices will depend on climate change and will be simultaneously affected by other resources, such as culture, economy and the availability of cultivable land.

To build a frame for analysing the observed impacts of climate in cold regions, some concepts recently used in climate impact assessment are introduced here briefly. For a more complete review see, for example, Parry et al., (1988) or Warrick et al., (1986).

3.1.2.1 Adaptation, adjustment and risk

In the long term, agriculture in a specific region has adapted itself to the prevailing climate, having settled with practices, such as selection of cultivars and technology, that best fit the natural and economic resources of the area. Adaptations evolve over the long term (greater than several generations) and may not always have a direct relationship to climatic or environmental fluctuations.

Temporarily adverse weather or a prolonged climatic anomaly may cause the farmer to adjust by, for instance, consciously adopting alternative practices such as selection of more suitable crop varieties, and using grain or irrigation reserves to cope with environmental fluctuations.

The climatic risk to agriculture is a result of short-term year-to-year variability of climate rather than long-term changes in the means of climatic factors. Towards the cold margin of agriculture, the impact of climatic risk, assessed from the probabilities of hazardous agroclimatic measures, eventually becomes so large that no counteracting measures can be taken to avoid crop failure in certain years.

The concepts of adaptation, adjustment and risk in climate impact research are well illustrated by considering the frequency distribution of a climatic element critical for the agriculture of a specific region (Figure 3.1). The zone of adaptation

---

**Figure 3.1**

Geographical changes in the northern cultivation of cereal crops in Finland, during the period from 1930 to 1975.

From Varjo (1977)
lies at the centre of the distribution, while the zones of adjustment lie more towards the outer edges. Here counteractivity such as frost protection, irrigation or selection between short-season and long-season varieties is necessary to cope with climatic risks of various types. Hazardous climatic events, representing the outer distribution edges, cause frequent crop failure at the environmental border of agriculture. At the border, the farmer is unable to adjust and has to take a greater economic risk, because he is forced to manoeuvre away from the adaptation zone of the distribution. In developed agriculture the level risk of crop failure induced by climate fluctuations and the comparative advantage between competing agricultural activities are factors which help to determine why some crops are grown in a region and some not (Parry and Carter, 1988).

It is evident from the shape of the frequency distribution of climatic variables that for a relatively small change in the mean there will be a large change in the frequency of extreme events, provided that the variability of climate remains constant. For example, Parry and Carter (1985, 1988) have demonstrated that in northern Europe near the present altitudinal limit of cereal cropping in Scotland, a 0.6°C increase in mean annual temperature can decrease the frequency of cool summer crop failure by a factor of 14. The effect of two cool summers occurring in consecutive years would further worsen the economic impact of such events.

3.1.2.2 Marginal-spatial analysis

Marginal-spatial analysis focuses on both the agricultural impacts within the marginal cultivation zones and the spatial shifts in the boundaries of these zones. The shifts would be particularly noticeable in cold latitudes where climate change on the one hand and the spatial ecosystem response on the other are expected to be most pronounced.

One way to analyse possible geographical shifts in agricultural practices, as discussed by Warrick et al. (1986), is to make parallels between natural ecosystems and agriculture, the so called spatial-ecologic approach. The method assumes that spatial cropping zones are largely regulated by climate and to a lesser degree by human influence. Under a climate change these zones would be forced to shift in a similar way to natural ecosystems without much influence from the side of human decision making.

The advantage of this approach is that it gives simple, early information about a possible change in the agricultural capacity of a region based, say, only on the data of the growing season length or accumulated degree days. Although practical and relatively easy to apply, the spatial-ecologic approach is, however, limited in many respects.

The method lacks, for example, a sound physical explanation of how the cropping zones are connected to the climatological indexes used. The other drawback is that in reality agriculture is able to respond much faster to a climate change than natural ecosystems in which species compete with each other. This is because in his managed ecosystem, the farmer is largely free to make choices about a crop cultivar or types of crop and practice at the start of each growing season.

Examples based on past climate data give a useful perspective on the applicability of this approach.

3.1.2.3 Spatial-economic approach

The other approach, termed spatial-economic, is to focus on the change in climatic risk and its economic impacts that evolve from season to season. This approach takes better account of the impact of short-term climate fluctuations and of economic decision making by farmers. Changes in the risk of crop failure, for example, can lead to adoption of new crops or crop varieties or, at the other extreme, abandonment of farms.

Parry and Carter (1985), for example, using a long-term temperature record, analysed the climatological risk of oat cultivation at their elevational margin in Scotland. Crop failure was assumed to occur when the growing season accumulated temperature sum failed to exceed 970 degree days. Frequencies of 1 in 10 and 1 in 50 for the occurrence of such a cool season were chosen to define the upper and lower borders of the high risk zone. The location of this zone would shift in the direction of elevation according to changes in climate. For a change from a cool period to a warm period the risk zone was estimated to shift about 85 m upwards.
CHAPTER 3

3.1.2.4 Crop-climate models

Case studies focusing on the impacts of historical climate periods on agriculture have traditionally relied upon the evaluation of agroclimatic indices or empirical-statistical relationships between climate and crop yield. Agroclimatic indexes are useful for obtaining information about the agroecological potential of a region. With empirical-statistical models, the relationship between crop yields and a number of climate variables is established by statistical methods such as regression analysis (see Section 2.5). These models have appeared to apply best in areas where crop production is strongly sensitive to a single climatic variable. Statistical models are useful when selecting the most important climatic variables, but they appear to be specific and have also the weakness of not supplying information on the functional relationships between the growth of crops and their physical environment.

During the two most recent decades there has been an increasing emphasis on crop simulation models which better account for the basic physical and physiological processes involved in the soil-plant-atmosphere continuum. The simulation models are particularly useful in assessing the impacts for climate scenarios outside the range of the observed climate variability, for which the use of empirical-statistical relationships may not apply (see Section 2.5).

3.1.2.5 Integrated approach

Climate can affect various levels of a human managed environmental sector such as agriculture or forestry. First-order relationships appear between the climatic variables and the biophysical supply or demand. Second-order effects are seen at various management levels, for example in the economy of a farm, in regional employment, and in national economy. Recently the main effort in climate impact research has moved towards an integrated assessment, in which climate is considered as one factor among the many societal or environmental factors affecting agriculture.

Methods of a partially integrated climate impact assessment were applied in the project supported jointly by the International Institute for Applied Systems Analysis (IIASA) and the United Nations Environment Programme (UNEP) as part of the World Climate Impact Studies Programme (WCIP) (Parry et al., 1988). The overall goal of the IIASA/UNEP project was to compile our present understanding of the first-order effects on agricultural productivity and assess their higher order effects on regional and national economies. Volume 1 of the above project report deals particularly with impacts of climate variations on agriculture in the cool temperate and cold regions, and represents the most recent large-scale effort in the climate impact research sector. Assessments of climate impacts were made in the form of case studies from regions representative of different types of agricultural practice, culture and economy.

In the IIASA/UNEP project, first-order biophysical models were constructed to reveal both the direct and indirect effects of climate on crop growth, crop yield and livestock production. Some case studies also incorporated economic models of various levels, namely those dealing with farm, regional or national level agricultural production and income. Short- and medium-term anomalies in climate were selected from the historical instrumental record as experiments covering the range of typical past fluctuations. Scenarios of the future climate corresponded to the modelled equilibrium state of the atmosphere under conditions of doubled atmospheric CO₂. To allow comparisons between regions, the GISS 2 x CO₂ scenario was used in each case study. Assessments of the climate impacts on agriculture were made by comparing present day baseline climate and agriculture (the period from 1951 to 1980) with the scenario periods.

The advantage of this approach is that it gives simple early information about a possible change in the agricultural capacity of a region based, say, only on the data of the growing season length or accumulated degree days. Although practical and relatively easy to apply, the spatial-ecologic approach is, however, limited in many respects. The studies reviewed in the next section are based on observed historical
climatological and agricultural data, and are based principally on the IIASA/UNEP project results. The discussion of the future climate scenarios for cold latitude regions is in Section 5.1.1.

3.1.3 Specific Case Studies

3.1.3.1 Western Canadian prairies

One of the case studies (Williams et al., 1988) of the IIASA/UNEP project for cold and cool temperate regions focused on the impacts of climate on wheat production and agricultural economy in the Canadian province of Saskatchewan. The province, located between 49°N and 60°N, covers nearly 40 per cent of Canada's farmland and produces nearly 60 per cent of Canada's wheat. The southern part of the province (south of 55°N) is fertile arable land, belonging to the North American wheat belt. The best arable land is in the southern central region, where soils are predominantly dark brown or black coloured, moderately calcareous and mainly loamy in texture. The southwestern corner of the province is less productive because of a higher moisture deficit in the summer, and its rougher terrain and higher altitude. Latitudinal shifts in cereal cultivation northward through 55°N are largely prevented by the pre-Cambrian shield that dominates the terrain in the region north of the present agricultural zone. A large-scale environmental problem in Saskatchewan is land degradation caused by wind erosion and cultural practices that fail to retain the fertile top soil organic matter. These processes have contributed to a 40–50 per cent decline in the organic matter of the soils since 1900.

The climate in Saskatchewan is markedly continental due to its location in the lee of the Rocky Mountains. Agroclimatic constraints consist mainly of the relatively short frost-free season, averaging 90–120 days with a minimum of 50 days and a maximum of 150 days. Average annual precipitation ranges from 300 mm in the southwest to 500 mm elsewhere in the province. Although the wettest month (about 60–80 mm per month) is June, a considerable degree of moisture limitation during the growing season is characteristic of most of the agricultural area of the province. The climate of Saskatchewan is in sharp contrast to the study areas of Iceland and Finland also reviewed in this section.

Although towards the northern border the frost-free season becomes marginally longer for spring wheat cultivation, the relatively large inter-annual variation in moisture reserves is reported to be the main cause of the great variability in crop yields in the province. Other factors such as pests, diseases, hail or delayed seeding due to very wet or very dry soils may degrade the yields, but these effects as well as the effects of frost tend to have less impact on final yield, and are often local rather than regional in scale.

Provincial spring wheat yields have varied, for example, between a low of 573 kg/ha in 1961, caused by severe drought, and a high of 1861 kg/ha in 1966. Climate was estimated to account for as much as 90 per cent of this difference. During the 20th century, a series of drought years between 1929 and 1938, including the occurrence of two consecutive drought years in 1937 and 1938, coinciding with an economic depression led to a large-scale abandonment of farms.

More recent drought periods, such as that from 1957–68, have contained more isolated drought events and, because of the improved economy, the effects have been felt mainly through the national trade balance rather than at the level of farm economy.

A series of models was used to simulate the change in the agroclimatic environment under different climatic scenarios. Changes in the indices relative to the baseline period are shown in Table 3.1 for accumulated degree days (base 5°C), Thornthwaite's precipitation effectiveness index, the index of agricultural potential, which reflects both thermal and moisture resources, and the potential for wind erosion. The gross biomass production capacity for spring wheat was calculated from its photosynthetic response to temperature and radiation, a maintenance respiration coefficient and the number of days to reach maturity. The development rate was estimated by a phenological model according to temperature and photoperiod. The calculation of potential spring wheat yields included the assumption of a sigmoidal cumulative growth curve. To calculate the actual dry matter yield, the only environmental constraint considered was moisture stress.

Based on the study by Williams et al. (1988), the core spring wheat production region in Saskatchewan is prone to the effects of occasional drought
periods, during which the yields are reduced and the agricultural economy tightened. Single anomalous drought years may occasionally cause losses greater than 70 per cent in the provincial production of spring wheat. These first order effects of climate would reflect upon provincial economy as significant reductions in average farm income, purchasing power and provincial employment in the agriculture and related sectors. Overall, the Canadian province of Saskatchewan represents a region having both a high agricultural productivity and a location on the climatological cold margin of agriculture. A climate warming would make the presently uncultivated regions in the north potentially cultivable. However, northward shifts in agriculture are largely prevented by the unfavourable soils in the north.

### TABLE 3.1

<table>
<thead>
<tr>
<th>Model/parameter</th>
<th>Dry year (1960)</th>
<th>Dry period (1929–1938)</th>
<th>Future scenarios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>GISS1</td>
</tr>
<tr>
<td>Agricultural potential</td>
<td>-100 to -53%</td>
<td>-60 to -26%</td>
<td>+1 to +30%</td>
</tr>
<tr>
<td>Spring wheat yields</td>
<td>-78%</td>
<td>-29 to -9%</td>
<td>-12 to -4%</td>
</tr>
<tr>
<td>Precipitation effectiveness</td>
<td>-53 to -18%</td>
<td>-26 to -21%</td>
<td>+1 to +13%</td>
</tr>
<tr>
<td>Degree days</td>
<td>+10 to +18%</td>
<td>+3 to +16%</td>
<td>+48 to +53%</td>
</tr>
<tr>
<td>Agroclimate: (May–August)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Provincial economy: (1933–1937)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Provincial wheat production</td>
<td>-76%</td>
<td>-20%</td>
<td>-18%</td>
</tr>
<tr>
<td>Farmhouse income</td>
<td>-78%</td>
<td>-25%</td>
<td>-7%</td>
</tr>
<tr>
<td>Employment in agriculture</td>
<td>-9.1%</td>
<td>-3.0%</td>
<td>-0.8%</td>
</tr>
<tr>
<td>Household purchasing power</td>
<td>-38.3</td>
<td>-12.7%</td>
<td>-3.4%</td>
</tr>
</tbody>
</table>

GISS1: a 2 x CO2 climate scenario allowing precipitation increase  
GISS2: a 2 x CO2 climate scenario not allowing precipitation increase

The possibility of a partial shifting from spring wheat to winter wheat, as an adjustment to adverse drought effects, was also evaluated. During years with mild winters, the cultivation of winter wheat in Saskatchewan has many advantages (Williams et al., 1988): the yield is about 25 per cent higher than for spring wheat; the moisture from winter precipitation is better exploited; winter wheat is less subject to cold injury during frost spells in the early summer; by sowing in the autumn the farmer's operations in the field are more evenly spread over the growing season; and winter wheat helps to mitigate wind erosion and other soil degradation effects in the spring. The evaluation of economic benefits revealed that cultivation of about 10 per cent of the spring wheat area with winter wheat would be advisable during drought years, but not in years with near normal climate.

Nevertheless, there has been an increase in the sown area of winter wheat from 18,000 ha in 1982 to 141,000 ha in 1983, and even to 400,000 ha in 1984 (according to provincial crop insurance statistics). Part of this increase was explained by the mild winters during the early 1980s.

**3.1.3.2 Northern Europe**

In northern Europe, particularly the Fennoscandian region (consisting of Norway, Sweden and Finland), extensive agriculture is practised at higher latitudes than anywhere else, due to the warming effective temperature sum (ETS) of the Atlantic Gulf Stream. All arable crops meet their northern limit of cultivation here. Extensive cultivation of spring wheat, winter wheat and rye is practised in southeast Norway, southern and central Sweden and southern Finland up to a latitude of 62°N, coinciding with an average of 1 100 degree days (base 50°C). In Iceland, the majority of agriculture is concentrated around animal husbandry and for the provision of hay and grasses as fodder. In Fennoscandia, the northern limit for forage crops is found in the northern river valleys of the Gulf of Bothnia shore belt (66°N), where the ETS averages near 900 degree days. Crops that require a long growing
season and high ETS, such as soybean or grain maize have been grown experimentally up to about 61°N during the warmest seasons and on the most favourable sites. Otherwise the northern limit for stable production of these crops lies near 55°N.

The basic climatological limitation to agriculture in northern Europe is the short growing season, lasting on average 180 days at the latitude of 60°N (with ETS near 1 200 degree days) and 130 days at latitude 66°N (ETS near 800 degree days), which is considered the northern boundary of the hardiest arable crops. The shortness of the growing season is compensated, in part, by the longer days during summer in the north, so that the total receipt of solar radiation varies little latitudinally. The effect of longer days is to reduce the time of development of crops. The first two or three weeks from the beginning of the growing season are normally unfavourable for sowing because of soil which is too wet and cool. Spring and early summer are relatively dry especially in coastal regions of the Baltic sea, even to the extent that an early summer drought may in some years suppress growth and the formation of yield. The annual precipitation maximum normally occurs in August–September, coinciding with the time of harvesting of long-season varieties and the sowing of winter cereals. The risk of harvest failure due to autumn frosts and excess rain is pronounced during cool summers. Wet weather has also, for example in Finland, delayed the sowing of winter wheat, resulting in the failure of wintering and occasional large reductions (up to 50 per cent) in the harvested area (Mukula and Rantanen, 1989).

The extension of agriculture further northwards in Sweden and Norway is more limited by geography and soil texture than in Finland, where soils are homogeneous and predominantly either fine sand or peat. Along with the cultivation of field crops, animal husbandry and forestry are often simultaneously practised on northern Fennoscandian farms to bring stability to the farm economy.

The case studies reviewed in this section were co-ordinated by the IIASA/UNEP programme and performed by Bergthorsson et al. (1988) for Iceland and by Kettunen et al. (1988) for Finland.

3.1.3.2.1 Iceland

Iceland is located at latitudes 64°30'-66°0'N near the boundary between the warm sea current from the southwest Atlantic Ocean and the cold sea current from the northwestern Arctic regions. The climate of Iceland is markedly maritime, characterized by mild winters and cool summers. For example, the October–April long term mean temperature for Stykkisholmur (western Iceland) is +0.7°C and the May–September mean temperature is +8°C. Mean annual precipitation in the southwest part of the country is near 1 000 mm, with a monthly mean in May–July near 40 mm, increasing to 50 mm in August and to 80 mm in September. Characteristic of the climate variations in Iceland is the persistency of climate anomalies (warmer or cooler than average years tend to be clustered near each other) due to the presence of sea ice around the island, and the relatively large amplitude of the long-term annual temperature fluctuation. For example, the decadal amplitude from 1851–1950 for Stykkisholmur is 0.74°C compared with 0.21°C for Edinburgh in the British Isles or 0.14°C for Berlin, representing the western European continent (Bergthorsson, 1985).

Both technologically developed agriculture and the boreal forest zone meet their northernmost limits in Iceland. The majority of agriculture is focused on livestock production and the provision of grazing and fodder. Barley is used as a partial supplement for hay, but the cultivation of barley as well as the planting of hardy trees is limited to a few sheltered lowland locations, and is feasible only during warmer than average years. The native birch covers about one per cent of the land area. There is considerable interest in the cultivation of birch and Norwegian spruce for timber and to provide shelter for crops and livestock.

Temperature can be considered the dominating climatic factor affecting agricultural production in Iceland. Precipitation during the summer months is important for barley production (with lower precipitation, the development rate of the barley crop is faster), but is noted to be of minor importance over long climatological periods and when agriculture for the whole country is considered. In
the special case of Iceland, the yield of grasses and hay is largely determined by the 
success of overwintering of these crops. Typical factors affecting fodder yields include,
for example, severe frosts during snow-free periods, successive thaw and freeze
periods, and deep ground frost resulting in low soil temperatures in the spring.

Berghorssson et al. (1988) used simple linear and second degree regression
models to simulate fodder yield variation as caused by climate variations. The
climatological model for hay incorporated three components: May–September mean
temperature, October–April mean temperature and the application of nitrogen
fertiliser in kg/ha. The annual application of nitrogen was estimated from the amounts
of artificial manure used and from estimates of natural manure input from livestock.
The return of natural manure in the form of active nitrogen was assumed to be 1 kg per
100 kg of forage used. The correlation coefficients between the computed and the real
yield varied between 0.89 and 0.98, depending on the period used, indicating good
applicability of the model within the range of observed climate variability.
Extrapolation to conditions such as the significant climate warming dictated by the
2 x CO₂ scenario of the GISS model should, however, be treated as suggestive only.

The climate scenarios selected by the Icelandic case study were the extreme
cold period of the little ice age from 1859–68, a collection of the 10 warmest and the
10 coldest years between 1931 and 1984, and the proposed equilibrium climate in
the doubled atmospheric CO₂ situation according to the GISS model. The impacts
of climate on agriculture in Iceland in the different scenarios are summarized in
Table 3.2.

To summarize, the climatic impacts on hay yield, livestock fodder
requirements and carrying capacity, and the potential cultivation of barley, birch and
Norwegian spruce were estimated for Iceland. For grass growth and livestock farming,

| TABLE 3.2 Estimated impacts of climate on hay production in Iceland (from Berghorssson et al., 1988) |
|---------------------------------------------------|-------------------------------|-------------------------------|-------------------------------|
| (a) Change of mean temperature (°C) and hay yields (per cent) for a constant fertilizer application (N application 160 kg/ha) relative to the baseline period (1951–1980). |
| (b) Change in percentage of weather stations permitting cultivation of barley, birch and Norwegian spruce. |
| (c) Required change of fertilizer application relative to baseline period (1951–1980) to maintain a constant annual hay yield (4000 kg/ha) in the selected scenarios. |
|---------------------------------------------------|-------------------------------|-------------------------------|-------------------------------|
| (a) Climate |
| Temperature (°C) (Oct.–Apr.) | 0.6 | -1.7 | -1.1 | +1.3 | +4.2 |
| Temperature (°C) (May–Sept.) | 8.0 | -0.6 | -0.4 | +0.9 | +3.7 |
| Precipitation (mean annual) | 704 mm | -9% | -3% | +12% | +15% |
| Hay yield | 4620 kg/ha | -19% | -13% | +18% | +66% |
| Hay needed for feeding live-stock cattle | 100 | +5% | +3% | -5% | -16% |
| Sheep, horses | 100 | +22% | +14% | -16% | -53% |
| (b) Extent of agriculture |
| Percentage of stations permitting cultivation |
| Barley (50% of years) | 4% | 0% | 0% | 60% | 100% |
| Birch | 29% | 4% | 10% | 85% | 100% |
| Norwegian spruce (8%) | 8% | 0% | 0% | 71% | 100% |
| (c) Use of fertilizer to keep hay field constant at 4000 kg/ha |
| Nitrogen | 110 kg/ha | +55% | +31% | -24% | -55% |
| Phosphorus | 31 kg/ha | +31% | +29% | -19% | -45% |
| Potassium | 79 kg/ha | +27% | +15% | -10% | -25% |
the effects of cooler than average conditions were to reduce the potential productivity and simultaneously to increase fodder requirements. Cultivation of barley would be inadvisable during the extreme cold period and the hardest trees would produce growth only in some sheltered lowland locations. In warmer than average years, similar to those that would not occur more often than once every five years, the productivity of fodder is significantly improved, as well as the potential for the land to support greater numbers of livestock. Cultivation of barley, birch and Norwegian spruce would be viable over more than half of the inhabited area of Iceland.

3.1.3.2.2 Finland

Finland is in the boreal vegetation zone between of 60°N and 70°N. Soils in the southwestern and western Baltic sea coastal belt are predominantly alluvial clay and fine sand, changing to tills in the central region. Peat soils are characteristic of the northern district. Two-thirds of the country is under forest and less than one-tenth of the area is agriculturally managed.

Farming in Finland is based on field cultivation, animal husbandry and forestry. A noticeable general trend in Finnish agriculture during the first half of the present century was an overall intensification of farming and increasing trends in production. During the period from 1920–35, hectare yields of field crops increased by 1.4–2.2 per cent per year depending on species (according to data by Westermark, 1950). The impact of climate warming on the increases in crop yields was concluded qualitatively to be important, but the quantitative contribution of the different factors such as climate, introduction of new cultivars and improvements in farming technology, was not resolved (Wallen, 1984).

During the post-war period, increases in the yields of field crops were slow at first but intensified in the mid-60s. The trends in hectare yields for the period from 1950–82 were on the average 3.4 per cent per year for spring wheat, 1.2 per cent per year for rye and 2.8 per cent per year for barley. The smallest trends were obtained on the northern margin of cultivation of these crops. The contribution of climate to these trends was estimated to be small, with nearly half of the rise in yield levels attributed to the development of domestic plant varieties, and the other to increases in fertilizer use (Elonen, 1983).

The northern limits of cereal cultivation during the period from 1930–75 are depicted in Figure 3.1. Concurrently with the intensification of farming in 1920–30, the cultivation of barley was even extended to the northern parts of Lapland, but a gradual southward shift of the cultivation border occurred in the post-war period. The northern limit of spring wheat and rye cultivation appears to have retreated from southern Lapland in 1950 to the lake district in south central Finland. Also a shift southwards is seen in the pattern for oats after 1950. It is interesting to observe that the rather distinct southward shift of the northern border for these crops coincides with the gradual cooling of climate after 1950 which continued until about 1975. Other factors such as changes in the relative profitability of these crops are noted to have been important in contributing to the shifts (Kettunen et al., 1988).

A recent case study (Kettunen et al., 1988) has been conducted as part of the IIASA/UNEP project, to obtain quantitative estimates of the impact of climate on agriculture in Finland. As an example, the results for barley and spring wheat are briefly discussed here.

As in the previously reviewed studies for Saskatchewan and Iceland, contrasting climate scenarios were selected from the historical climate record: a cool period from 1974–82 and a warm period from 1966–73. To assess impacts of climate change for the near future, the GISS model climate scenarios, corresponding to an equilibrium situation under a 2 x CO₂ atmosphere, were used. The different scenario periods were compared with a reference period from 1951–80.

To explain deviations in yield from the trend due to meteorological factors, a multivariate selective regression analysis was applied. The growing season was divided into successive phases based on the phenological development of the crop. The lengths of the phases were determined according to ETS values selected to fit the transition from one phase to another. The model for spring wheat yields
CHAPTER 3

explained 81.5 per cent of the variation in yield, while the model for barley explained 56 per cent and 72 per cent of the variation for northern and southern Finland, respectively. A summary of results is shown in Table 3.3. In southern Finland the effect of a warm period was to slightly reduce barley yields but to increase spring wheat yields. Concurrently the variability of yields for both crops was lower compared with the baseline period. During the cool scenario, yields for barley increased slightly, but spring wheat yields declined. The effect of a cool period was also to increase the variability of yields for both crops.

In northern Finland the results for barley are rather inconclusive. For a warm period, spring wheat yields increased with a decline in yield variability and for a cool period yields were reduced with no change in variability.

<p>| TABLE 3.3 Effect of climatic variations on agricultural production in Finland |</p>
<table>
<thead>
<tr>
<th>-------------------------------------------------</th>
<th>----------------</th>
<th>----------------</th>
<th>-----------------</th>
<th>-----------------</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOUTHERN FINLAND</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective temperature sum</td>
<td>1263 degree days (121)</td>
<td>-5% (-4%)</td>
<td>+2% (-39%)</td>
<td>+37% (+0%)</td>
</tr>
<tr>
<td>Mean May–October precipitation</td>
<td>342 mm (67) -3% (-14%)</td>
<td>+50% (+0%)</td>
<td></td>
<td>+7% (+29%)</td>
</tr>
<tr>
<td>Crop yields:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barley</td>
<td>3075 kg/ha (429)</td>
<td>+4% (+17%)</td>
<td>-8% (-28%)</td>
<td>+9% (+37%)</td>
</tr>
<tr>
<td>Spring wheat</td>
<td>2300 kg/ha (450)</td>
<td>-15% (+22%)</td>
<td>+10% (-50%)</td>
<td>+10% (-11%)</td>
</tr>
<tr>
<td>NORTHERN/CENTRAL FINLAND</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Effective temperature sum</td>
<td>1080 degree days (134)</td>
<td>-2% (-15%)</td>
<td>+3% (-10%)</td>
<td>+35% (+0%)</td>
</tr>
<tr>
<td>Mean May–October precipitation</td>
<td>313 mm (61) -9% (-5%)</td>
<td>+59% (+0%)</td>
<td></td>
<td>+2% (+19%)</td>
</tr>
<tr>
<td>Crop yields:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barley</td>
<td>2560 kg/ha (479)</td>
<td>-1% (-39%)</td>
<td>+3% (-39%)</td>
<td>+14% (+37%)</td>
</tr>
<tr>
<td>Spring wheat</td>
<td>2000 kg/ha (400)</td>
<td>-12% (+0%)</td>
<td>+15% (-25%)</td>
<td>+20% (+25%)</td>
</tr>
</tbody>
</table>

Crop yields under a warm scenario tended to be more dependent on thermal resources in northern than in southern Finland. Table 3.3 shows the effect of climatic variations on agricultural production in Finland, with baseline values given in the first column. Estimates are relative to the 1959–1983 baseline climate and assuming ca. 1980 technology level.

Values in parentheses are standard deviations (or indicating a change of scenario values relative to baseline values), from Kettunen et al. (1988).

Southern Finland crop yields during the warm period were occasionally reduced by drought during early summer while in northern Finland a slightly increased moisture deficit did not cause problems. Cool periods coinciding with above normal rainfall tended to reduce yields over the whole country. In conclusion, precipitation appeared to be important in explaining the differential responses of barley and spring wheat yields to the warm and cool scenario climates.

According to the GISS2 × CO₂ scenario, increases in precipitation and thermal resources introduce a climate outside the observed variability in the instrumental record. Simulated effects of the 2 × CO₂ scenario on the cultivation of barley and an adapted spring wheat variety indicated increases in hectare yields only slightly greater than those for the warm period from 1966–73. Warmer conditions would allow new long-season varieties to be grown in the south and the extension of present day varieties towards the north. Excess rainfall, if coincident with warmer temperatures would, however, somewhat reduce the generally positive effects of warm climate periods on crop production in Finland.
3.2 TEMPERATE CROPS—WHEAT
by O.D. Sirotenko

This section gives examples of the impact of climate variability on wheat yield as determined by the crop weather models described in Section 2.5. The problems of adaptation, in the case of temperate crops, is similar in some respects to those of cold latitude crops (see Section 3.1.2.1). The zone of adaptation lies at the centre of the distribution of a critical climatic element, while the zone of adjustment lies more towards the tails. Hazardous climatic events, cause frequent crop failure at the environmental border of the temperate cropping activity.

Critical types of climatic variability to temperate cropping include changes in climatic extremes and changes in thermal limits to agriculture. A number of estimates have been made concerning the shift in productive potential in temperate zones (Parry et al., 1989; Salinger et al., 1990) because of year-to-year variability. These suggest a 1°C change in mean annual temperature would tend to change the thermal limit of cropping by about 150–200 km of latitude, and change the altitudinal limit by 150–200 m. Warming in core areas of current production may reduce yield potential because of more rapid maturation. This shortens the grain filling period. An important additional effect is the change in winter chilling. Low chilling in warm years results in low flower bud production and ultimately reduces yields.

Adaptability to variability is most difficult at the warm and cold margins of a crop's range in the temperate zone. However, even in a crop's core area, yield potential can be affected.

3.2.1 STATISTICAL ANALYSIS OF YIELD DATA

From the value of climatic component of yield, Cm, (Equation 3, Section 2.5) the climatic favourability to obtain sustainable yields can be judged. The main grain producing countries of the northern hemisphere can be compared by this index. The higher the value of Cm, the more efforts are needed to obtain the sustainable yields.

Table 3.4 (Pasov, 1986) presents the climatic components of the yield fluctuations. The index suggests that the climatic conditions of the USA are better for more sustainable yields, than the climatic conditions of the then USSR. For most countries of Europe (Table 3.5) Cm is also considerably lower than for the then USSR. The relationship between Cm and the degree of climate continentality is brought out clearly.

<table>
<thead>
<tr>
<th>TABLE 3.4</th>
<th>Climatic component of yield fluctuation of wheat Cm on the territory of the former USSR, USA and Canada (Pasov, 1986)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Spring wheat</td>
</tr>
<tr>
<td></td>
<td>Former USSR</td>
</tr>
<tr>
<td>Economic regions</td>
<td>Economic regions</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>0.33</td>
</tr>
<tr>
<td>Volga</td>
<td>0.23</td>
</tr>
<tr>
<td>Ural</td>
<td>0.27</td>
</tr>
<tr>
<td>West Siberia</td>
<td>0.34</td>
</tr>
<tr>
<td>East Siberia</td>
<td>0.16</td>
</tr>
<tr>
<td>Central</td>
<td>0.19</td>
</tr>
<tr>
<td>USA (total)</td>
<td>0.14</td>
</tr>
<tr>
<td>States</td>
<td>States</td>
</tr>
<tr>
<td>North Dakota</td>
<td>0.19</td>
</tr>
<tr>
<td>South Dakota</td>
<td>0.28</td>
</tr>
<tr>
<td>Minnesota</td>
<td>0.22</td>
</tr>
<tr>
<td>Montana</td>
<td>0.10</td>
</tr>
<tr>
<td>Idaho</td>
<td>0.08</td>
</tr>
<tr>
<td>Washington</td>
<td>0.15</td>
</tr>
<tr>
<td>Canada (provinces)</td>
<td>Canada (provinces)</td>
</tr>
<tr>
<td>Manitoba</td>
<td>0.18</td>
</tr>
<tr>
<td>Saskatchewan</td>
<td>0.24</td>
</tr>
<tr>
<td>Alberta</td>
<td>0.15</td>
</tr>
</tbody>
</table>
CHAPTER 3

Another technique to investigate yield fluctuations due to climate is by correlation analysis. Table 3.6 is the correlation matrix of rows of wheat yield with the linear trend removed for the basic grain producing countries of the world. There is clearly synchrony in wheat yield fluctuations. All the coefficients of correlation (but two) are positive, and 11 correlations coefficients are significant at the 5 per cent level of significance, and seven coefficients at the 1 per cent level. Thus the agrometeorological conditions of wheat yield production in the northern hemisphere vary interannually with a high degree of synchrony which could be caused by common planetary processes in the atmosphere. The highest degree of synchrony is between the former USSR and the USA, India, and EEC countries. This is important because more than one third of the world wheat yield comes from North America and the former USSR, while the EEC countries are next in the total harvest of wheat (Anderson, 1984).

The recurrence of the negative anomalies simultaneously in the three most important regions of spring wheat production (Kazakhstan, Volga region and the Urals) amounted to 26 per cent, while the recurrence of the common negative anomaly for six economic regions amounted to 7 per cent, which is four times greater than the zero level. The expansion method by orthogonal components is used to typify yield fluctuations for the then USSR (Pasov, 1986). The first eigenvector describes about 20 per cent of the variance, the first three eigenvectors describe about 47 per cent. The most important conclusion drawn from the analysis of the first eigenvectors of the climate dependent yield matrices is that two zones with asynchronous fluctuations of yield can be distinguished: the Ukraine, and the south of West Siberia and Kazakhstan. This is supported by the investigation of the patterns of climatic anomalies. In most cases there is the inverse relationship between the south of the former European USSR and Kazakhstan by anomalously dry and wet years.

An example of the physical and mathematical approach is given in Konstantinov et al. (1981). The physical and statistical scheme accounts for the factors of temperature and moisture of the air by stages of growth (meteorological block), soil moisture and volume weight (soil fertility block), amount of fertilisers and the influence of the preceding crop (cultural practice block). Winter air temperature and snow cover depth are also measured for winter wheat. Calculations use graphical analysis with residuals being correlated with the three factors.

Maps are drawn allowing separate evaluation of the climatic resources, soil fertility and a more complex assessment. The calculations were made for spring and winter wheat, as well as for rye, oats, barley and corn. The scale and approach are more complex but the technique itself has deficiencies. Relating soil moisture to characteristics of soil fertility is doubtful. In such a case climate is represented only by temperature and humidity of the air, which is a gross simplification.

The same analysis for the former USSR is shown in Table 3.7 (Sirotenko, 1986). Here there is a high degree of synchrony of climate dependent yield variations by economic regions.

TABLE 3.5
Climatic component of wheat yield variation Cm for the territory of several European countries

<table>
<thead>
<tr>
<th>Territory</th>
<th>Territory</th>
</tr>
</thead>
<tbody>
<tr>
<td>Europe (total)</td>
<td></td>
</tr>
<tr>
<td>Austria</td>
<td></td>
</tr>
<tr>
<td>Belgium</td>
<td></td>
</tr>
<tr>
<td>Bulgaria</td>
<td></td>
</tr>
<tr>
<td>Czechoslovakia</td>
<td></td>
</tr>
<tr>
<td>France</td>
<td></td>
</tr>
<tr>
<td>Denmark</td>
<td></td>
</tr>
<tr>
<td>Germany</td>
<td></td>
</tr>
</tbody>
</table>

TABLE 3.6

<table>
<thead>
<tr>
<th></th>
<th>Australia</th>
<th>USA</th>
<th>Canada</th>
<th>EEC</th>
<th>Former USSR</th>
<th>Argentina</th>
<th>China</th>
<th>Mean yield</th>
<th>Standard Deviation</th>
<th>Coefficient of Variation %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Australia</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td>-0.18</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.21</td>
<td>0.213</td>
</tr>
<tr>
<td>Canada</td>
<td>0.21</td>
<td>0.58*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.72</td>
<td>0.13</td>
</tr>
<tr>
<td>EEC</td>
<td>0.19</td>
<td>0.67**</td>
<td>0.21</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3.34</td>
<td>0.21</td>
</tr>
<tr>
<td>Former USSR</td>
<td>0.11</td>
<td>0.68**</td>
<td>0.47</td>
<td>0.65**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>1.34</td>
<td>0.22</td>
</tr>
<tr>
<td>Argentina</td>
<td>0.27</td>
<td>0.4</td>
<td>0.10</td>
<td>0.06</td>
<td>-0.04</td>
<td>1</td>
<td></td>
<td></td>
<td>1.43</td>
<td>0.24</td>
</tr>
<tr>
<td>China</td>
<td>0.23</td>
<td>0.45</td>
<td>0.26</td>
<td>0.59*</td>
<td>0.37</td>
<td>0.57*</td>
<td>1</td>
<td></td>
<td>1.09</td>
<td>0.13</td>
</tr>
<tr>
<td>India</td>
<td>0.16</td>
<td>0.88**</td>
<td>0.63*</td>
<td>0.83**</td>
<td>0.69**</td>
<td>0.03</td>
<td>0.53*</td>
<td>1</td>
<td>1.16</td>
<td>0.09</td>
</tr>
</tbody>
</table>

* 5% significant ** 1% significant
TABLE 3.7
Correlation matrix of climate dependent yields of spring wheat by economic regions of the former USSR

<table>
<thead>
<tr>
<th>Economic regions</th>
<th>Coefficients of correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>1 Central and Central Chernostion regions</td>
<td>1</td>
</tr>
<tr>
<td>2 Volga and Viatka regions and Volga region</td>
<td>-</td>
</tr>
<tr>
<td>3 Ural region</td>
<td>-</td>
</tr>
<tr>
<td>4 West Siberian region</td>
<td>-</td>
</tr>
<tr>
<td>5 East Siberian region</td>
<td>-</td>
</tr>
<tr>
<td>6 Kazakhstan region</td>
<td>-</td>
</tr>
</tbody>
</table>

* 5% significant  * 1% significant

Using the technique of statistical trials by correlation matrices of yield rows, samples were generated with 500–700 cases (over years of observations). The information contained in correlation matrices is presented in more illustrative and accessible form, i.e. graphs, schemes and tables. The quantitative assessment of the degree of synchrony of yield fluctuations for different groups of economic regions are described for European and the former Asian USSR by Pasov (1986).

The recurrence of the negative anomalies of yields for winter wheat was assessed with increasing scale (for two, three, four, etc. economic regions simultaneously). Thus, the recurrence of the negative anomaly at the same time for the Ukraine and the North Caucasus Region amounted to 36 per cent; for the Ukraine, the North Caucasus Region and the Volga region to 30 per cent, while for the same regions with the addition of Kazakhstan it amounted to 19 per cent. The recurrence of the general (for all eight economic regions) negative anomaly of yield equals 8 per cent. In case of independent yield fluctuations in these regions, the recurrence should amount to 25, 12.5, 6.2 and 0.4 per cent correspondingly.

3.2.2 CROP-CLIMATE MODELS

TABLE 3.8
Dynamics of crop yield predictions and estimates of conditions for spring wheat growth and development for 1976–1979, calculated from the data collected at an agrometeorological station in the Volga region

<table>
<thead>
<tr>
<th>Year</th>
<th>Yield, t/ha</th>
<th>Estimate, %</th>
<th>% w.r. to emergence</th>
<th>10-day period of the season</th>
<th>May 10</th>
<th>May 20</th>
<th>May 31</th>
<th>June 10</th>
<th>June 20</th>
<th>June 30</th>
<th>July 10</th>
<th>July 20</th>
<th>July 31</th>
<th>Harvest</th>
</tr>
</thead>
<tbody>
<tr>
<td>1976</td>
<td>0.43</td>
<td>0.59</td>
<td>0.48</td>
<td>0.43</td>
<td>0.70</td>
<td>0.73</td>
<td>0.86</td>
<td>10.4</td>
<td>1.08</td>
<td>1.09</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.90</td>
<td>1.37</td>
<td>1.21</td>
<td>1.12</td>
<td>1.63</td>
<td>1.70</td>
<td>2.00</td>
<td>2.42</td>
<td>2.51</td>
<td>2.53</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1977</td>
<td>1.35</td>
<td>1.75</td>
<td>1.07</td>
<td>1.05</td>
<td>0.63</td>
<td>0.70</td>
<td>0.80</td>
<td>0.59</td>
<td>0.67</td>
<td>0.75</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>1.00</td>
<td>0.98</td>
<td>0.55</td>
<td>1.09</td>
<td>1.49</td>
<td>1.00</td>
<td>0.75</td>
<td>0.95</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1978</td>
<td>1.61</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.57</td>
<td>1.70</td>
<td>2.03</td>
<td>2.05</td>
<td>2.33</td>
<td>2.32</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>1.57</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.54</td>
<td>1.39</td>
<td>1.19</td>
<td>0.94</td>
<td>0.85</td>
<td>0.97</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.00</td>
<td>0.98</td>
<td>0.89</td>
<td>0.76</td>
<td>0.94</td>
<td>0.85</td>
<td>0.97</td>
<td>0.98</td>
<td>0.93</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Up to now the assessment of the impact of the current weather conditions was carried out subjectively using the experience of specialists. It is clear that it is extremely difficult to account for the state of the crop, soil moisture and the impact of the current climate anomalies at the same time. Table 3.8 presents three types of the current evaluation of the agrometeorological conditions: of the last week, of the former part of the growth period (from the emergence) and of the former part of the agricultural year (from the harvest of the preceding crop). All assessments are determined from the row of the tentative yield forecasts: Y_{m}, Y_{m-1}, ..., Y_{m-n}, Y_{r}. Here Y_{r} is the yield forecast by the dynamic model on the date of crop emergence, Y_{m} is the same for the end of the first 10-day period and Y_{r} is the yield calculated by the actual data. If any of the assessments reach 100 per cent, agrometeorological conditions of the period are equal to the reference period, in this case, the long-term mean conditions.
CHAPTER 3

To assess the impact of climatic variability on the yield, it can be viewed as the stochastic generalization of the problem of current weather conditions in the same manner as the notion "climate", is the generalization of the notion "weather". Thus the same technique that is applied to evaluate current events can be used.

Figure 3.2 shows the variations of yield production for wheat during 31 years. Separate year conditions vary from zero to 200 per cent compared with the average. Yield fluctuations under conditions of dry steppe are determined mainly by precipitation during vegetative periods and initial water storage accumulated during the winter. The role of temperature is not as important.

Dolgi-Trach (1989) assessed the climatic conditions of winter wheat growth in the former European USSR using simulations of climatic and soil conditions. The yield was calculated using the soil characteristics of the Krasnodar region (which was taken as a reference). The meteorological conditions of the Krasnodar region (moisture storage calculated by the model automatically) were used to obtain the climate assessment for all regions.

Field experiments can serve as an analogue to the above numerical experiments. Climate assessment soil samples are sent from the Krasnodar region to every other region and brought into moisture equilibrium with the surrounding soils growing winter wheat on them. To obtain soil assessments, typical soil samples are...
taken from every region which has been previously brought into moisture equilibrium with the soils from the Krasnodar region. Simulation modelling allows substitution of such costly experiments in the field by computer calculations.

From Table 3.9 it can be seen that poor soils have good climatic conditions to grow winter wheat, while regions with fertile soils have unfavourable climatic conditions. The moderately humid climate of the Baltic republics is the most favourable for winter wheat, but the southern economic region (Ukraine and Moldavia) has the most fertile soil.

As the calculations and conclusions are based on one crop, it is not possible to evaluate the climate productivity for agriculture as a whole. However, techniques have been developed for this purpose. Such techniques use the index of productivity of the total biomass of the grass ecosystem, calculated for the whole growing period

<table>
<thead>
<tr>
<th>REGION</th>
<th>Climate assessment</th>
<th>Soil assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With winter</td>
<td>Without dressing</td>
</tr>
<tr>
<td></td>
<td>Without dormancy</td>
<td></td>
</tr>
<tr>
<td>1 North and Northwest</td>
<td>116</td>
<td>30</td>
</tr>
<tr>
<td>2 Baltic</td>
<td>141</td>
<td>37</td>
</tr>
<tr>
<td>3 Belorusian</td>
<td>129</td>
<td>34</td>
</tr>
<tr>
<td>4 Central</td>
<td>116</td>
<td>30</td>
</tr>
<tr>
<td>5 Central Chernoev</td>
<td>94</td>
<td>56</td>
</tr>
<tr>
<td>6Volga and Vianta</td>
<td>108</td>
<td>33</td>
</tr>
<tr>
<td>7 Ural</td>
<td>86</td>
<td>60</td>
</tr>
<tr>
<td>8 Volga, north</td>
<td>86</td>
<td>57</td>
</tr>
<tr>
<td>9 Volga, south</td>
<td>57</td>
<td>81</td>
</tr>
<tr>
<td>10 North Caucasus</td>
<td>80</td>
<td>58</td>
</tr>
<tr>
<td>11 Donets and Dnieper</td>
<td>85</td>
<td>85</td>
</tr>
<tr>
<td>12 Southwest</td>
<td>121</td>
<td>45</td>
</tr>
<tr>
<td>13 South, Moldavian Region</td>
<td>75</td>
<td>108</td>
</tr>
</tbody>
</table>

* without Krasnodar region

Figure 3.3
Dry biomass yield of the agroecosystem for the warm period of the year at optimum mineral dressing (bioclimatic potential, BC)
of the year (when temperatures exceed 5°C). The above ground biomass of the crop is cut by 90 per cent, when the standard state (LAI = 5) is reached and on the following day the calculation continues from that stage up to the same standard state again or when growth ceases due to temperature drop. Figure 3.3 shows the total biomass at the optimal mineral dressing.

The total dry biomass produced by agroecosystem during the warm period of the year at the optimum mineral dressing (i.e. the possible yield, limited only by climatic conditions), characterizes climate productivity very precisely and can be named bioclimatic productivity (BP).

The BP shows a meridional distribution according to moisture conditions, and preserves some longitudinal characteristics, related to radiation and thermal conditions. A productivity maximum occurs in the Trans-Karpathy region, while a minimum occurs in semi deserts of the Caspian Sea region.

3.3 TROPICAL AND SUB-TROPICAL AGRICULTURE (INCLUDING GROUNDNUTS, COTTON AND CATTLE)
(by S.B.B. O’tengi)

Agriculture in the tropics includes growing of food and cash crops, agroforestry and animal husbandry.

Food crops in most tropical areas are sorghum, millet, groundnuts, beans and cotton. In eastern Africa for example, maize, sorghum, Irish potatoes and beans are used extensively as food crops. Major cash crops in Kenya, Uganda, Tanzania, Ethiopia and Somalia, though not discussed here, are coffee, tea and pyrethrum. Agroforestry with mulching (see Section 2.3) is becoming widely accepted as a technique for increasing crop production through soil and water conservation. Improved nitrogen fixation and reduced mineralization and volatilization take place in mulched plots. The mulches also tend to moderate the effects of climate extremes.

Livestock husbandry, whether on large ranches, nomadic or sedentary is also vulnerable to weather extremes. Beekeeping in forestry is an important form of livestock husbandry especially in semi-arid tropical areas. Tropical agriculture falls within seven agroecological zones (FAO, 1978, Table 3.10).

The issue of adaptability differs for sub-tropical and tropical agriculture. Variation of moisture limits, particularly to rainfed activities, are critical. Annual variability in some areas is very high. The drier summer seasons have increased rates

<table>
<thead>
<tr>
<th>TABLE 3.10 Agroecological zones of the tropics (After FAO, 1978)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TA</strong> Tropical alpine zones. Annu. mean 2–10°C.</td>
</tr>
<tr>
<td>Gheren mountain swamp</td>
</tr>
<tr>
<td><strong>UM</strong> Upper Highland zones. Annu. mean 15–15°C.</td>
</tr>
<tr>
<td>Seasonal night frost.</td>
</tr>
<tr>
<td><strong>UL</strong> Upper Highland zones. Annu. mean 5–15°C.</td>
</tr>
<tr>
<td>Seasonal night frost.</td>
</tr>
<tr>
<td><strong>UM</strong> Upper Midland zones. Annu. mean 18–21°C.</td>
</tr>
<tr>
<td>Mean min. 11–14°C.</td>
</tr>
<tr>
<td><strong>LM</strong> Lower Midland zones. Annu. mean 21–24°C.</td>
</tr>
<tr>
<td>Mean min. 14°C.</td>
</tr>
<tr>
<td><strong>L</strong> Lowland zones.</td>
</tr>
<tr>
<td>II. Inner Lowland</td>
</tr>
<tr>
<td>zones. Annu. mean 24°C.</td>
</tr>
<tr>
<td>Mean max. 31°C.</td>
</tr>
<tr>
<td><strong>C</strong> Coastal Lowland zones. Annu. mean 24°C.</td>
</tr>
<tr>
<td>Mean max. 31°C.</td>
</tr>
</tbody>
</table>

* Not in Kenya
of moisture loss from plants and soils with reduced soil water availability. In low-latitude zones season-to-season moisture variability will determine seasonal crop success through drought frequency. Small decreases in water availability can readily produce drought conditions. Changes in risk and intensity of drought represent the most important impact of climate variability. Adaptive solutions include better soil and water management, modified tillage practices, and introduction of animal husbandry practices.

### 3.3.2 Rainfed agriculture in tropical and sub-tropical lands

#### 3.3.2.1 Humid tropics

Agriculture in the humid tropics is not limited by water availability. However, frequent storms and strong winds from deep convective cloud systems cause massive lodging and loss of biomass through uprooting and tearing. This is common around the Lake Victoria basin and the peripheral highlands. Not only food crops such as maize and sorghum, but also tea and coffee yields get reduced in the western highlands of Kenya, (around Kericho) and Uganda and in parts of Rwanda and Burundi.

Frequent heavy showers also cause destruction through flooding and waterlogging, resulting in anaerobic conditions due to poor soil aeration, and changes in the chemical composition of the crop rooting zone through leaching and salinization. Plant, animal and human diseases and pests form an added burden (Bohn et al., 1979; Greene, 1966; Gould, 1970) caused by inadequate sanitary conditions. Almost all the food crops in the humid tropics are grown in rainfed conditions.

#### 3.3.2.2 Semi-arid tropics

Rainfed agriculture in semi-arid conditions is limited mostly by high climatic variability with the principal limiting factor being rainfall. The yields of agricultural crops are heavily dependent on rainfall spread evenly through the growing seasons. Table 3.10, covers the agroecological zones found in the tropical area, i.e. from per-humid to per-arid (FAO, 1978).

The names of crops grown in these zones are indicated. With good husbandry intervention and improved crop varieties, crops grown in more humid zones could be introduced into less humid zones at a higher level of profitability.

For east Africa, 750 mm of annual rainfall is the threshold for successful growing for a crop. In Kenya, the pastoral areas receive less than 625 mm. Approximately two-thirds of Kenya, one-third of Tanzania and some areas in Uganda are pastoral areas. In more than half the remaining areas, ecological conditions are often unreliable and marginal, being highly susceptible to even minor climatic fluctuations.

Agroecological classifications based on length of growing period, soil type, evapotranspiration rates, altitude and cropping practices (FAO, 1978) include parameters that give direct plant responses to limiting values (very high and very low). Ultimate productivity is based on rainfall reliability alone (Whyte, 1966; O'tengi and Ogallo, 1984) and is solely climate dependent.

### 3.3.3 Irrigation in tropical and sub-tropical semi-arid lands

A mathematical model for calculation of the theoretical water requirement values and the actual water consumption values in monthly and decadal stages applicable to plants with specific ranges of crop coefficients ($K_c$) and root characteristics could be used to answer basic theoretical and practical questions of the type:
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3.3.4 Role of rainfall variability in soil conservation in tropical and sub-tropical areas

Soil conservation practices are essential for maintaining or increasing food production. The selection of a desirable conservation system is difficult because the system must satisfy several requirements including:

1. Providing an economic level of crop production;
2. Controlling run-off;
3. Limiting movement of nutrients from agricultural land (Kilewe and Ulsaker, 1984),

and must allow for such changes in land use as:

4. Converting forests and grasslands to agricultural and pastoral uses;
5. Urbanizing rural lands for road and building constructions, which can also cause erosion (Ulsaker and Kilewe, 1988).

The basic principles of protection of soil against erosion include ploughing and planting along the contour, rotation of crop and grass, application of manure favouring the growth of crops and leaving crop residue on the ground (Wenner and Njoroge, 1982). Average annual soil loss can be assessed from rainfall erosivity; soil erodibility, slope length management and supporting conservation practice (Wishmeir and Smith, 1965). The effectiveness of soil loss is reflected in the rainfall behaviour. Rainfall in marginal areas displays unpredictable characteristics. A season’s rain may occur in less than a week. Such rain occurs in heavy downpours and is highly erosive. In other years rain may not occur at all. Since both the seasonal and annual variability are high, soil conservation practices should be adopted.

3.3.5 Response of tropical and subtropical crops to climatic variability

3.3.5.1 Sorghum (Sorghum vulgare)

Sorghum is an important cereal crop produced in tropical and subtropical countries such as India, Brazil, Africa and northern Australia. It is drought-resistant, and more resistant to waterlogging than other important cereals, except rice. Its well branched root system and stomatal control prove useful in drought resistance and internal control over respiration (Jackson, 1982). Sorghum also responds well to the plentiful water supply during the tillering and shooting stages. Drought during tillering and shooting reduces sorghum crop yields.

Sorghum is rainfed in most parts of the tropics and subtropics. The climatic impact on sorghum depends on the fluctuations in the onset of rains. Water deficiencies may occur where rainfall deviations from the average are generally large.

Kakamega is a wet locality in western Kenya where sorghum is widely grown. The growing period here begins in March and ends in August (O’tengi, 1979), during the long rainy period from March to May. Harvesting is just before the next short rainy season, from October to early December.

Kitui, another locality where sorghum is grown, shows the reverse, with high rains in October to December during which high variability occurs. Here the growing season for sorghum is during the short rains.

Temperature determines the rate of development. At the soil surface, higher temperatures (40°C) may be experienced by the emerging plumule, and sorghum
can tolerate temperatures as high as 68°C (Peacock and Heinrich, 1984). Temperature stress is often accompanied by water stress and there are usually interactions within the plant to these stresses. Sorghum is sensitive to chilling. Cold tolerant strains of sorghum are grown in the highlands of Ethiopia, Uganda, Kenya, Cameroon and Mexico. Konate (1984) shows that maximum temperatures in sorghum areas in the Sahel region of west Africa vary between 28°C and 42°C and the minimum temperatures between 15°C and 28°C.

A regression production model (number of grains/panicle) of a late maturing sorghum variety based on the sum of temperatures between planting and heading was given by Cocheme and Franquin (1967) as:

\[ G = 0.000104 \times x^2 + 1.05110 \times x - 1744 \] (1)

where: \( x \) is \( \Sigma T \) (sum of temperatures), and \( G \) is number of grains/panicle.

Periods of consistent high (or low) temperatures can be summed and fed into the model to obtain the effect of high (or low) temperatures.

3.3.5.2

Millet

Major producers of millet in sub-Saharan Africa include Uganda, Mali, Senegal and Niger. The highest producers are Uganda and Mali and the lowest, among this group, is Niger. In Kenya, millet is grown in marginal areas around Kirinyaga, Embu and Meru districts.

Like sorghum, millet is drought-resistant and gives reasonable yields on infertile sandy soils in the semi-arid areas of Africa which would be unsuitable for most other crops. Water deficiency at heading and flowering has the same effect as in sorghum (Jackson, 1982). Millet seedlings are drought tolerant and early planting needs to be carried out to extend the effective moisture period (Konate, 1984).

At Embu, one of the millet growing regions in Kenya, high variabilities are observed during the dry periods. The short rains and long rainy periods (not sufficiently long) are generally too short although they do accommodate the millet growing periods. Low variabilities are observed during the rainy periods.

Variabilities in other physical factors such as temperature and evaporation are the same as for sorghum in most localities.

3.3.5.3

Cotton (Gossypium hirsutum)

Cotton is produced in most countries of the tropics and sub-tropics, with the leading producer in Africa being Sudan. Some cotton is produced in Uganda, Kenya and Tanzania. Cotton is a drought-tolerant crop which has regular cycles of flowering provided moisture is not limiting.

The time of sowing in Kenya, October to December in central and eastern provinces, and March to early April in western and coastal provinces, is consistent with the water requirements of the cotton crop and seasonal rainfall variability (O'tengi, 1985).

Very high rainfall is undesirable for cotton. It does most harm by causing lint discoloration after the bolls have opened, but also contributes to decreased yields by causing waterlogging, flooding, excessive leaching and high incidence of fungal and bacterial boll rots. Poor soil aeration is common under waterlogged conditions.

Droughts during the periods of high water demand cause premature shedding of leaves, flowers, buds and bolls and the development of short immature lint.

Cotton is a warm climate crop. Very low night temperatures (say below 15.5°C) encourage production of a short staple, and poor quality cotton lint. Low temperatures cause a slow rate of node production, slow vegetative growth, and late flowering.

3.3.5.4

Groundnuts (Arachis hypogea)

Low amounts and highly variable rainfall in areas that grow groundnuts (e.g. the Sahel) coupled with soils of low water-holding capacity are the major constraints to crop production (Ong, 1986). It has been observed that yields are poorly correlated with rainfall in Senegal (Ong, 1986).

A severe water deficit can delay the onset of flowering and rapid pod growth. Results from series of experiments at ICRISAT Centre (ICRISAT, 1984) show that:

(1) Early stress does not influence pod yield greatly;
CHAPTER 3

TABLE 3.11
Minimum ($T_{\text{min}}$) and maximum ($T_{\text{max}}$) temperatures of 14 groundnut varieties (Wang, 1988)

<table>
<thead>
<tr>
<th>Varieties</th>
<th>$T_{\text{min}}$</th>
<th>$T_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valencia R 2</td>
<td>8</td>
<td>43</td>
</tr>
<tr>
<td>Flamingo</td>
<td>8</td>
<td>42</td>
</tr>
<tr>
<td>Mokota</td>
<td>8.5</td>
<td>42</td>
</tr>
<tr>
<td>KCSG 10</td>
<td>8</td>
<td>44</td>
</tr>
<tr>
<td>BGRET</td>
<td>9</td>
<td>43</td>
</tr>
<tr>
<td>ICO 47</td>
<td>9</td>
<td>47</td>
</tr>
<tr>
<td>Robert 33-1</td>
<td>10</td>
<td>46</td>
</tr>
<tr>
<td>TMV 2</td>
<td>10</td>
<td>42</td>
</tr>
<tr>
<td>MK 374</td>
<td>10</td>
<td>44</td>
</tr>
<tr>
<td>Fiever</td>
<td>10.5</td>
<td>42</td>
</tr>
<tr>
<td>ICO 73</td>
<td>11</td>
<td>45</td>
</tr>
<tr>
<td>KT 13</td>
<td>11</td>
<td>45</td>
</tr>
<tr>
<td>SwatLow</td>
<td>11</td>
<td>42</td>
</tr>
<tr>
<td>N. Common</td>
<td>11.5</td>
<td>41</td>
</tr>
<tr>
<td>Ranges</td>
<td>8-11.5</td>
<td>41-47</td>
</tr>
</tbody>
</table>

(2) Pod yields are increased by 15 g/m² cm⁻¹ of water applied, i.e. at seedling filling phase.

Billaz and Ocha, (1961), found that mid-season drought decreases yields more than 1/2 of season drought while Nageswara Rao et al. (1985) found the reverse was true. Williams et al. (1986) estimated sensitivity to drought using regression as the average yield loss per unit of water deficit. In the very long-term stresses, there was a curvilinear response of pod yield to increasing drought intensity; 90 per cent of the yield variations were accounted for by the intensity of drought and the cumulative duration of stress.

Temperature controls the rate at which groundnut develops. The diurnal temperature range is more important for plant development and growth than either the diurnal temperature cycles or the random effects of weather.

Temperature extremes over a period of days or hours may severely reduce the growth and development of many crops. Wang (1988) obtained values of temperature range for germination of 14 groundnut varieties. The minimum temperature ($T_{\text{min}}$) required was 8°-11.5°C, while the maximum temperature ($T_{\text{max}}$) beyond which germination did not take place was 41°-47°C (Table 3.11).

Beans (Phaseolus vulgaris)

Beans form a staple food for many people in the world. Beans are not drought-resistant and need moisture throughout the growing season.

The length of the wet season depends on the growth habit according to species, cultivar and high altitude. Rainfall at the end of the season causes high incidence of pests and diseases which discolour the seeds. Splashes of rain water during this period fall on pods and stain the seeds. Heavy rain causes waterlogging and leaf yellowing.

High temperatures cause poor fruit set and low temperatures delay maturation.

3.3.5.5

Forestry

by W.T. Sommers

Climate largely determines the distribution, productivity, health and diversity of natural ecosystems and has a controlling effect on managed ecosystems. Forests are a major worldwide component of both natural and managed ecosystems. A mapping of forest ecosystems is closely comparable with a map combining maximum and minimum temperatures with average precipitation. The coincidence of climate and vegetation zones is used to model plant community distributions by, for example, correlating vegetation type with the gradients of temperature, precipitation, and the ratio of potential evapotranspiration to precipitation (Holdridge, 1964).

Past climate changes have caused forest ecosystems to migrate and change in composition as the climate changed (Bernabo and Webb, 1977). Examples of primary effects of climate variation on forest ecosystems exist in the paleoclimatic and paleoecological records.

When considering the impact on forests of climate variability, it must be approached in a systematic way with respect to both the climate variability and the forest. In this section, climate variability will be viewed from four spatial scales: global, regional, topo and micro, and forests from three perspectives: forest type, forest ecosystem component, and forest ecosystem dynamics. The spatial scales of climate variability roughly correspond to equivalent temporal scales. The global scale is of the order of thousands of kilometres and weeks to years. The regional scale is hundreds of kilometres and days to weeks. The topo scale is metres to tens of kilometres and diurnal in nature as it reflects the importance of terrain in determining the specific climatology of any location. The micro scale is centimetres to metres and seconds to hours as it reflects climate variability of consequence to the individual, and that individual's interaction with the atmosphere. These space and time scales have different impacts on the biosphere. The tripartite forest viewpoint derives from differing biological perspectives. Forest type provides a classical view comparable to a taxonomic approach to biology. Forest ecosystem component recognizes the importance of species interactions in forests, but allows a particular
component to be singled out as an example for study. Forest ecosystem dynamic also provides an ecosystem perspective, but describes what happens to processes rather than components. Forest type may be viewed as a vegetational pattern response, forest ecosystem component as a biotic response, and forest ecosystem dynamic as an environmental response to climate variation. This framework allows for a complete cataloguing of impacts of climate variability on forests, but only examples are discussed here.

On a global scale, climate change is an important forcing function of forest change (Delcourt and Delcourt, 1987). The boundaries between forests and other natural ecosystems are largely determined by precipitation and evapotranspiration. Forest type (mixed conifer for example) is largely determined by temperature and precipitation. Forest soils slowly evolve from the source materials available, namely climate, and forest species. Past global scale climate changes, such as glacialiation, often have a dramatic impact on existing soils and forest types.

At a regional scale, variations in climate cause variations in the relative boundaries between forest ecosystems (ecotones) and have major impacts on forest management. Here climate effects are not viewed as primary (acting in direct correlation), but as secondary, in that they are viewed as contributing factors to species competition, forest fires, insect and disease outbreaks, seedling failures, and essentially all other disturbances that play a role in determining forest productivity, health, and diversity. For example, the incidence and severity of forest fires is largely determined by the wind, temperature and fuel moisture (based on precipitation history and atmospheric humidity) in the period leading up to and during the fire (Pyne, 1984).

Changes in climate, even expected variations within a stable climate, that bring with them extremes in forest fire weather inevitably result in increased and more severe outbreaks of fires. More subtle relationships between climate variations and forest disturbances exist. When forest vigour is affected by drought, and damage or early frost, a decline in forest health begins, resulting in insect attacks and/or forest fires several years later. Here the forest disturbance is linked to the climate variation through a time-delayed, intermediary forest decline.

At the toposequence, climate variability manifests itself particularly in forest ecosystems located in complex terrain. A large percentage of the world’s unmanaged to lightly managed forests are found in complex terrain where agriculture has proved to be impractical. Aspect and slope are important parameters to consider for such diverse forest management practices as tree planting and forest fire protection.

At the microscale, the climate within a forest is the result of a highly complex interaction of the external climate-forcing factors and the forest itself. At this scale, forests modify their environment so the response of biota or ecosystems to shorter term climate events is often difficult to determine (Geiger, 1965). However, to fully understand the effects of climate variations on forests, we need to integrate the interactions taking place at small spatial and short temporal scales, upward through forest stand, topo and regional scales to the global scale where the primary effects of climate variation on forests are viewed. The global scale of forest atmosphere interaction is the integrated aggregate of events at the smaller scales.

Examples follow for the four scales of climate variability (global, regional, topo, and micro) and how they affect a particular forest type, ecosystem component within that type, and forest dynamic affecting the ecosystem.

3.4.1 Climate scale: Global—
Forest type: temperate/boreal coniferous;
Ecosystem component: spruce (Picea); Forest dynamic: tree population dynamics

The most useful example of the effects of global scale climate variability on forests is the evolution of temperate forest since the end of the last Quaternary glaciation, beginning about 14,000 years before present (BP). Evolution of forest ecosystems during the subsequent global warming is of particular interest as a possible analogue to predicted changes (warming) in the global climate due to anthropogenic forcing. Evidence is that as the global climate warmed and northern hemisphere continental ice sheets retreated northward, the mean position of the Arctic polar front also moved northward bringing warmer air masses to temperate (currently) latitudes, a northward migrational biotic response, and northward migration of mixed conifer-northern hardwood forest and cool-temperate deciduous forests in North America and Europe (Delcourt and Delcourt, 1987).
CHAPTER 3

Species distributional dominance can be represented by ecocline mapping, with the limits of distribution represented by ecotones, or ecological transition zones (Gauch, 1982). Spruce (Picea) was a dominant species in regions of eastern North America during most of the past 20,000 years. During the period when glaciers reached their fullest extent of land coverage in eastern North America, spruce covered 80–100 per cent of the region that formed a belt along the southern extremity of the ice sheets. By 12,000 BP the zone of spruce dominance was in a tight band stretching north eastward from Minnesota to southeastern Ontario, and closely tracked the northward retreat of the ice sheet. As the glaciers retreated more rapidly northward between 10,000 and 6,000 BP, maximum values of dominance declined to below 50 percent and mean values to about 11 per cent from a full glacial value of about 40 per cent. Of interest in this period was the ability of spruce to migrate across the extensive water barrier formed by the great lakes and St. Lawrence river valley. This was probably accomplished by wind-driven seed dispersal.

By 4000 years ago, spruce formed a continuous northern boundary from as far north as 60°N to the west of Hudson Bay to the vicinity of Labrador in the east. At that time spruce dominated large sections of the Canadian boreal forest. By 500 BP, the principal population centres of spruce were distributed across the northern half of the boreal forest and isolated populations remained in high elevation locations as far south as North Carolina, where they remain today. The southern border of continuous spruce occurrence was found at about 42°N.

Migration of spruce in eastern North America demonstrates the effect of global scale climate variability through tree population dynamics, on the spruce (Picea) component of the eastern North American temperate/boreal coniferous forest type. During the past 20,000 years the centre of Picea dominance along the 85th meridian moved northward by almost 20° of latitude in response to global warming and the regional retreat of the Laurentide ice sheet.

3.4.2 CLIMATE SCALE: REGIONAL—
Forest type: mixed conifer;
Ecosystem component: western larch (Larix occidentalis);
Forest dynamic: forest fire

Regional scale climate variability has several effects on the forest ecosystems and their management. One of the most severe effects being catastrophic fires that occur when regional scale droughts combine with lightning storm ignitions of dry forests and strong variable winds associated with synoptic weather patterns. Such a combination of events occurred in 1967 in western North America and led to the Sundance fire (Anderson, 1968; Pinklin, 1973). The Sundance fire occurred in the mountains of northern Idaho in a mixed conifer stand composed of western larch (Larix occidentalis), alpine fir (Abies lasiocarpa), and Engelmann spruce (Picea engelmannii). It was the largest of several fires to occur in the northern Rocky Mountains during the summer of 1967. At its peak of destructiveness, it consumed over 20,000 hectares in 9 hours as it spread forward at rates approaching 8 m/s.

The Sundance fire was one of five lightning caused fires that started on 11 August 1967. The other four fires were discovered and put out, but the Sundance continued to burn slowly under light winds and warm, dry, rainless conditions. Forest fire danger measurements (a combination of observations and climatology of precipitation, temperature, and humidity) reflected the most dangerous values in the 14 year recorded history of the area. The region had been under the influence of a blocking ridge in the western United States most of the summer. On 23 August, winds increased in response to a change in the synoptic weather pattern and the Sundance fire flared up. Winds were moderate to strong, and very variable in the period from 3 August to 1 September, when the fire made several rapid advances coincident with increases in wind speed. On 1 September 1967 the synoptic weather pattern changed again as a major upper level trough approached from the west, and surface winds in the area of the fire reached 30 m/s. These strong winds drove the fire from a size of about 1 600 ha to 20,000 ha in the 9 hours between 2 pm and 11 pm. Firebrands and burning embers consisting of larch and hemlock cones, and small branches aided the fire's spread as the wind carried them far ahead and they started spot fires. flaming cones and brands were carried 10 to 15 km in advance by this wind-driven spotting.

The Sundance fire finally began subsiding on 2 September when the regional weather changed and winds decreased in speed and variability. Before the fire, larch
covered about 33 per cent of the forest lands in the area but with the disturbance of the Sundance fire, larch stand replacement occurred.

Regional climate variability as manifested in a prolonged drought, high temperatures and low humidities established conditions in the forests of the northern Rockies that primed them for the occurrence of catastrophic fire disturbance. Such an occurrence took place when winds arose on 23 August to fan the fire, and then reached hurricane force speeds on 1 September driving the Sundance fire to catastrophic dimensions. The same type of regional climate variability manifested itself 21 years later in the Lodgepole pine (Pinus contorta) stand which replaced larch following fires in Yellowstone National Park.

3.4.3
CLIMATE SCALE: TOPO—
Forest type: mixed conifer;
Ecosystem component: red spruce (Picea rubens);
Forest dynamic: forest decline

Considerable interest has been aroused by reported decline of important forest species in Europe and North America in recent years. Examination of decline of red spruce (Picea rubens) on Whiteface Mountain in the Adirondack Mountains of New York state reveals some strong elevational characteristics of the decline (Johnson et al., 1988). Red spruce decline, as evidenced by unusually high mortality, occurred at elevations above 900 m in the Adirondacks between the early 1960s and the mid-1980s. Above 900 m, more than 50 per cent of the spruce canopy is presently dead.

In the zone between 950 and 1,100 m, where maximum red spruce importance lies, red spruce death is 300–400 per cent greater than other species. There is no evidence of decline in the co-occurring dominants (balsam fir and paper birch). Below 800 m where hardwoods dominate forest composition, there is no evidence of similar red spruce decline.

The concentration of the air pollutants H+, SO42-, NO3-, and NH4+ is five times higher in cloud water than in precipitation. Topography causes vegetation above 900 m to be exposed to cloud water 20–30 per cent of the time. The absence of diurnal variation of ozone at elevations greater than 1,000 m means ozone exposure is greater at higher elevations than at lower elevations. Seeding exposure experiments conducted in chambers have shown reduced resistance of red spruce to winter injury at ambient pH levels found in clouds (3.0 < pH < 4.0). Similar exposure experiments have not demonstrated any quantifiable effects on carbon allocation. Chamber experiments on in situ red spruce branches have shown that ambient levels of pollutants adversely affect foliar pigments, stomatal waxes, and cuticle thickness. Branches from which ambient cloud water was excluded showed less winter injury than those exposed to ambient cloud water. Repeated, severe winter injury is considered to be an important cause of observed red spruce decline at elevations above 900 m on Whiteface Mountain (A.H. Johnson, pers. com., 1989).

A combination of multiple stresses including exposure to relatively high levels of air pollutants and winter injury, both clearly related to toposcale climate variability, believed to be causing forest decline in the red spruce component of mixed forest stands at elevations above 900 m in the Adirondack Mountains as evidenced by a series of experiments and observations on Whiteface Mountain.

3.4.4
CLIMATE SCALE: MICRO—
Forest type: mixed conifer;
Ecosystem component: mycorrhizae;
Forest dynamic: nutrient uptake

Soil fungi infect the fine roots of forest trees forming symbiotic mycorrhizae (fungal roots) that are of great importance to individual tree and forest nutrient cycling, particularly on nutrient poor sites (Smith, 1981). In addition to advantages of nutrient availability and uptake, mycorrhizae increase water uptake efficiency and reduce risk of soil pathogen infection for host trees. The mycorrhizae absorb the nutrients and translocate them to the host tree root system for use in tree growth. They are particularly necessary for the uptake of relatively immobile ions like phosphate and zinc from the forest litter and soils, and so are especially beneficial in many areas of nutrient-poor, thin forest soils found in many mountainous areas around the world. Mycorrhizae are particularly vulnerable to the effects of microclimatic variability often associated with disturbance of forest stands and resultant disturbance of the local hydrologic cycle. When drought accompanies disturbance of the local forest ecosystem the influence of microclimate becomes paramount.

Mycorrhizal roots are found to be concentrated in the humus, decayed wood, and charcoal of the upper layers of forest soils. As much as 95 per cent of the mycorrhizal roots are concentrated in these upper layers. This locational concentration
makes the fungi susceptible to drought stress and to effects of materials deposited from the atmosphere which tend to concentrate in the upper layers of forest soils. The relative closure of the forest canopy, the interception by the canopy of depositional materials, the availability of moisture from longer retention of snow pack, and several other factors which influence the microclimate in forests, also influence the concentration of mycorrhizae. And the presence of sufficient concentrations of mycorrhizae is a major determinant of the ability of the trees to mobilize sufficient nutrient resources from nutrient-poor soils. Microscale variability of climate thus affects the dynamics of nutrient cycling in forest ecosystems through the relative abundance and vigour of the mycorrhizal component of those ecosystems.

3.5 THE SOUTHERN OSCILLATION PHENOMENON: EL NIÑO AND LA NIÑA
by M.J. Salinger

The Southern Oscillation phenomenon has become well known recently because it causes dramatic climatic anomalies specially in the southern hemisphere.

The two opposite phases of the Southern Oscillation, when the largest climatic anomalies occur, are known as El Niño and La Niña. El Niño is the invasion from time to time of warm surface water from the western equatorial part of the Pacific Basin to the eastern equatorial region and along the coasts of Peru, Ecuador and northern Chile. La Niña is the enhancement of the normal pattern along the equator within which easterlies cause upwelling of cold water along the coasts of South America and the equator. In the La Niña phase the surface water in these areas is much colder, by up to 3°C, than in the El Niño phase.

3.5.1 THE SOUTHERN OSCILLATION AND ASSOCIATED CLIMATE ANOMALIES

3.5.1.1 The Southern Oscillation

The Southern Oscillation is an exchange of mass between two centres of action, the permanent area of high pressure in the southeastern Pacific and the lower pressure in the Indonesian region. When atmospheric pressure is higher than average in the southeastern Pacific, it is lower than average in the Indonesian area. Conversely, when atmospheric pressure is lower than average in the southeastern Pacific, it is higher than average over Indonesia.

The Southern Oscillation was first documented this century in a series of papers by Sir Gilbert Walker. It is described by Walker and Bliss (1932) as:

"When pressure is high in the Pacific Ocean it tends to be low in the Indian Ocean from Africa to Australia; these conditions are associated with low temperatures in both these areas, and rainfall varies in the opposite direction to pressure."

A frequently used index of the Southern Oscillation, known as the Southern Oscillation Index (SOI), is the difference in the normalized pressure anomaly Tahiti minus Darwin. The atmospheric pressure at Tahiti is taken as representative of the south eastern Pacific, and Darwin (Australia) as representative of the Indonesian centre of action. When the SOI is highly positive, it is in La Niña phase, and when the index is negative it is in El Niño phase.

The relationship between climate fluctuations in the equatorial Pacific and the Southern Oscillation is very strong. Figure 3.4 shows a schematic of the Walker Circulation (Nicholls, 1987). When the SOI is positive, pattern (a) is enhanced; the surface Pacific equatorial easterlies are stronger, the South Pacific Convergence Zone is further west and above Indonesia-New Guinea, there are other convergence zones over Africa (Zaire) and the Amazon Basin. The jet stream over western North America moves polewards (north). Figure 3.4(b) shows tropical circulation during the 1982–83 El Niño, when the SOI was very negative. The surface Pacific equatorial easterlies are weak with the South Pacific convergence zone located over the central Pacific. Convection is suppressed over the rest of the tropics. Over the North American west coast, the jet stream which is normally at 40°N drops to 30°N.

3.5.1.2 El Niño anomalies

Globally, annual rainfall variability is greater in areas where there is a strong relationship with the SOI than those areas where the linkage is weak (Nicholls, 1988).
The relationship between climate fluctuations in the South Pacific and El Niño is extremely strong (Nicholls, 1987). During El Niño events, rainfall is above average in parts of Peru and Ecuador and in the central and eastern equatorial Pacific (Rasmussen and Carpenter, 1982), with drought over New Guinea (Nicholls, 1984) and Indonesia (Quinn et al., 1978). Tropical cyclones (hurricanes) are much more frequent in the Central Pacific (Revell and Goulter, 1986).

The beginning of the wet season over Australia is usually delayed (Nicholls, 1984), with drought in eastern Australia (Pittock, 1975). New Zealand has wetter conditions in the west and south, with below average rainfall elsewhere (Gordon, 1986). The 1982 El Niño produced a monsoon in India that arrived late, was erratic and withdrew early (Sinha, 1987). The 1982–83 El Niño was marked by severe and persistent drought over much of southern Africa.

Both Nicholson and Entekhabi (1986) and Lindesay (1988) have shown that a negative SOI is correlated with lower rainfall over southern Africa. In South America droughts in the north east of Brazil and floods in the south are related to El Niño events (Rao et al., 1986).

Relationships between El Niño events and climate anomalies are strongest in the South Pacific and southern continents. However, linkages have been made with anomalies in Japan and North America (Rasmussen, 1984) and on the Pacific Rim (Glantz et al., 1987). In Japan, El Niño events produce cool, wet summers with marked Baiu (rainy season) frontal activity. The winters are warm. In the central North Pacific a hurricane hit the Hawaiian Islands in late 1982, the first to do so in 23 years. On the North American west coast winters are much wetter, particularly in southern California.

Researchers have examined relationships for western Europe, west African Sahel and the now Russian Federation and, apart from India, other areas of the northern hemisphere show no climate linkages with El Niño events.

3.5.1.3
La Niña (anti-El Niño) anomalies

Once again, relationships between climate fluctuations in the South Pacific and La Niña are strong.

However, attention has only mounted recently on this phase of the Southern Oscillation. During La Niña events rainfall is below average in Peru and Chile and in the central and eastern equatorial Pacific (Rasmussen and Carpenter, 1982). However, it is above average over Indonesia (Quinn et al., 1978) and New Guinea (Nicholls, 1984).

Tropical cyclones are more frequent in the southwest Pacific (Salingar, 1981; Revell and Goulter, 1986). In New Zealand it is wetter in the northeast but drier in the southwest (Salingar, 1981; Gordon, 1986) and temperatures are warmer than normal.
A positive Southern Oscillation gives above average rainfall in eastern Australia (Pittock, 1975). In southern Africa there is a strong positive relationship between high rainfall and high SOI (Lindsey, 1988; Nicholson and Entekhabi, 1986).

As with El Niño events, relationships with La Niña events and climate anomalies are strongest in the South Pacific and southern continents. However, some linkages are apparent for Pacific rim countries. Japan has drier summers, because of less Baiu (rainy season) frontal activity, and cold winters. The North American west coast has drier conditions with the jet stream further north.

In India, the southwest monsoon tends to be more vigorous. Relationships of climate anomalies with La Niña events have yet to be demonstrated for other areas of the northern hemisphere.

### 3.5.2 Effects on Agriculture and Fisheries

It must be considered that each El Niño exhibits broad climate anomalies that are similar between events. However, each event has unique anomalies as well. Only the broadscale effects on agriculture and fisheries are considered.

#### 3.5.2.1 Pacific islands

During El Niño events, countries in the western Pacific such as Fiji have depressed yields of sugarcane crops. The yield anomalies are greater than during La Niña events when increased crop yields are experienced. Crop yields in the central and eastern Pacific islands (Tahiti) are increased during El Niño events, except when tropical cyclones cause crop destruction.

#### 3.5.2.2 Indonesia

El Niño phases cause drought, and the main impact of the 1982–83 event was a drastic reduction in the rice production growth rate (Malingreau, 1987). Production of secondary crop was affected initially until crop substitution mitigated drought impacts. Despite the drought intensity, the rice production system appears to have shown good resilience as no province dropped as far as pre-1980 production levels. However, the tropical forest of Kalimantan in Borneo did not fare as well. The prolonged drought and land use practices exacerbated outbreaks of major fires which destroyed large areas of tropical forest.

La Niña events can bring above average rainfall, but these do not have the same economic impact on agriculture as El Niño events. The effects would be positive on crop production.

#### 3.5.2.3 Australia

Inter-annual fluctuations of Australian crop production are highly correlated with the SOI. Nicholls (1985) demonstrated that crop yields per hectare of wheat, oats, barley and sugarcane, four of the five major crops, show significant positive correlations with the Southern Oscillation. Furthermore, fluctuations in gross crop value are highly significant. Grain sorghum, an important rainfed Australian summer crop, has yield limited by moisture. Yield anomalies show significant positive correlations with the Southern Oscillation (Nicholls, 1986). Clearly the Southern Oscillation, in both phases has a marked impact on Australian crop production. Over half the variation of gross crop value, after removing the long-term trends, is explained by the Southern Oscillation.

The Southern Oscillation affects agriculture especially through drought. The relationship between droughts in eastern Australia and ENSO is one of the best documented teleconnections; the impacts are clearly demonstrated in the 1982–83 ENSO. This event affected 60 per cent of the nation's farms, with crop production falling 31 per cent and farm incomes by 24 per cent. This drought also caused accelerated land erosion with all the future long-term problems (Allan and Heathcote, 1987).

#### 3.5.2.4 New Zealand

The two extreme phases of the Southern Oscillation have opposite effects on agriculture. The 1982–83 ENSO event had many impacts (Salingar, 1981). Drought conditions in the north and east and wet conditions in the southwest, with cold temperatures and frequent strong winds reduced pasture growth dramatically resulting in below average dairy, meat and wool production. Cereal crops, clover production and horticultural yields were poor because of the cooler conditions. Most crops were between two and three weeks late in maturation. Cereal crop yield was particularly low because of the dry conditions. In contrast, La Niña phases, which
exhibit warm temperatures with wet conditions in the north and east, have a positive effect on agriculture. Generally, pasture growth is high in the north giving above average dairy and meat production. Warm conditions cause maturation of cereal and horticultural crops between two and three weeks earlier than usual.

3.5.2.5 India

Compared with the La Niña phase, the El Niño phase of the Southern Oscillation has the most impact on India through drought. However, weak monsoons and consequent water deficit are a feature of the Indian climate. While ENSO events cause summer drought, the winter rains are usually enhanced. The consequence is a reduction in monsoon season food grain production, but an increase in the winter crops (wheat, barley, grain and rice in coastal areas) (Sinha, 1987).

3.5.2.6 Southern Africa

El Niño events have significant impact on agriculture, with the best documented being the 1982–83 event. Direct agricultural losses are put at US$ 575 million. The clearest links between the ENSO-induced drought and production are shown in Zimbabwe and Mozambique (Ogallo, 1987). Zimbabwe agricultural production was 92 per cent of the 1976–78 base rate and Mozambique 88 per cent (Ogallo, 1987).

In Zimbabwe, wheat production was dramatically suppressed. A decline also occurred in rangeland production in Mozambique, leading to livestock deaths.

The impact of La Niña events has not yet been examined for southern Africa, but the significant linkage of the Southern Oscillation with rainfall and temperature should result in increased agricultural production.

3.5.2.7 Brazil

The Southern Oscillation has the most impact on the northeastern area of Brazil. In this region, ENSO events cause drought as in 1982–83 (Gasques and Magalhaes, 1987) when there was a 16 per cent decline in the region's agricultural production. Subsistence crops were more affected than livestock. Thus the impact of this ENSO-induced drought (and earlier ones) was high. The drought challenged the ability of farmers to subsist. In southern Brazil the ENSO event was characterized by heavy rainfall and flooding. Losses to agriculture amounted to US$ 95 million, with damage to corn, soybeans and coffee crops. Although the floods caused a decrease in per capita income and in agricultural production, the population's ability to subsist was unaffected. The effects of La Niña events have yet to be documented.

3.5.2.8 Southeastern Pacific fisheries

The effects of ENSO events on the Peruvian anchoveta fisheries have been well documented (Glantz, 1984). Essentially the anchoveta fisheries collapsed in 1957–58, 1972–73 and 1982–83 because of El Niño events and overfishing.

Recently, more evidence of impacts on the fisheries' resources have been uncovered (Serra, 1987). The catches decrease significantly in Ecuador and Peru, but increase in northern Chile. These effects are explained by opposite reactions of fish populations. Fish become less accessible off Ecuador and Peru, whereas in northern Chile the large vulnerability of sardines produces an important increase in catches that compensates for decreases in mackerel and jack mackerel. The 1982–83 ENSO also had a serious adverse effect on the abundance of anchoveta, abalone and sea urchins, which had an impact particularly on small-scale fisheries.

These changes in catches cause significant economic losses for the ocean fisheries of northern Ecuador and Peru but are extremely profitable, in the short-term, for the fisheries of northern Chile.

Colder than usual ocean temperatures (La Niña events) have yet to be studied in detail, but may show the opposite impacts on southeastern Pacific fisheries.

3.5.2.9 Other regions

Although other climate teleconnections between the Southern Oscillation and especially ENSO events have been made with other regions in the northern hemisphere, linkages, as discussed, are not very strong outside the Pacific Basin.

For ENSO events, these include wet cool summers and lower crop yields in Japan (Yoshino and Yasunari, 1987) and drought and crop losses in the west African Sahel (Glantz, 1987).

In 1982–83, the hurricane which passed over Hawaii caused severe crop loss and damage to orchards and sugarcane fields. In the United States, severe storms
occurred along the west coast, heavy rainfall and flooding along the Gulf coast and midwest, a very warm winter, then a summer drought and heatwave with crop losses of $10–12 billion (Wilhite et al., 1987). Although all these events have been linked to the 1982–83 El Niño, they have yet to be strongly related to ENSO events in general. No studies have been made on the impact of La Niña events.

3.5.3 CONCLUSIONS

The Southern Oscillation phenomenon causes major variations in global climate. This phenomenon particularly affects the tropical Pacific and low and mid-latitude regions of the southern hemisphere.

In fact, a significant percentage of the climate variation displayed in these areas is explained by the Southern Oscillation. Regions have a higher rainfall variability as the influence of the Southern Oscillation increases. Climate linkages have been made with other areas of the globe, but teleconnections are much weaker.

The Southern Oscillation has a positive phase (La Niña) and a negative phase (El Niño). Each phase is distinct in that it causes marked climate anomalies in many areas. For example, events El Niño produce have cold surface temperature anomalies in the eastern Pacific, drought in Australia, Indonesia, and southern Africa and other climate departures. However, each La Niña or El Niño event displays an evolution of weather and climate anomalies that is unique.

These climate anomalies significantly affect agricultural production in the tropical and South Pacific, Australia, India, southern Africa and South America, and fisheries in the southeastern Pacific. El Niño events generally have greater impact than La Niña events. El Niño events, because they cause widespread drought and displacement of tropical cyclone tracks eastward in the South Pacific, are responsible for lower agricultural production and are devastating in areas of subsistence agriculture and economies. The impacts of La Niña events are more positive, although relatively unstudied by comparison.

In summary, the Southern Oscillation phenomenon, because it is responsible for major variation in global climate, causes large impacts on agriculture and fisheries. Therefore planning of agriculture and fisheries’ production must be made with a knowledge of these major variations in climate.
CHAPTER 4

AGRICULTURAL AND FORESTRY APPLICATIONS AND CLIMATE VARIABILITY
by A.P. Delmotte

4.1 AGRICULTURAL OPERATIONS AND CLIMATIC VARIABILITY (INCLUDING FORESTRY)

Agricultural operations based on climatological and meteorological data should be primarily concerned with the biological or agroeconomic requirements of the organisms.

The biological/agroeconomic requirements and responses were reviewed in Chapter 2 and they will not be developed further here. Consideration will be given to the response curves of the organisms, followed by a review of some physical parameters which should be considered in agricultural operations.

4.1.1 Biotic Factors

Any biological system at any level (from a single cell to a whole ecosystem) will respond to different parameters of the environment following a bell-shaped curve (Figure 4.1).

![Figure 4.1: General response curve of a biological parameter to an environmental factor (a: lethal zone; b: sub-optimal zone; c: optimal zone)](image)

The form of the curve can vary but the three zones remain constant. It is the response of the whole organism or community to all the parameters of the climate of a given place which will condition the adaption of the organism or community to that place.

The broader the response curves, the easier will be the adaptation of the biological system. The growth and development of an organism will thus be dictated by the combination of different parameters of the environment.

To achieve a high production (growth or yield) in agriculture, the plant or animal should be grown or raised where best adapted. The choice will be based on a knowledge of the biology (ecophysiological response) of the organism and of the values encountered for the different ecological parameters.

Very often the response can be explained by temperature and humidity only where these greatly affect the organisms as for example in the survival of insect larvae (see Figure 4.2).

4.1.2 Physical Factors

An operational use of the physical parameters implies an analysis of the spatial variations, continents and countries on a small scale, and local variations and microvariations on a large scale, as well as of the time variations—short-, medium- and long-term.
The analysis is easier if the two types of variations are separated but agricultural operations are based on a global view of the two types together, in relation to biological and agricultural parameters, as in agrometeorological zonation. This meteorological/climatological approach should also include soil parameters.

4.1.2.1 Spatial variations

4.1.2.1.1 Continental and country scale

(1) Latitudinal variations:
Moving away from the equator, the climate changes and one encounters successively the equatorial, tropical, subtropical, temperate and polar climates. The changes are gradual and can be seen in the ecosystems (flora and vegetation, fauna, agricultural systems). There is very rarely a country without latitudinal variation of the climate even where there is no major change in climatic conditions. This latitudinal variation is more or less modified or shifted according to the continental masses and the influence of the ocean.

(2) Altitude:
Climatic variations are also due to the elevation above sea level. This variation is generally more sensitive than the latitudinal variation because the differences are more rapid over short distances.

4.1.2.1.2 Local scale and microvariations

(1) Aspect effect:
The greater the distance from the equator, the more important the influence of aspect, not only from the point of view of radiation and light but also with regard to temperature. In mountainous regions of the temperate zone this is clearly shown in the different vegetation found on slopes exposed to the north or south. Often, there are specific names for the different slopes: adret (exposed to south) and subac (exposed to north) in French; sonnenseite (S) and schattenseite (N) in German; sunny side (S) and shady side (N) in English.
Depressions and temperature inversion:
In topographic depressions the air masses are more stable, and cold or warm air masses could stagnate long after the neighbouring air masses have evolved. This brings particular climatic conditions. The same phenomenon is often repeated at the same place; special ecosystems develop, creating a noteworthy station often revealed by the vegetation. The phenomenon of temperature inversion is also more frequent at certain places, creating, for example, zones of atmospheric pollution but also differing climatic and ecological conditions.

Rainfall, erosion and wind:
Locally the amount of rainfall and its intensity can vary greatly. The altitudinal effect and the exposure to the rain winds are well marked and are increasingly used at the sea coast to catch the water contained in the sea breezes. In some places the vegetation shows a natural utilization of this effect. On the crests, the wind is generally much stronger due to the compression of the flux by the convergence on the mountain. After the crest there could be locally permanent whirlwinds (on a distance varying with the wind speed) and turbulence which could render agriculture impossible.

Screen effect:
When the wind flow is modified artificially with a screen, care should be taken not to interrupt the wind completely, to avoid creating deflation and whirlwinds after the break.

Border effect:
Transition zones often show intermediate conditions even if there is a clear division. A forest edge can be clear cut but there is a transition zone with more light in the forest, and in the open area a zone which is more protected and humid. This transition zone will generally present specific ecosystems where the agricultural systems will react differently such as with modified growth and development or lower branches on the trees.

Internal gradients in the cultivated areas:
In the cultivated areas there are strong gradients in the climatic factors such as a decrease in light, wind and often temperature, and an increase in humidity. In contrast, above bare ground during the day, there is generally a very sharp increase in temperature close to the ground, in some cases several tens of degrees. When the field is cultivated under mixed cropping (several crops mixed) there is a reciprocal influence of one crop on the other. Agricultural practices should be adjusted in such a way that production is not reduced by concurrence; but that there is a beneficial effect in mixed cropping in, for example, protection or better utilization of soil layers and light. When the mixed cropping is permanent, with trees as in agroforestry, the evolution of the system as a whole should be taken into consideration. For example, with annual crops under trees or palms, the trees should be spaced sufficiently to take the later development of the branches into account and not only the space occupied during the young stages.

4.1.2.2
Time variations
4.1.2.2.1
Short-term variations

Less than one day variations:
The local meteorological conditions can vary very quickly under the influence of the general weather: a cold or warm front bringing a sudden frost or thaw, or storm lines modifying the humidity and temperature. Under stable weather conditions there could also be perceptible variations: a succession of clouds (sunny and cloudy periods) modifies the temperature and indirectly the relative humidity. If the length of the period is short, the variations are relatively insignificant; longer periods will have a more marked effect (this could be important, for example, in greenhouse management).

Daily variations:
The day/night succession induces a strong rhythm for some biological systems. Some phenomena only happen with light, and others in the dark. Helminthosporium sativum (on wheat) releases its spores only with light during the day; some Sansevieria bloom only at night and the flowers fade before dawn.
Cycles:
Outside the equatorial zones with their relatively constant climate throughout the year, the majority of environments show an annual cyclic variation: rain, daylength, temperature cycles. Occasionally unfavourable periods or events can reduce the period useful for agriculture. On the other hand, many organisms need a period with a specific type of climate (which could sometimes be considered as negative) to allow a normal development. This is the case with vernalization (a cold period necessary to initiate the processes of flower formation), with quantity variation (short and long days) or quality (more or less infrared) in light.

Annual crops:
The annual crops must achieve their development and growth within one year, within the favourable growing season. This implies one sufficiently long favourable season during which the conditions match the requirements.

Pluriannual crops:
The pluriannual crops should be able to survive the unfavourable climate seasons. This is often achieved by reducing the metabolism to a minimum. During these periods of slow life the growth processes stop almost completely but the changes linked to the development can continue. As mentioned in 4.1.2.2.2(1), some unfavourable periods for growth are sometimes required for development to progress.
Many crops cultivated in areas where conditions do not ever become really unfavourable still need variations of some climatic factors to allow normal growth and development to produce a good yield.

Indirect links and complex systems:
Agricultural production is not always linked to a unique species. Some agricultural practices, mainly when the production deals with animals, involve many species, each of which has its own requirements.
Bee-keeping for example depends not only on the bee species and their behaviour in relation to climate (for instance a period of shortage inducing honey-stocking behaviour; too high a temperature which would weaken the combs and melt the wax; resistance to cold). It also depends on the existence of honey and pollen producing periods, sufficiently large and well distributed throughout the year, to allow the bees to stock enough reserves for the needs of the colony during the dearth periods. These dearth periods are not only dry or cold periods in subtropical and temperate zones, but also periods of high rainfall in tropical and equatorial zones when there are few flowers.
It is also important to stress that if the biological organisms can adjust themselves to the conditions - so that a crop could be grown outside its optimal area, the full agricultural system including pests, diseases and weeds has to be considered. Those which are closest to their optimal or sub-optimal conditions will be more competitive than crops which have to adjust to the conditions and compete with other organisms.

At present, knowledge about long-term variations is too imprecise to be of value in agricultural operations.

At the level of vegetation distribution, however, the combination of ice ages and mountain chains explains the disappearance of the tertiary flora in Europe, blocked to the south by the Alps and the Pyrenees, while in America the north-south orientation of the mountains allowed a retreat followed by a subsequent recovery of the tertiary flora.

The adjustment of agricultural practices will need to occur in a relatively short time if the forecast of global climatic warming materializes. Before changes occur, the transition zones will experience greater variability in climatic factors than at present, affecting agriculture in unpredictable and possibly disastrous ways.

Variation of the climate on a spatial and a temporal scale refers generally to mean values of the climatic parameters.
Climatic variability at a given location should also be taken into account. This could reduce the potential of an area which otherwise seems suitable for an agricultural system.

For example, it has been noted that the variability of a climatic parameter (especially rainfall) increases when the mean value of the parameter decreases (Figure 4.3). Furthermore, this variability is also dependent on the time scale used, decadal rainfall being much more variable than monthly rainfall.

When a rare event occurs, it will affect agriculture immediately but it could also influence subsequent agricultural practices. For example, very low rainfall during a cropping season will result in a decrease in yield. This could also influence future irrigation potential if the water table cannot be restored.

Very often, the effect of the climate variability is more marked when extreme events occur, as in the very cold winters of 1984 and 1985 in Europe which caused extensive damages to trees, especially citrus and olive in Mediterranean areas.

4.1.3 Agricultural Operations

4.1.3.1 Planning and agroecological zoning

By combining information on the biotic and physical factors (climate, topography and soil), planning of agricultural practices according to needs and availabilities can occur. Agroclimatic and agroecological zones can be defined as zones more or less favourable for a given crop, variety or agricultural practice.

The classification thresholds used in zonation will be directly or indirectly biological. It is in relation to the behaviour of the organisms that the thresholds should be defined. These will, however, be more or less artificial, because, on the one hand, the physiological processes implied are complex and insufficiently known, and on the other, the studies are carried out on mean conditions.

As mentioned earlier, variability of climate parameters is just as important as the mean values of the parameters. For example, in a transect from desert to rain forest, often rainfall becomes more erratic when moving from the equatorial to the arid desert zones.

Rainfall may not be a relevant characteristic for all locations. It is important for the humid zones, but it is only accidental to the desert zones where aridity is the characteristic parameter. It should be noted that climatologically stable areas exist at both extremes: desert—aridity; and rainforest—rainfall. Reliable agricultural systems have been developed for these areas, in that the adapted systems have a low probability of failure.
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There is a higher probability of failure in the intermediate zones (subtropical and tropical) where mean rainfall values are sufficient but the year-to-year variability could result in either crop failure or bumper production. The latter cannot usually be fully exploited.

What is true for agricultural systems is also observed in forestry. Adapted forestry systems can suffer greatly from exceptional weather conditions, despite the fact that woody organisms are generally more resistant and that complex forest ecosystems offer some autodamping of the climate variation. However, a forest system will have good production only if the ecological conditions are favourable, as with an agricultural system. This differs from general management practices which relegate forestry to the marginal areas where agriculture is less than optimum. Furthermore, forestry necessarily includes activities which are more related to horticultural practices, such as nurseries and multiplication processes which require more stable conditions.

In both agriculture and forestry, extreme events should be taken into account; these include cyclones, typhoons and hurricanes, frost, gales, and strong winds. The mechanical effects of these events should be considered together with the physiological response of the organisms.

4.1.3.2 Real-time operations

Once an agricultural system is established, at best after careful planning including full agrometeorological analysis, the day to day activities are still influenced by the meteorological conditions.

Some of the meteorological information currently used include:

1. Establishment of crop calendars and daily monitoring of the season;
2. Water management (irrigation);
3. Crop forecasting based on models including meteorological, pedological and agroeconomic parameters;
4. Frost warnings, incidence of diseases;
5. Warnings about pests where the conditions of appearance, development, growth and propagation are known; well documented cases include locust and acridians;
6. Zonation and treatment of some disease vectors such as the tse-tse fly;
7. Forest-fire warning.

4.1.3.3 Models

Most of the agricultural operations using climatic models use agriculture/soil/climate models. The models are classified as:

1. Crop-growth simulation models:
   In these models a simplified representation of physical, chemical and physiological mechanisms underlying plant growth processes is used to simulate plant growth. Simulations of the entire response of the plant to environmental conditions are attempted. These models need a thorough knowledge of the basic plant processes and are generally restricted to special researches.

2. Crop-weather analysis models:
   Here a few factors are considered which are a simplified functional relationship between a particular plant response (e.g. yield) and the variations of selected variables at different plant development phases. These models are practical research and operation tools. The most generally used climatological parameters are solar energy, temperature and soil moisture (as such or through a water balance, potential evapotranspiration and rainfall).

3. Empirical statistical models:
   One or several variables (weather or climate, soil, time trend) are related to a crop response such as yield. The weighting coefficients are obtained in an empirical manner using standard statistical procedures. This statistical approach does not require an understanding of the crop weather relations. These models are generally restricted to one type of culture and to one area which should be as homogeneous as possible.

The models used depend on the scale of the operation: the smaller the spatial scale, the greater should be the number of observation and measurement...
points and, consequently, the smaller the number of parameters to collect. There very soon arises a problem in data acquisition regarding quality, quantity and diversity. The more complex the model, the greater the number of parameters included and the more difficult is the rapid data acquisition for all the observation points.

In addition, the basic data are often missing; for example, the soil waterholding capacity, the rooting depth or the actual crop calendar.

4.2 STORAGE AND TRANSPORT OF AGRICULTURAL AND FORESTY PRODUCE AND CLIMATE VARIABILITY

After production, agricultural and forestry products should be stored and transported to the site of use. These activities are also affected by the meteorological environment. Too often in tropical areas, the conditions are good for production but not so for storage. For example, the storage of potatoes requires quite a low temperature to avoid tuber rust or early germination. For most grains, dry conditions are required. These are not always possible, especially just after harvest when the rainy season is not completely over.

In less developed countries the road network is difficult to maintain and there are mainly earth roads, most of which are unusable during and after the rainy season. As this often corresponds with the time when agricultural products would be transported, these have to be stored temporarily under less than favourable conditions.

Unfavourable meteorological conditions for transport and storage account for a great percentage of the losses of agricultural products.

4.3 DECREASING THE VULNERABILITY OF AGRICULTURE AND FORESTY TO CLIMATE VARIABILITY

The climate change forecasts for the next decades will greatly modify the environment of agricultural and forestry systems. Existing systems will be much more vulnerable and in some circumstances will become unsuitable for the area. To reduce this vulnerability, action will have to be taken at international, national, regional, community and farm level.

National and intranational actions are carried out under the sovereign right of states to manage their natural resources independently, as stated in the Noordwijk Declaration on Climate Change (1989). Changes at national and regional level are more easily implemented than changes at community and farm levels, since the latter require strong communication channels which are insufficient in many countries.

Intergovernmental co-operation and co-ordination should ensure that less favoured countries receive the help they need from industrialized countries. Various international organizations are concerned with the impact of climate change. In particular, FAO has initiated programmes to examine possible climate changes in order to assess their implications for agriculture, forestry and fisheries and to consider future activities (FAO, 1989).

4.3.1 Planning

Careful planning, including simulation of the probable results of the different scenarios, should precede any action. Agroecological sonation, including agrometeorological analysis, allows the selection of agricultural and forestry systems better adapted to ambient conditions. These analyses should be based on mean values and variability parameters, and the time-span should be as short as possible for the systems considered.

There may be conflict between the different requirements of agricultural and forestry systems. For example, all other parameters remaining constant, a longer growing season results in higher crop yield. Varieties with longer growing periods should be used, but very often the variability at the beginning and end of the
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growing season, especially with respect to rainfall, demands faster growing varieties with lower production potential. Furthermore, there is always the risk that both the harvest and the transport and storage may be affected by a prolonged rainfall season.

Basic research is needed on agroecological zonation at regional level, with simulation of different agricultural and forestry systems, and different variations of the climatological environment. These simulations should include socioeconomic variables as well as technical parameters.

4.3.2 Action on the Environment

The variations of the environment could also be reduced by better agricultural practices. Agricultural and forestry practices contribute to the production of greenhouse gases and hence to climate changes, so these emissions should be decreased (Morin, 1990).

Increasing productivity of existing farmed areas would slow down or reduce both deforestation and extension of rice paddies which contribute to methane emissions. Nitrogenous fertilizers that release N₂O should be replaced by other sources of nitrogen.

Soil deficiencies and modifications are counterbalanced by the use of fertilizers. Water requirements can be fulfilled by irrigation if the climatological supply of water fails or is not distributed as required. Action on other climate parameters such as temperature, light and humidity involves greater technology and hence is much more costly. This reduces the applicability to small surfaces like greenhouses, to shorter periods of time and, at present, mostly to more developed countries.

Manipulation of the microclimate by such means as windbreaks, tunnels or greenhouses to reduce the effects of climate change could only be temporary. More dramatic changes to agricultural and forestry systems would be needed to cope with long-term climate change.

4.3.3 Modification of Agricultural and Forestry Systems

When changes of varieties or action on the environment are not practicable, the agricultural or forestry systems should be modified. New techniques should be adopted and new species should be considered (Morin, 1990). In this case major changes should occur in socioeconomic habits.

This could be the most probable scenario if, in the next decades, major climate warming due to increased greenhouse gases does occur.

The situation could be worsened if coastal land, which is very densely populated most of the time and much exploited, is lost through a rise in sea level (FAO, 1989). New land should be colonized or more intensely exploited, even though large parts of these new lands are considered at present to be marginal. Development of better agricultural and forestry systems is needed to respond to the increasing needs of the growing human population.

More diversified agro and agroforestry systems should be used. In this respect, in the evaluation of new suitable systems one should not forget to take into account the old, so-called primitive systems which very often are progressively abandoned because they are less productive than newer systems. But it should be realized that some of the new systems (mixed cropping, agroforestry) fundamentally re-use old practices with the input of new knowledge.

Furthermore, old systems, despite their low productivity, tend to be very robust with respect to environmental variability.

4.3.4 Breeding of More Adaptable Varieties

New varieties with a broader climatological spectrum should be developed to respond to climate variability. Unfortunately, this is generally obtained at the detriment of high productivity or, more precisely, it has been observed that varieties bred for higher productivity are generally less tolerant of the variations in their ecological environment.

International research organizations such as CIMMYT and IRRI have started breeding schemes to produce mega-environment varieties.

4.3.5 Research

Research is needed on the analysis and simulation of global agricultural and forestry systems (FAO, 1989; Morin, 1990).
In particular, systems which are adaptable or can be modified quickly are needed to respond to the greater climatic variability which will occur during the change of climate.

The risk of failure of any existing system will progressively increase from year to year. It should be possible to shift quickly from one system to another when ambient conditions bring failure. In the long run, new systems should replace the old ones.

Basic information is often not known or not well understood (see Section 4.1.3.3). Data acquisition and analysis of this information should be organized and carried out (Morin, 1990).

On the other hand, a great amount of information is archived and not utilized. For example, rainfall and temperature/humidity records for many decades from all over the world have not been fully exploited (Morin, 1990).

4.3.6 Conclusion

The climate change forecast for the future will introduce an important time-shift variable in all environmental parameters, affecting the spatial and temporal pattern of all physical factors and their variations at micro-, meso- and macro-scales. This in turn will have a profound impact on agricultural and forestry operations including storage and transport. Actions must be taken to lessen any negative effects.
CHAPTER 5
THE EFFECTS OF GREENHOUSE GAS WARMING ON AGRICULTURE AND FORESTRY

5.1 AGRICULTURE
by C.C. Wallen, M. Heikinheimo and O.D. Sirotenko

The UNEP/WMO/ICSU international conference held in Villach, Austria in 1985 (UNEP/WMO/ICSU, 1986) concluded that, due to increasing concentrations of some specific gases in the atmosphere, "it is now believed that in the first half of the next century a rise of the global mean temperature could occur which is greater than any in man's history". This conclusion, based upon a thorough assessment of our present knowledge about the likely impact on climate of increasing amounts of greenhouse gases in the atmosphere, is of considerable importance to the human race (Bolin et al., 1986). The critical types of climate changes for agriculture include climatic extremes, warming in high latitudes, poleward advance of monsoon rainfall, and reduced soil water availability, particularly in mid-latitudes in summer, and at low latitudes. Adaptation measures require the development of new technologies for better land use, conservation, breeding and propagation; the problems of adaptation are similar to those discussed in Sections 3.1.2.1, 3.2 and 3.3. Before considering various aspects of the consequences for agriculture, we shall discuss briefly the processes involved in this anticipated warming.

The atmosphere in its natural state contains, in addition to nitrogen and oxygen, small amounts of so-called trace gases, like carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄) and ozone (O₃). It also contains small but significant amounts of anthropogenic trace gases, mainly chlorofluorocarbons (CFC). The problems for the atmosphere created by these gases, also called greenhouse gases, are the following:

1. They are essentially transparent to incoming shortwave solar radiation but absorb and emit longwave radiation from the Earth's surface. This greenhouse-like process has a warming effect on the lower atmosphere and hence on the Earth's climate;

2. Due to ever-increasing anthropogenic emissions of the above trace gases, mainly to meet energy demands through burning of fossil fuels, their amounts in the atmosphere are steadily enlarged and their warming effect on the climate is therefore increasing.

The rising amount of CO₂ in the atmosphere has been a matter of detailed study for the last 30 years. The present amount is 350 ppm (Bouldina, 1988), compared with 315 ppm in 1958 when regular measurements started at the Mauna Loa Observatory on the island of Hawaii (Figure 5.1). It is presumed that the increase started at about the time of the industrial revolution in the mid-19th century, when the estimated amount was about 275 ppm (UNEP/WMO/ICSU, 1986).

A more recent finding has been that, due to human activities, the other above-mentioned trace gases are also increasing in the atmosphere. It is therefore necessary to consider the future impact on climate of the combined warming effect of CO₂ and other trace gases (see Table 5.1). Five years ago, it was estimated that the doubling of CO₂ in the atmosphere since the time of early industrialization would not occur before the year 2060 and would lead to an increase of the global annual mean temperature of between 1.5 and 4.5°C. By adding the likely greenhouse effect of the other trace gases, it is now expected that the same global warming could be reached as early as around 2030 (Dickinson, 1986).

As to the question of the impact of global warming on climates in various regions of the world and in different seasons, it must be admitted that we are far from clear about the consequences. So far, there are indications from studies using general circulation models (GCM) that the warming may be greater in high latitudes in autumn and winter than in any season in the tropical regions. It is also
suggested that rainfall and annual runoff will increase in general in high latitudes but decrease in summer in mid-latitudes of both hemispheres. Potential evapotranspiration is likely to increase with a rise of temperature, particularly in middle and low latitudes. It is strongly recommended that future research efforts should be concentrated on the problems of the impact of global warming on regional climates, and on the consequences of these changes for human activities (UNEP/WMO/ICSU, 1986).

5.1.1 Direct effects of an increase of CO₂ on vegetation

Before entering into a discussion on the impact on agriculture of a climate change due to a greenhouse gas warming, it is necessary to consider to what extent direct effects of an increasing amount of atmospheric CO₂ may influence vegetation. Indeed, there is not yet agreement among scientists whether the direct effects of an increase of CO₂ concentration in the atmosphere on vegetation will be less or more important than the indirect climatic effects (Rosenzweig and Dickinson, 1986).

Although various types of plants behave differently with an increase of CO₂, both C₃ and C₄ plants have been shown in laboratories to be stimulated by increased CO₂ concentrations as a result of enhanced photosynthesis and increased efficiency of water use through the reduction of stomatal apertures. However,
uncertainties remain, particularly in extrapolating the positive effects on water use to regional and global ecosystems (Bolin et al., 1986). Jarvis (1986) made a theoretical analysis of the response of the water use of plants to increased CO₂ in the atmosphere and concluded that transpiration from tall vegetation (forests) is likely to be sensitive to rising CO₂ whenever stomatal action or leaf growth of the species is sensitive to CO₂.

As far as transpiration from short and sheltered vegetation (crops) is concerned, Bazzaz (1986) summarized the impact of higher CO₂ concentrations on plants at the population and community levels in the following way. As a general rule, C₃ plants show greater photosynthetic enhancement than C₄ plants, but differences in response among various species are so large that at the community level quite contradictory results may occur.

Considering a normal water stress situation, Bazzaz (1986) also concluded that with increased CO₂ concentration, C₃ plants should do better than C₄ plants. In a case of strong water stress, there would be little difference in the reaction between C₃ and C₄ plants.

An important observation regarding evapotranspiration of plants in relation to increasing CO₂ has been reported by Goudriaan (1986). Through reduction of stomatal aperture a doubling of atmospheric CO₂ may reduce the potential evapotranspiration ratio by as much as 30 per cent, implying that vegetation would be considerably less water stressed even without any accompanying change in precipitation.

Conclusions about the reaction of high latitude natural ecosystems to increased CO₂ in the atmosphere have been drawn by Oechel and Riechers (1986), who showed that photosynthetic adjustment to higher CO₂ levels occurs rapidly in Arctic ecosystems while plant respiration appears to be little affected.

Summarizing the not very conclusive results of available research on the direct effects of increasing amounts of CO₂ in the atmosphere, Bolin et al. (1986) stated that laboratory experiments on plants have shown that a doubling of CO₂ could result in a 0–10 per cent increase in growth and yield of C₄ crops (maize, sorghum, sugar cane) while C₃ crops (wheat, soybean and rice) could gain an increase of growth and yield of as much as 10–50 per cent. They further emphasized that, even keeping in mind the large fluctuations existing between growing conditions, it is reasonable to expect that the direct effect from increased CO₂ would in most cases be positive and would in particular benefit regions where C₃ plants rather than C₄ plants are dominant. Among feedbacks within plants which may further enhance the primary response to higher CO₂ concentrations, the most important is the increase in radiation intercepted by leaves in C₃ plants which have been expanded due to the CO₂ stimulated growth. Observations in C₄ plants indicate that a non-photosynthetic effect of CO₂ is acting in their case.

Another important question in relation to direct effects of CO₂ needs to be considered. Namely what can be expected to be the future response of CO₂-enriched plants to a warmer average global temperature. Very limited information on this subject is available but according to Warrick and Gifford in Bolin et al. (1986), it seems that the potential for higher CO₂ concentration to stimulate photosynthesis would increase with higher temperature. However, this effect is, to a certain degree, counterbalanced by various negative effects on the growth cycle of many plants.

The above authors point out finally that most of the results regarding the direct response of plants to increasing CO₂ concentration have been obtained in glasshouses where the environment is very different from the one in nature. Although field studies of the problem have been attempted, their results are ambiguous due to lack of control of environmental conditions. Another approach to study the problem is at present under way, namely through the use of simulation models. Progress is being made in that approach (Goudriaan et al., 1984).

5.1.2 Global scenarios for climate change due to greenhouse warming

To provide a basis for discussion on the impact of greenhouse gas warming on agriculture and forestry, a set of scenarios are needed for likely climate change in different latitudes. For this purpose, we have chosen to refer to the scenarios presented in the UNEP/WMO workshop on policies for responding to climate
Three scenarios of global temperature change from now until the end of next century presuming different rates of increase of emissions of greenhouse gases (according to Jager, 1988).

Figure 5.2 presents three scenarios of global temperature change which give the most probable developments that may occur from now to the end of next century presuming three different paths of emissions of the greenhouse gases. The past development of the annual global mean temperature is also included in the picture. The temperature values are plotted as differences from the 1985 values. In each of the scenarios, account has been taken of the time-lags in climatic response which would result from the ocean heat storage capacity.

The middle curve gives the conservative and best-estimate picture, i.e. it reflects a scenario where the present increasing trends of emissions (except for CFCs which are expected to be reduced*) continue while the sensitivity to climate remains moderate. The rate of increase of the global annual mean temperature with this scenario would be 0.3°C per decade and that temperature would be 1.4°C higher than now by the year 2030. The upper curve represents a scenario where greenhouse gas emissions are accelerated and where climate sensitivity is contemporarily increased as some models predict. The rate of increase of global mean temperature with this scenario is 0.8°C per decade and that temperature is expected to be about 3.5°C higher than at present in 2030. The low scenario presumes that greenhouse gas emissions will be radically decreased by international political action. It gives a global mean temperature rate of increase of 0.06°C per decade and a temperature rise until 2030 of only 0.3°C. According to the experts gathered in Villach in 1987, there is a 50 per cent chance that the development will follow a path below the middle scenario and a 90 per cent chance that it will fall somewhere between the lowest and the highest curves.

On the water balance side, it is expected that both evapotranspiration and precipitation will increase globally by 2–3 per cent with each degree of global warming, while distribution of precipitation will depend upon changes which are bound to occur in the general circulation.

It should be noted that in the upper two of the scenarios given in Figure 5.2 the anticipated temperature change significantly exceeds the average rate of increase during the last century. It should also be noted that factors like fluctuations in aerosols and in incoming solar radiation which could affect the global temperature, have not been taken into account.

*According to the Montreal protocol of 1987.
5.1.3 
LATITUDINAL RESPONSES TO A GLOBAL WARMING IN ACCORDANCE WITH THE GLOBAL SCENARIOS

An enhanced greenhouse effect will lead to considerable changes of climate in various regions of the globe. There are great uncertainties about how global population and human activities will affect global climate and even greater uncertainties with regard to regional changes of climate, mainly because global models do not have sufficient resolution to explain regional changes, and, so far, there are no regional models to tackle general circulation. The following suggestions derived from the global scenarios about likely climatic changes in middle and low latitudes by the year 2030 are therefore extremely tentative and, at this stage, are suggested only to present a basis for further considerations of impact on agriculture (Jager, 1988).

For the high scenario, in the mid-latitudes (30-60°N and S), mean temperature would rise by 2-4°C in summer, by up to 6°C in northern hemisphere winters and by up to 4°C in southern hemisphere winters. With the middle scenario, mean temperatures in mid-latitudes are expected to rise by 1.5°C in summer and by 3°C in winter. With the lowest scenario, temperature would change in both summer and winter by about 0.5°C.

With respect to precipitation for the middle scenario it is assumed that in higher mid-latitudes an increase of 5 per cent in summer and as much as 15 per cent in winter would occur. In lower mid-latitudes, with changes in the general circulation, summer rainfall is likely to become non-existent and winter rainfall would decrease by 5-10 per cent.

In very low latitudes (0-30°N and S), mean temperatures are assumed to rise by 2.0°C all year with the high scenario, but by only 1.5°C with the middle scenario. In the case of the low scenario, an increase of only 0.6°C for the whole year is assumed. Precipitation in low latitudes is expected to increase by about 5-10 per cent with both the middle and high scenarios. The increase may be strong in the equatorial regions but diminish towards higher latitudes where arid and semi-arid rainfall mechanisms may continue to dominate.

In all latitudes it is expected that potential evapotranspiration would be enhanced by the order of 2-3 per cent per degree of warming. It is important to recall that 2-3 per cent of the annual rainfall is not the same amount of water as 2-3 per cent of annual evapotranspiration, particularly in semi-arid and arid lands where rainfall now is low and evapotranspiration is high. Only in relatively dry, high mid-latitudes is an increase of evapotranspiration with rising temperature likely to be counterbalanced by an increase in the amount of precipitation. In semi-arid and arid rainfall regimes in low mid-latitudes, it is even possible that rainfall would decrease at the same time as evapotranspiration increased, leading to intensified drying up and desertification, which could have a disastrous impact on agriculture in those already marginal land areas.

In the following regional analysis we have in most cases used the middle scenario to obtain assumptions about the development of various climate parameters.

5.1.4 
IMPACT OF GREENHOUSE GAS WARMING ON AGRICULTURE IN COLD LATITUDES

In this section we review some recent studies that have assessed the impacts of climate change on agriculture in cold latitudes on a regional basis using GCM-based climate scenarios and crop-climate models.

According to the GISS (Goddard Institute of Space Studies) model scenarios, for example, climate warming in latitudes that represent the northern hemisphere cold margins of agriculture could be even more pronounced, being in the range of 2-4°C in summer and 4-6°C in winter depending on the region (Bach, 1988). Despite the great uncertainty concerning the timing and ultimate magnitude of these estimates, they provide the basis for a sensitivity analysis of agroclimate potential and crop yields.

The coordinated projects directed by the IIASA/UNEP organizations (Parry et al., 1988) and the Canadian Climate Centre (Smit, 1989) are used as guidelines. Their assessments are discussed in the light of other recent studies and workshops that have focused on cold latitudes. Case studies for Canada, Iceland and Finland are discussed. The potentially changing role of Arctic tundra in the global CO₂ cycle is also reviewed shortly.
CHAPTER 5

Direct effects of CO₂ on crop physiology and crop production are ignored here because very few studies have emerged which give a comprehensive assessment of the overall long term response of crop communities to elevated CO₂ and climate change. Based on the knowledge accumulated so far, an elevated atmospheric CO₂ concentration would in general tend to increase production in high latitudes where practically all crops are C₃ species.

Simulations of crop production under the estimated future climates include many other simplifications; for example they usually assume a step (rather than a transient) change of climate, and trends in agricultural practice and technology, or the effects of pests and diseases, have seldom been included.

Conclusions from these studies are, to date, only suggestive. In most cases we are mainly able to estimate the direction (rather than the magnitude) of the change in crop production and its profitability as affected by climate warming. Figure 5.3 shows the climatic regions used in the discussion.

Figure 5.3
Climatic regions

5.1.4.1
North America, Canada

5.1.4.1.1
Northern Great Plains region

Despite their northern location, the Canadian provinces of Saskatchewan and Alberta represent an internationally important spring wheat production region. In the north of the provinces, wheat cultivation is limited by unfavourable soil (precambrian shield) and thermal resources. Wheat production in the south of the provinces is regulated mainly by moisture availability (Walker, 1989), with other main limiting factors being the shortness of the frost-free season, excess heat during the summer, and soil erosion. During a 5–10 year drought, spring wheat production in Saskatchewan dropped by about 50 per cent below the average level and even more in a single extreme drought year (Williams et al., 1988). Droughts such as 1929–38 or 1957–68, caused losses totalling over $2 billion in western Canadian wheat production in terms of today's technology and prices (Williams, 1983).

The Canadian climate change case study by Williams et al. (1988), co-ordinated by IASAS and UNEP, was based on a simulation model for spring wheat and climate scenarios by GISS. Two scenario estimates were derived to
illustrate the climate under doubled atmospheric CO₂ concentrations, one allowing a precipitation adjustment (GISS1), and the other fixing precipitation at the current 1951–80 baseline level (GISS2).

Growing season temperatures in southern Saskatchewan were projected to be 3.5–3.6°C above the baseline, indicating a substantial increase in the thermal resources under both scenarios. The corresponding increase in the effective temperature sum (ETS) was 48–53 per cent.

Precipitation effectiveness, which is proportional to monthly precipitation and inversely proportional to normal monthly temperature, was estimated to increase by 5–12 per cent for GISS1, but for GISS2 a climate warming alone with present-day precipitation would decrease effectiveness by 10–12 per cent. Despite the apparent increase in moisture resources under GISS1, a drought analysis showed that the increase in precipitation would not be enough to offset the increase in evapotranspiration caused by high temperatures in both scenarios. Overall, the future climate of southern Saskatchewan was characterized by an increased frequency and length of droughts.

On a long-term basis an 18 per cent reduction in the provincial spring wheat production was projected under scenario GISS1. Losses of about 700 jobs or $160 million annually in farm income could be faced by the agricultural sector. Under scenario GISS2 with fixed precipitation, losses in spring wheat yields could be as high as 28 per cent due to increased drought frequency. Corresponding losses in the agricultural sector could be 1 200 jobs and $275 million annually.

Estimates for the province of Alberta (Williams, et al., 1988) indicate that increasing the temperature by about 2°C over the summer months, without a change in precipitation, would increase productivity substantially in the coldest locations in the north, and reduce it somewhat in warm dry locations in the south. The overall productivity in the province would benefit from the proposed warming of the climate.

Differences in agroclimate between the northern and southern parts of the two provinces were in general estimated to become less pronounced under the proposed scenarios, because of greater climate warming in the north. Moving towards greater latitudinal homogeneity in terms of thermal resources in the region would mean that the major adjustments in spring wheat cultivation would be in the north. For example, higher yielding varieties could be introduced from the south.

In the southern part of the region, cultivation of winter wheat (over about 10 per cent of the area) is already practised during drought years to stabilize the effects of drought on overall wheat productivity (Williams et al., 1988). If winters become progressively milder, western Canada could shift from the lower yielding spring wheats to become a major producer of winter wheats (Smith, 1989). As droughts could become even more severe in the southern parts of the North American wheat belt, the production prospects for wheat in western Canada could improve overall with global climate warming.

5.1.4.1.2 Ontario Two scenarios were adopted by the land evaluation group of the University of Guelph to assess impacts of climate change on agriculture in the Ontario region. A condensed summary of this study, funded by the Canadian Climate Centre, is to be found in Smith (1987). The first scenario was based upon a model developed by the Geophysical Fluid Dynamics Laboratory (GFDL). The second scenario was based on the GISS model similar to the one used in the Saskatchewan study described above.

Climate change in the GFDL scenario was characterized by an increase in the growing season length by 35–54 days. As a result the growing season in northern Ontario would become similar to that presently in south central and western Ontario, with a total of 150 days. In the case of Saskatchewan, precipitation increases would be significant (about 70–90 mm), but the increases in evapotranspiration would be even greater, ranging from 170–213 mm.

The GISS scenario exhibited a climate with even higher temperatures and precipitation than with the GFDL scenario, but again the increase in evapotranspiration would be greater than the increases in precipitation.
In south central, western and southwestern Ontario, yield levels of most major crops were estimated to decline due to increased moisture stress. Losses in small grain, oil seed and potato yields were estimated to be greatest. In central and eastern Ontario an increase in moisture stress would be noticeable, particularly in regions with low drought tolerance. Yields of most crops were expected to increase in areas with higher tolerance.

Both scenarios clearly indicated positive effects on yield levels for northern Ontario; for example, yields of forage and cereal crop varieties presently grown in the region would increase substantially. Estimates of the sensitivity of the northern boundary of corn cultivation are about 175 km/°C (Newman, 1980). As the southern and western boundary of the North American corn belt became vulnerable to drought, corn cultivation would shift northeastwards to cover large areas of Ontario, provided factors such as excess soil moisture were not limiting (Smith, 1987). Also other new crop varieties such as those of winter wheat and soybeans could be introduced into the area. The climatic potential for apple growing would change from poor to good due to a warmer winter climate. More than 60 per cent of the cultivated area could become economically suitable for soybean cultivation (Smit, 1987).

The analysis by Smit (1987) also included classification of land types from well drained to poorly drained land. In the north, drier years under a warmer climate would limit production on lands with low water storage capacity.

Lands with higher tolerance to drought would compensate for this effect with enhanced production. However, interannual variability in precipitation would impose considerable risk overall to crop production in northern Ontario.

5.1.4.2 Northern Europe

Extensive agriculture can be practiced in northern Europe at much higher latitudes than elsewhere in the world due to the relatively warm North Atlantic Gulf Stream. Climate in northern Europe is sub-maritime, reflecting potential sensitivity to climate warming. Recent analysis shows that the importance of northern Europe as a grain producing region could well increase relative to the current major grain growing areas in mid-continental Europe and the Russian Federation.

5.1.4.2.1 Iceland

Iceland is located at the northern limit of technologically developed agriculture, and represents an area where agriculture is profitable mainly in warm years and severely limited during cold years. The GISS 2 x CO₂ scenario estimate of the greenhouse gas induced warming, adopted by the Icelandic case study (Berghorson et al., 1989), was 4°C above the 1951–80 mean annual baseline temperature. In comparison, the mean annual temperature during the 10 warmest years during 1931–84 was only about 1°C above the baseline.

Model simulations for the 2 x CO₂ climate with other environmental and technological factors unchanged indicated a 66 per cent increase in hay yield. Alternatively, in order to maintain the present-day level of hay production, a 50 per cent decrease in fertilizer application could be allowed. Winter time feeding of livestock with hay could be replaced to a great extent by grazing. This would correspond to the present day situation in Scotland where sheep require only a very limited amount of hay during winter months.

Under the current climate, barley cultivation is profitable only during warmer than average years in many lowland areas. In the 2 x CO₂ scenario climate, however, barley cultivation in Iceland was estimated to be advisable in most years.

On the whole, climate warming such as illustrated by the GCM models for a doubling of greenhouse gas concentrations would considerably increase the potential farming area in Iceland, and bring about farming options similar to those presently available in Scotland (Berghorson et al., 1988). However, significant differences in the photoperiod between Scotland and Iceland would largely prevent the direct transfer of Scottish crop varieties to Iceland.

5.1.4.2.2 Fenno-Scandinavia

Plant production in Fennoscandia is limited primarily by temperature and the length of the growing season. Soil moisture reserves are adequate on an annual basis, but in some years, early season drought on clay soils in eastern Sweden and
southwestern Finland may cause losses in crop yields. Heavy precipitation may also severely restrict crop harvesting from mid-August to September (Heinonen and Torsell, 1989).

A case study on the impact of possible future climate warming on Fenno-Scandinavian agriculture is available for Finland (Kettunen et al., 1988). Scenarios by the GISS model for a 2 x CO₂ climatic equilibrium condition indicated that April–October temperatures in Helsinki, would become similar to those under the present climate in Friedrichshafen in West Germany. The mean annual ETS for Helsinki for the 2 x CO₂ scenario was estimated to be about 31 per cent higher than the 1951–80 baseline value, a figure rarely achieved in the historical record even in a single warm growing season. The mean May–October precipitation was estimated to increase by 49 per cent. Slightly greater increases in temperature and precipitation were projected for the northern margin of crop production in northern Fenno-Scandinavia.

For southern Finland under the 2 x CO₂ scenario, estimated barley yields were 9 per cent higher relative to the baseline, the corresponding increase in northern Finland being 14 per cent. The relatively low increase in barley yields with respect to the marked 2°C warming of the growing season for the 2 x CO₂ scenario indicates that the relatively cool summer temperatures associated with these latitudes may not be the only limiting factor for barley yields in southern Finland. Other factors, such as lack of soil moisture during early summer and unsuitable soil, would remain limiting even under the changed climate. The importance of temperature as a limiting factor seems, however, to increase towards the northern margin of barley cultivation.

A profitability comparison between barley and oats showed that under the baseline climate, barley was about five times more profitable than oats. Under the 2 x CO₂ scenario climate, due to the risk of excess moisture, barley would be only about twice as profitable as oats. Overall, the net return on barley would increase 77 per cent in the south and 47 per cent in the north of the country.

More demanding cereals such as spring wheat would benefit markedly from a warmer and longer growing season in their northern margin of profitable cultivation. Estimated increases in yields were 20 per cent in central and 10 per cent in southern Finland, achieved by substituting new varieties suitable for the proposed 2 x CO₂ climate. The increase in spring wheat yields during the poorest years would be even greater relative to normal years. Under a warmer climate, cultivation of spring wheat in southern Finland would thus involve reduced uncertainty.

During a milder winter climate the period of snow cover and soil frost would be shorter. This would allow an extension of the cultivation of winter crops further north. Higher temperatures, such as projected by the 2 x CO₂ scenario, would also allow sowing two to three weeks earlier, thus enabling the cultivation of winter crops during a longer period of vegetative growth. Varieties with high heat requirements could be substituted for the present-day varieties in southern Finland.

Climate warming could, in principle, open opportunities for introducing new crop species from the south. As an example, Carter et al. (1990) analysed the potential shift of the northern boundary of profitable corn cultivation in Europe. The northern margin was simply defined as ETS 850 degree days above a base of 10°C. Ignoring other possibly limiting factors, such as soil moisture, soil texture, day length, solar radiation or the potentially greater adverse impact of pests and diseases under a warmer climate, the sensitivity of the northern boundary of corn was obtained as approximately 250 km/1°C in western Europe and as 200 km/1°C in eastern Europe. Regionally then, a temperature increase of only 1°C could provide the potential for grain corn cultivation over large areas of Ireland, UK and Denmark. Further increases in temperature would open opportunities in mid-Scandinavia.

5.1.4.3 The role of Arctic tundra in the global carbon cycle

Large areas of the vegetation-covered land in cold latitudes are composed of boreal forest and tundra. These regions are of interest because they represent 10–27 per cent of the terrestrial biospheric carbon in the form of organic matter above and below ground. Large portions of the Arctic are presently frozen all the year round,
but a mean climate warming of 4–8°C, such as proposed by the GCM scenarios for high latitudes, could lead to increases in the depth, season length and extent of the annual summer melt (Gifford, 1988). This could in principle lead to acceleration of the decomposition of organic matter, and the role of Arctic tundra could possibly change from that of a small sink of CO₂ to a new source, as proposed by Billings et al. (1982).

Recently, experimental evidence has been sought to assess the role of Arctic tundra in the global CO₂ cycle. The direct response of tussock tundra vegetation to elevated CO₂ and temperature was studied over a period of three years in Alaska (Oechel and Riechers, 1986). Results obtained with 11 common species after 22 months of treatment indicated an overall positive response of photosynthesis by an average of 41 per cent when CO₂ was increased from 350 ppmv to 675 ppmv (Oechel and Strain, 1985). However, by the end of the third season the ecosystem flux of one species, Eriophorum vaginatum (one of the most abundant species in the Arctic tundra), had declined to that of the ambient treatment. It was supposed that high rates of photosynthesis were not possible due to the strong limitation on growth caused by lack of nutrients. Respiration was observed to be unaffected either in the long- or the short-term by either higher CO₂ and/or a 4°C increase in temperature.

These results show that direct effects of CO₂ on tundra vegetation may be less important than indirect effects via climate warming. Climate warming could increase the depth and extent of the active layer in which soil decomposition takes place. Warmer temperatures could enhance the decomposition rate. At the ecosystem scale, complex physiological interactions and physical feedbacks are involved. More complete assessment of the role of tundra is currently sought through ecosystem modelling (Oechel and Riechers, 1986).

### 5.1.4.4 Conclusions

The proposed climate warming of a few degrees due to increases in greenhouse gas emissions into the atmosphere would substantially lengthen and intensify the growing season, particularly in cold maritime climates. Little is known of the possible changes in seasonal rainfall and its variability. Rainfall is, in general, estimated to increase with climate warming, and this increase could compensate, at least partly, for the increased rate of evapotranspiration.

Assessments of the possible impacts of future climate change in cold latitudes show clearly that significant changes in agricultural potential are likely to occur (Kwadijk and de Boois, 1989). On the cold margin of agriculture, climate warming could bring about large spatial shifts of agroclimatic potential. This suggests that agricultural practices and crop cultivars now adopted in a specific region would become suitable in another region presently experiencing greater limitation, for example due to thermal resources. Investigations in Europe and North America have shown that the cultivation of corn, for example, would become potentially suitable in locations such as central Scandinavia and central Ontario. Present day varieties of cereal crops in many locations could be substituted with higher yielding, long season varieties. Estimated increases in spring wheat yields with new varieties were of the order of 20 per cent for central Fennoscandia.

Climate warming is expected to cause increases in evapotranspiration and possibly further shortages of available water, especially in regions sensitive to drought under the present-day climate. As a result, spring wheat yields in the wheat belt of western Canada are expected to decline in the southern part of that region, but these losses would be compensated by increases in wheat production in the north. Milder winters could allow extensive cultivation of winter wheat in the area, thus improving the overall production prospects for agriculture relative to regions further south (Smit, 1989). Similar trends in production were projected for Ontario, particularly on soils with a greater than average water-holding capacity.

### 5.1.5 Impact of a Greenhouse Gas Warming on Agriculture in Temperate Latitudes

It is essential to define temperate latitudes as is used in this section. From the climate point of view, the latitude belt 30–60°N and S includes climates which are not temperate, such as a Mediterranean or monsoon type; there are some zones above 60°N and S which are often considered temperate although they belong to the high latitudes (Jager, 1988). It is suggested that in the context of this section,
EFFECTS OF GREENHOUSE GAS WARMING ON AGRICULTURE AND FORESTRY

temperate latitudes should be defined to include the various climates existing within the latitude belt 30–50°N and S. It should be kept in mind that for many climatic regions, information is scarce or non-existent and that any attempt to analyse the impact of global warming is therefore very preliminary. The following climatic regions will be considered in this chapter:

1. All climates in the westerlies between latitudes 45–50(60)°N and S;
2. Climates in the Mediterranean basin, the Near East, Central Asia, the Far East and California between 30° and 45°N and S.

5.1.5.1
Northern hemisphere

5.1.5.1.1
Climates in the westerlies of North America

The Rocky Mountains of the USA and Canada between 45° and 55°N

This zone comprises the following sub-regions:
(a) The Rocky Mountains of the USA and Canada between 45° and 55°N;
(b) California;
(c) The Great Plains of the USA north of 35°N;
(d) USA east of 90°W between 30° and 60°N.

Assuming that the warming will follow the middle scenario (Jager, 1988), it has been estimated that temperature in both winter and summer will increase by 1.5–3.0°C. Although changes in precipitation are difficult to estimate, it is assumed that, as the area is close to high latitudes in a mountainous region on the western side of the continent, the present amounts, around 1 000 mm per year, will increase by 5–10 per cent in winter and decrease slightly in summer. The temperature rise is expected to lead to a percentage increase of the potential evapotranspiration of the same order of magnitude. However, as the present annual amount of evapotranspiration is only about half that of precipitation, the water supply for agriculture is expected to increase rather than decrease. It should be kept in mind that, as the region includes the states of Oregon, Washington, Idaho and British Columbia which are all highly mountainous, the local variations will continue to be very great. As far as agriculture in general is concerned, it is likely that it will benefit from the higher temperatures and increased water supply. In fact, there is no reason to expect that pasture growth, cattle raising or crop production, as they exist presently in this region, would encounter difficulties from a greenhouse warming, except in localized dry regions where increased evapotranspiration would counterbalance increased precipitation. Potato growing in Idaho may, for instance, suffer from this problem. On the whole, climate warming would otherwise be particularly beneficial in the northern part of the region.

California

The Mediterranean winter rainfall climate of California is also expected to warm by 1–3°C in both winter and summer. The warming will probably lead to increased winter rainfall in the northerly part of the region with a weaker general circulation and reduced winter rainfall in the south. (This is discussed in more detail in connection with the Mediterranean region.) As evapotranspiration is bound to increase with higher temperatures, a drying up of the southern half of California must be considered possible.

Agriculture and horticulture, in particular citrus growing, would benefit in the northern part of California, and the latter would spread farther north in the region. On the other hand, it is quite possible that agriculture in the south would suffer from a drying up in all areas where irrigation cannot be applied.

The Great Plains of the USA
North of 35°N

This area is at present one of the most important crop producing areas in the world where wheat, corn and soybeans in particular are cultivated. The expected temperature rise in this area would be about 1–3°C in both summer and winter. The crop production area extends over the Great Plains all the way down to latitudes 30–35°N but, as one proceeds further south, the climatic circumstances become more suitable for cattle raising than crop production, mainly due to lack of precipitation. For long periods of the growing season the synoptic/climatic conditions over the Great Plains are characterized by the establishment of a ridge of high pressure extending from the southern Rockies towards the Canadian Prairies. The states which are dominated by this high pressure system, are eastern Colorado, Wyoming and Montana, the whole of North Dakota, South Dakota, Nebraska and Kansas, and western Illinois, Wisconsin and Minnesota. In normal years, the high pressure system in the lee of the Rockies is not strong enough in the early months of
the growing season to prevent the rain-bearing cyclones from the Mexican Gulf moving northwards over the plains giving considerable amounts of convective precipitation. However, under certain circumstances the high pressure system develops into a strong stable blocking high which, during the growing season, prevents cyclones from both the Pacific and the Gulf producing the rains necessary for normal crop production. The most severe case of this climatic anomaly occurred during nine years in the 1930s leading to disastrous crop failures and soil degradation. These years are famous under the name of the dust bowl years. Similar conditions occurred recently in the summer of 1988.

Coincidentally, the 1930s were also the decade when the warming, which took place over the northern hemisphere in the first half of this century, reached its maximum (Wallen, 1984). It is argued therefore, that the summer of 1988 over the Great Plains would be due to the greenhouse effect, indicating that such hot and dry summers could become more frequent as warming continues. At this stage, this argument would be considered mainly speculative if it were not supported by a number of modelling studies carried out during the last 10 years which indicate that a drying up of the climate over the Great Plains is a likely consequence of a doubling of the greenhouse effect.

In the late 1970s and early 1980s, Sakamoto (Waggoner, 1983) made an attempt to study the combined impact of a temperature increase of 1°C and a decrease of 10 per cent in precipitation by month on the yield of spring and winter wheat in various states of the Great Plains. For this purpose, he used a multiple linear regression model including effects of various weather elements on yield, which had been developed by NOAA, NASA and the US Department of Agriculture. The calculated changes in yield, compared with the average for 1978–80, were as follows: North Dakota, -12 per cent; South Dakota, -11 per cent; Nebraska, -5 per cent; Kansas, -5 per cent.

These early calculations obviously confirmed that an increase of temperature and evapotranspiration coupled with a decrease of precipitation enhanced by a greenhouse effect would lead to a decrease of wheat yield in the Great Plains, not considering the possible direct impact of an increased amount of CO₂. Manabe and Weatherald (1980), predicted similar results of a greenhouse warming in the Great Plains due to reduced soil moisture.

However, other scientists have expressed great concern about the above conclusions and in predicting the change of water balance in a CO₂ enhanced atmosphere from the rough Manabe-Weatherald's model of 1980 (Rosenberg, 1982). Rosenthal (1985) used the GISS GCM with observed precipitation to generate a simulated map of current wheat production regions in the Great Plains which is in good agreement with the present situation. Results from a double CO₂ run of the same model were then used to predict the yield in the wheat regions under new climatic conditions. In support of the caution expressed by Rosenberg (1982), it was found that the yield would not change significantly with a CO₂-enhanced atmosphere.

However, Manabe and Weatherald (1987), using a more elaborate model, have recently presented new and more convincing evidence that the soil moisture in summer in the Great Plains would be significantly reduced under a warmer climate. It seems prudent therefore to conclude at this stage that Sakamoto's estimates of future wheat yields in the Great Plains are reasonable, whether they are due to more frequent synoptic weather situations described at the beginning of this section (Warrick, 1984) or simply to changes in the water balance leading to a deterioration of the soil moisture conditions.

The future of the corn belt, at present situated in the northeastern corner of the region under consideration has also been predicted by the use of the modelling approach (Newman, 1982; Blasing and Solomon, 1983). The prediction of Newman is that the corn belt would move towards the northwest by about 175 km for every increase of 1°C of the annual mean temperature. Blasing and Solomon used scenarios including reductions of precipitation, and predicted that with a decrease of 60 mm in the July–August rainfall, corn production would be mostly eliminated in the southwestern part of the present corn belt, leaving production only under
irrigation. The belt would otherwise shift to the north where production would depend on how suitable the soil would be for corn growing. Decker et al. (1984) concluded further that sorghum would become suitable for production in the eastern part of the present corn belt if this shifted as predicted by Bliss and Solomon (1983). These authors also present a number of other important agricultural factors in the Great Plains which may change with greenhouse gas warming. The interested reader is referred to their article.

Recently, Wilks (1988) has made a more detailed analysis of the impact on agriculture using modelling simulation of a doubling of the greenhouse effect over the Great Plains of the USA. He concluded that the results would probably be less definite than is indicated from the above discussion, implying that in some areas yields might increase although in others they may decrease. The area under cultivation in general is likely to increase, compensating for any decrease in overall yields. One could also expect an increase in yields due to the direct effect of increased CO₂ (Decker, 1988).

As far as agriculture in the eastern USA is concerned, a doubling of the greenhouse effect is not expected to cause any significant problems in the northern part of the region. In general, most models indicate that both temperature and precipitation would increase by 1–3°C both in summer and winter and by 5–10 per cent respectively, which means that an increase of evapotranspiration would be counterbalanced by an increase in precipitation, at least in the northern regions. In the southern areas it is possible, however, that the increase of evapotranspiration will not be counterbalanced by precipitation increase and agriculture will then suffer from a decrease in soil moisture (Cohen, 1986). How the general circulation of the westerlies would change with an increased greenhouse effect is, however, still quite unclear. Such a change may have impacts on temperature and precipitation conditions that cannot be predicted yet.

5.1.5.1.2

The European sector of the temperate latitude zones (30–55°N) comprises the following sub-regions to be described in this section:

(a) Western Europe (45–55°N and 10°W–15°E);
(b) Eastern Europe (45–55°N and 15–60°E);
(c) Mediterranean Europe (30–45°N and 10°W–40°E).

Western Europe (45–60°N and 10°W–15°E)

A number of early attempts have been made to estimate how temperature and precipitation would change in Europe with a doubling of the greenhouse effect. Most of these attempts are quite preliminary and based upon still not fully developed models.

A special problem arises when interpreting attempts for an impact on agriculture: the outcomes from different models are not consistent, neither as far as geographical distribution of changes nor as far as their quantities are concerned. In the following interpretations it has been attempted to draw conclusions only where different models generate similar results for geographical regions. In cases where differences exist in the order of magnitude, averages between the model results have been adopted (for reference, see Wilson and Mitchell, 1987, and Bultot et al., 1988).

Practically all modelling attempts agree that both summer and winter temperatures would increase with a doubling of the greenhouse effect. As reasonable values of increase, 1.5–3°C for the annual mean, 3–5°C for the winter mean and 1–3°C for the summer mean have been adopted. With such increases the growing season will be prolonged by as much as one month, both at the beginning and the end (Kwadijik and de Boois, 1989). Similarly, both potential and actual evapotranspiration will increase by 10–15 per cent annually and in particular from March to August. Precipitation is expected to increase in winter as westerlies will intensify but decrease during the prolonged summer, as in the west coast of the USA at the same latitudes.

The above climatic circumstances, as we have seen earlier, are likely to be beneficial to agriculture in the northern parts of western Europe but the advantages will be gradually smaller in the southern parts of the region due to less precipitation
and a less favourable water balance. With an increase of temperature and extension of the growing season, basic conditions for cultivation of maize would improve in the southern parts and the area presently cultivated would probably increase considerably. For climate sensitive crops like vines, the situation may become difficult if temperature increases and precipitation decreases, particularly on certain types of soils.

Using the conclusions of the case study on Iceland presented in the IIASA/UNEP publication (Parry et al., 1988), some ideas can be obtained regarding the likely development in very maritime areas of western Europe at a more southern latitude, such as the British Isles. It seems clear from these conclusions that winters as well as autumns and springs would become considerably warmer with a CO₂-enhanced atmosphere while summers would be only slightly warmer. This points to the prediction that the growing season in maritime areas would be significantly prolonged whatever impact this might have on crop growing and cattle raising in such areas. A probable increase of precipitation amount of about 0.5 mm/day in maritime areas is consistent with other indications from modelling attempts.

The conclusions from the case study on Finland (Kettunen et al., 1988) (see Section 5.1.4.2.2), confirm the suggestions presented above about the future climate in the central and more continental parts of the west European sector.

**Eastern Europe (45°–55°N and 15°–60°E)**

This region includes countries like Poland, Hungary, Austria, Romania and other areas south of 55°N. It is expected that with a doubling of the greenhouse effect, temperatures would increase by 2–3°C during the winter months. Precipitation is expected to increase in the western and southwestern parts of the region by 20–50 per cent, while it is likely to remain constant or even decrease in the central and eastern parts of the Russian Federation. With the increase of winter temperature, snow cover in this region will become more scarce, which will be unfavourable to the winter crops presently common in the region. Hence yields of winter wheat would probably decrease in the northern parts of the region but increase in the southwest due to increased precipitation and prolongation of the growing season.

According to the more detailed studies in Parry et al. (1988), rye yields, which are most common in the Baltic States and the area around Saint Petersburg (slightly north of the region discussed here) would increase during a period of about 20 years due to the expected rise in precipitation, but then start to decrease because summer precipitation would become too high. This possibility of a change from an increase in winter crop yields to a decrease could therefore apply also in the western part of the region under discussion here.

Due to the lack of snow cover and gradual increase of summer precipitation over and above the optimum amount, according to the above scenario, it may be wise to consider changing from cultivating winter wheat to summer wheat in parts of the region.

The case study in the Cherdyn region (Parry et al., 1988), slightly to the north of the region under discussion, where spring wheat is the typical crop, found spring wheat yield increased by as much as 17 per cent with a doubling of the greenhouse effect. This seems to indicate that spring wheat would be the most suitable crop to cultivate in the central and southern areas of the European part of the former Soviet Union, even after a doubling of the greenhouse effect. The Cherdyn region study, however, indicates also that an increase of both summer temperature and precipitation could prove dangerous to spring wheat yield because of too rapid a ripening of the wheat in a warmer and wetter climate. The selection of more slow maturing varieties of wheat is an obvious farming response to this situation. In fact, it is likely that, with the considerable changes in climate which will take place in this large agricultural area, the system of agricultural management, including the selection of crop varieties, will be replaced by one where the new favourable climatic conditions will be used to maximum advantage.

In the eastern and southeastern part of the spring wheat belt (Bolga region and North Caucasus) studied in particular in the Saratov region by Parry et al. (1989), precipitation may decrease rather than increase with a doubling of the greenhouse effect, according to an empirically derived scenario. This in combination with increased evapotranspiration could cause a decrease in spring wheat yield.
New scenarios of possible climate changes based on combined calculations using models of the general atmospheric circulation and paleoclimatic reconstructions have become available. Here simulation by models gives the global background of the expected temperature, while paleoclimatic reconstructions of the geological epoch corresponding to the given temperature increase are used to derive regional characteristics of temperature and precipitation.

Paleoclimatic analysis allows one to assess the temperature of the year to the nearest 1°C, and annual precipitation to + 25 mm (Budyko and Israel, 1987).

Scenarios developed by Budyko and Velichko suggest a temperature increase of 1.3°C in 2000 and by 2.5°C in 2025. In the first case the paleoclimatic analogue used is from the optimum of Holocene (5,700 years ago), i.e. the scenario OH. In the second case the analogue is the optimum of the Miculian interglacial stage (MIGS) (125,000 years ago), i.e. the scenario MIGS. These scenarios contain the data on the change of January $\Delta T$ and July $\Delta T$ air temperatures, °C, as well as annual precipitation $\Delta R$, in mm (Table 5.1). The changes expected in annual precipitation by the year 2000 (scenario OH) are viewed in two variants: scenario $\Delta R_{dry}$ that predicts a decrease of annual precipitation SR in the south of the European part of the former USSR, and the scenario $\Delta R_{wet}$ that predicts the same for central and middle-west regions. Current trends in precipitation indicate that scenario $\Delta R_{wet}$ may be more probable (Budyko and Groisman, 1989).

Table 5.2 presents the final results, i.e. the possible changes of the following agroclimatic indices: dates of vegetation cessation $\Delta D_{vel}$ and dates of vegetation renewal $\Delta D_{vrel}$ of plants (in autumn the shift to later dates and in spring to earlier dates is possible); storage of soil moisture in 1 m layer (in mm) on the date of sowing $\Delta W_{sow}$ and the date of vegetation renewal $\Delta W_{vrel}$; dates of sowing $\Delta D_{sow}$; percentage of crop area perished in winter $\Delta S$. The last columns of Table 5.2 present the index $\Delta y$ characterizing possible changes in winter crop production in percentage due to the spring and summer growth and development.

Data in Table 5.2 show that the change of agroclimatic conditions of winter crop growth leads to gradual smoothing differences on the East European Plain. At the same time, considerable improvement of these conditions in the south (dry) part of the region occurs.

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Note: Numbers of regions correspond to Table 5.1; denominations are explained in the text above.
CHAPTER 5

Calculations just completed of bioclimatic potential change (see Section 3.2) according to paleoclimatic scenarios OH and MiGS are presented in Figure 5.4. It relates two kinds of forecasts: the assessment of the influence of technological development and the improved application of mineral fertilizer, and the assessment of the influence of proper climatic conditions. The results show an initial decrease in productivity after which agroclimatic conditions become more favourable. By 2025 one might expect an average productivity increase of 10–20 per cent, although this conclusion is true only if the paleoclimatic scenarios are correct.

Figure 5.4
Modern state and forecast of bioclimatic potential change (total yield of biomass during warm period of the year) in European part of the former USSR, at real (ACP) and optimum (SCP), provided adequate mineral fertilizer is applied. Denominations of economical regions corresponding to numbers 1–13 are given in Table 5.1

Mediterranean region of Europe and the Near East (30°–45°N and 10°W–40°E)

The changes of climate likely to occur in this region due to a global warming caused by a doubling of the greenhouse effect have been predicted by the use of a number of GCMs (Wigley, 1988) which have given contradictory results. According to the scenarios adopted, temperature would increase by 1–3°C by the year 2030, reaching an increase of 3.5°C by the year 2050. It is difficult to make a similarly straightforward prediction for precipitation. The GCM results indicate that precipitation is likely to increase in the northern areas of the Mediterranean region while it would decrease in the southern part. It must be emphasized that these indications are very uncertain and any conclusions to be drawn regarding the impact of those anticipated changes must be considered tentative at this stage. This having been said, it is important that we study in further detail the tentative results that for the southern part of the region, imply a disastrous development towards increased aridity and desertification (UNEP, 1989).
As far as impact on agriculture of the above scenario is concerned, it is first of all essential to define the borderline between the northern and southern part of the Mediterranean region, so that we know where we can expect climate to continue to be reasonably good for agriculture, and where we would have to start thinking of adapting to much drier conditions. At this stage it is not possible to establish even roughly where this borderline will eventually establish itself. Much will depend upon the changes in the general circulation that will accompany the process of global warming.

There are two main mechanisms that must be taken into account with regard to likely changes of the circulation systems in the Mediterranean:

1. The possible movement into the Mediterranean region of the subsidence conditions causing the Sahara desert, together with a general moving north of the circulation systems in the northern hemisphere;

2. The possible increase of the frequency of blocking high pressure systems over the Mediterranean with a general slowing down of the circulation in the northern hemisphere.

The first of these two mechanisms is not likely to move the drying up area in the south much further than latitude 38°N, but the second mechanism could cause droughts for long periods over the whole of the Mediterranean region. In early 1989, a long drought period over central Europe and the northern Mediterranean was caused by an unusually stable high pressure system which lasted for more than two months. If these blockings were to become more frequent, the likelihood of an increase of precipitation due to an increase in temperature would vanish.

With all these uncertainties it is obviously difficult to state very much regarding the future for agriculture in the Mediterranean region. However, according to studies in Tunisia (Hollis, 1988) based upon the assumption of an annual temperature increase of 1.5°C, evapotranspiration would increase by about 10 per cent. Even without a decrease of precipitation, this would lead to a decrease in river flow of 10 per cent. With a decrease of precipitation of about 10 per cent, a conservative estimate, river flow would go down even further. As potential evapotranspiration is calculated to increase by as much as 12 per cent, water for irrigation in the North African coastal zone will diminish at the same time as demand increases. Average storage in actual water reservoirs has been calculated to be reduced by 25 per cent, a reduction which could reach 40 per cent as filling of reservoirs with sediments would increase. Under these circumstances, agriculture, in particular crop growing, would suffer considerably and would have to shift to even more intensive irrigation in some regions. In other areas it is likely that a shift to cattle raising would be necessary which in turn could mean increased desertification in the area.

In the northern region one might have to expect increasing frequency of droughts but otherwise increased precipitation, i.e. a more variable climate which indeed could mean more problems for the farmer, particularly in areas marginal to the southern region.

These, however, are likely to be less severe than those in the southern region.

5.1.5.1.3 Climates of the Asian sector

The following important agricultural regions will be considered within the Asian sector:

(a) Western and central Asian plains of the former USSR (30–55°N and 50–80°E);

(b) Mongolia, East Siberia and North China (30–55°N and 80–140°E);

(c) Middle China, Korea, Japan and east coast of Siberia (30–55°N and 100–145°E).

Western and Central Asian plains of the former USSR (30–55°N and 50–80°E)

As in parts of the former European USSR, this region is sensitive to droughts and spring wheat is the main crop. The impact on agriculture of a doubling of the greenhouse effect, implying a temperature increase of 1.5–3.0°C during the growing season is likely to be felt in an increased frequency of droughts which might endanger the yield of spring wheat. Any increase in precipitation is expected to be considerably reduced in the interior of the Euro-Asian continent in areas which are...
already semi-arid, so there is a clear risk that the increase of evapotranspiration associated with the higher temperatures will not be compensated for by the increase of precipitation, which could be only 10 per cent. A switch to a crop more adaptable to a drier climate might be a reasonable solution. On the other hand, it should be pointed out that different modelling approaches may give quite different results for a doubling of the greenhouse effect in this region, as with the steppe region around southern Volga in the former European USSR (Saratov region). Everything will ultimately depend upon the water balance after an increase of both temperature and precipitation. Under all circumstances the further south and closer to already semi-arid regions one proceeds, the greater will be the risk for an increased frequency of drought conditions, which will require the introduction of large irrigation schemes to maintain present yield conditions.

Mongolia, East Siberia and North China (30–55°N and 80–140°E) According to recent comparisons between existing model simulations for a doubling of the greenhouse effect (DOE, 1988), this region could get an annual increase of temperature of about 2–4°C. In winter the increase may reach 5–6°C and in summer be only 1–3°C. Similar comparisons have indicated an increase in annual precipitation of about 10 per cent, mainly due to more rain than at present during the winter season (+20 per cent). At least one model indicates lower rainfall in summer than at present, while others show an insignificant increase.

The general conclusions for the impact on agriculture in this region are that winter crops would benefit from the higher temperatures and precipitation in winter. Spring crops and pasture land, however, might be subject to problems of a decrease in soil moisture due to increased evapotranspiration but no significant increase in rainfall (Manabe and Weatherald, 1987).

Earlier this century, farmers in North China often suffered from floods of the Yellow River and other rivers in the region. Thanks to flood regulations and control works, such events have occurred infrequently since 1950 (Bell, 1986). These efforts may prove inadequate if autumn and winter precipitation in the source regions of the rivers increases by as much as 30 per cent with a doubling of the greenhouse effect.

As in other areas of the same latitude belt, forests will be dependent upon the rate of temperature increase.

Middle China, Korea, Japan and east coast of Siberia (30–55°E) In this region, one might expect considerable differences in the impact of climate changes depending both upon regional climates and crops cultivated. All over the region, temperature is expected to increase in winter by 4–5°C and in summer by 2–4°C (Grotch, 1988). Precipitation is expected to increase by a small amount in winter and to stay unchanged in summer. Precipitation in Japan and Korea in winter should increase more than in China. As evapotranspiration in China is likely to increase without a compensating increase in precipitation, a drying up of the continental parts of mid-China is possible.

For Japan we have a very detailed study of the impact of climate change on agriculture, in particular on rice yields, in the northern islands (Parry et al., 1988). According to this study, with present varieties of rice, yields would benefit from a warmer climate in the northern islands, as evidenced by a marked decrease in yield when summer temperatures are below normal. On the other hand, if a doubling of the greenhouse effect results in 2–4°C higher summer temperatures, rice yield on the southern islands could be damaged by excessive heat and even on Hokkaido these temperatures could sometimes be too high for presently used rice varieties. It is therefore suggested that as warming proceeds, Japanese rice cultivation should adapt to new climates by introducing alternative rice varieties, as well as changing planting dates and procedures.

Although there are no recent studies in Korea and China, it is logical to conclude that problems similar to those discussed for the southern islands of Japan, would be likely to occur in Korea and at least the more southern parts of mid-China. However, as with Japan, it should not be too difficult to adapt rice cultivation in Korea and China to warmer climatic conditions through the use of suitable varieties and changes in planting dates.
5.1.5.2
Southern hemisphere

(a) Climates of New Zealand and south Australia (south of 30°S);
(b) Climates in Argentina and Chile (30–60°S).

Very detailed analyses of the impact of a doubling of the greenhouse effect have recently been carried out for Australia (Pearman, 1988); a more general analysis of the needs for action has been carried out in New Zealand (Ministry for the Environment, 1988), and a general study of climates past and present in New Zealand has been published by Salinger (1988).

In New Zealand it has been found that an increase of annual mean temperature by 2°C in the north and 3–4°C in the south would lengthen the growing season by as much as 4–6 weeks. If the rise in winter temperature is as much as 4–5°C and in summer 3°C, the growing season would be even longer. One could then expect pasture growth to be extended during the colder season and an increase in dry matter production; the altitude range within which production would be possible would also rise by more than 400 m. Another interesting consequence of global warming would be the possibility of introducing subtropical crops in the northern parts of New Zealand. Also it would be possible to cultivate other crops in higher areas. Yields are likely to increase except in southern and eastern areas where a decrease of precipitation could cause crop growing to suffer.

Due to high variability in the amount of rainfall and the frequency of drought conditions in most of the south Australian agroecological system, the impacts of an increase in CO₂ and the greenhouse effect are much more complicated in this region than in New Zealand. In these areas climates are in general of a Mediterranean type characterized by winter rainfall where dryland farming of winter crops and grazing dominate agricultural activities.

According to the scenario applied in the above studies, a greenhouse warming by the year 2030 would imply an increase in annual mean temperature in southern Australia of 1–3°C, for example in winter 3–5°C and in summer 1–2°C. With such a rise in temperature, convective summer rainfall is expected to increase and expand southwards, but winter rainfall in the southeast may decrease by as much as 10 per cent according to Pittock (1983). In the southwest it is expected that winter rainfall would increase with intensified westerlies (Pittock and Salinger, 1989). One would then expect a climatic improvement for summer crops in areas bordering the subtropics, but a deterioration of conditions for the more important winter crops in some areas. The adverse conditions for winter wheat in the southeast are likely to be exacerbated by increased evapotranspiration during the growing season (Russel, 1988). To some extent, the adverse conditions for winter wheat mentioned above may be compensated for both by increased yields due to the direct effects of the increased CO₂ and by improved conditions in the southwest.

The main agricultural activities in Argentina are growing wheat and raising cattle on the great plains called pampas. Argentina is indeed one of the main wheat exporters in the world and also one of the main beef exporters.

According to the GCM models, a doubling of the greenhouse effect would cause more or less the same increase in temperature until 2030 in the mid-latitude zone from 30–60°S in both the southern and northern hemispheres, i.e. from 4–6°C in the winter and 2–4°C in summer with an annual increase of 3–5°C (Grotch, 1988). In typically wet areas, precipitation would probably increase while the situation may be the opposite in the semi-arid areas in the shade of the Andes. As evapotranspiration would increase by at least 10 per cent there is a risk of a drying up of parts of the pampas areas, making cattle raising less productive and profitable.

This question cannot be settled more definitively without more detailed analyses of how the general circulation in this sector of the globe is likely to be affected by global warming. On the whole it may be concluded that the impact on agriculture in Argentina of a doubling of the greenhouse effect will probably be negative in the dry areas and positive in the wetter areas.

Chile is expected to be rather similar to Argentina as far as the impact of temperature is concerned. However, with the strong influence of the westerlies on climate in southern Chile, the favourable impact of an increase of winter precipitation is likely to be much stronger in Chile than in Argentina. With the
CHAPTER 5

maritime climate the increase of evapotranspiration will be smaller than in Argentina, and hence the impact of a precipitation increase in Chile will not be reduced to the same degree. It is expected that agriculture, in particular growing of pastures and cattle raising, will benefit from a wetter climate in southern Chile.

In the northern arid and semi-arid areas of Chile the situation will depend very much upon which changes in the general circulation accompany a warming. It is possible that the atmospheric subsidence effects dominating northern Chile would be strengthened. No improvement for agriculture could therefore be seen. However, if the impact of increased precipitation affects part of northern Chile, agricultural conditions will improve. Further studies are needed to clarify the likely development in those areas.

5.1.5.3 Conclusions regarding the temperate latitudes

It is essential to stress the tentative character of the ideas presented for various regions. In some cases, detailed studies are available as a basis for our considerations about the future, while in others there exist only some general conclusions about the temperature increase drawn from the simulations of a doubling of the greenhouse effect carried out by various GCMs. As the resolution of the GCMs is not sufficient for any detailed conclusions to be drawn, it is necessary at this stage to be somewhat vague regarding even future temperature levels, and effects on other variables like precipitation and evapotranspiration are even more uncertain. The suggestions presented about future conditions for agriculture in many of the areas are, therefore, mainly speculations; they should under no circumstances be considered as predictions. In all regions the possibility must be recognized that the direct impact of the higher \( CO_2 \) content of the atmosphere may have a counterbalancing effect on any adverse consequences of a climate change.

5.1.6 Impact of greenhouse gas warming on agriculture in low latitudes

For this study, low latitude climates must be defined and divided in a way that is suitable for our purpose.

Because of the earlier definition of temperate latitudes, low latitudes are now defined as lying between the Equator and 30°N and S. It is, however, climatologically incorrect to treat this belt as one entity because it involves arid and semi-arid climates around 23°N and S but very wet climates in the monsoon areas and around the Equator. It is therefore taken that within the belts from 30–15°N and S, there are two climates, namely arid and semi-arid climates, and monsoon climates. The climates of the belt from 15°N to 15°S are covered under the name tropical and equatorial humid climates.

As there are many regions in low latitudes where little information exists on what can be expected to happen to agriculture with global warming, this section deals with the above climates as overall entities instead of separating them in regions of each continent. If in any geographical region particularities call for separate treatment, they are discussed specially.

5.1.6.1 Arid and semi-arid climates in low latitudes

These climates are to be found in all continents around 23°N and S, for instance Baja California and northern Mexico, Sahara with the Sahel belt, Egypt and the Arabian peninsula with adjacent areas of the Near East, and central India are well known examples in the northern hemisphere. In the southern hemisphere, there are the Australian desert, the arid and semi-arid lands in southern Africa and the deserts of Argentina and northern Chile.

From the viewpoint of general atmospheric circulation, these areas are all located more or less under the influence of the so called subtropical high pressure systems, where the air almost permanently is in subsiding motion, thereby preventing rain mechanisms from operating. In areas marginal to the deserts, such mechanisms do operate occasionally and semi-arid conditions are thereby created. It is important, however, to separate the rain mechanisms operating on the high latitude margins of the arid regions from those which operate in low latitude marginal lands. The marginal lands on the high latitude side are bordering on Mediterranean climate with winter rainfall associated with the temperate latitude westerlies and varying with fluctuations in the temperate latitude winter circulation. In semi-arid lands marginal
to the deserts on the low latitude side, rain mechanisms are connected instead with the wanderings of the inter-tropical convergence zone (ITCZ) or the monsoon circulation. Rainfall is therefore mostly a summer phenomenon in those regions.

In order to analyse the possible impact of global warming on the climate and agriculture in the semi-arid land areas of the sub-tropics on the one side, and those of the tropics on the other, it is necessary to develop scenarios about how the circulation conditions on the high latitude and low latitude sides are likely to change. Obviously, it is also necessary to understand how the microclimate and mesoclimate would change in the respective areas.

In general, it is obvious that agriculture in the semi-arid regions is already marginal and is extremely vulnerable to fluctuations in climate conditions. We must therefore expect a global warming to be of particular significance in those areas. On the other hand, as these are already under extremely variable climatic conditions (particularly with respect to rainfall), it is also true that agriculture in those areas is often more adaptable to climate change than in many other areas.

5.1.6.1.1 Semi-arid regions in the northern hemisphere

Semi-arid regions in the northern hemisphere which border the desert areas on the high latitude side, are to be found in western USA and northern Mexico, in north Africa, the Near East and India.

As with Mediterranean climates, it is quite possible that these semi-arid areas might become drier if the sub-tropical high pressure systems that cause the deserts which border move northwards in the winter seasons. Earlier periods of warming have indeed shown movements towards higher latitudes of these high pressure systems as a typical feature (Flohn, 1979; Bryson and Murray, 1977).

From the point of view of the microclimate and the water balance in these areas, a reduction in the amount of winter rainfall and an increase of evapotranspiration are to be expected. As this implies a reduction of soil moisture, rainfed agriculture in particular will suffer, and in many cases become impossible. Also irrigated agriculture will have increasing problems as areas for cattle raising will be reduced and pasture land will become rangelands. These last mentioned problem will be of particular significance in southeastern USA and north Mexico, including Baja California.

It is normal procedure to put the limit between semi-arid and arid regions on the high latitude side of the deserts at an annual rainfall of 250 mm. If rainfall were reduced below this amount by 2–3 per cent per degree of annual warming (estimated at 2–3°C), the annual amount would decrease to about 230 mm. This would imply that in the Near East an additional area of 100 000 km² would have its normal rainfall amount reduced to below the minimum required for dry land farming (Wallen and Gwynne, 1978).

In the areas on the low latitude side of the deserts in the northern hemisphere it is much more difficult to foresee what is going to happen with the general circulation conditions. If, as anticipated above, the circulation systems of the northern hemisphere were displaced northwards with global warming, one would expect that the equatorial rain belt would move into the areas south of the deserts and the rainfall would therefore increase. For various reasons, however, the rainfall mechanisms connected with the ITCZ are much more diversified, variable and unreliable than the ones connected with the temperate latitude westerlies. This is why there are several contradictory conclusions about the likely consequences to agriculture of a global warming in the areas south of the desert regions (Jager, 1988).

It would be expected that with higher temperatures rainfall would increase in these areas but it has also been pointed out that over the last 20 years rainfall has shown increasing variability and a decrease rather than an increase. If global warming is already having its impact on the general circulation, it is not inconceivable that both variability of rainfall and frequencies of droughts and floods would increase as a consequence of a non-steady state situation and of long distance teleconnections. There is, for instance, some evidence that with ENSO events there is a general increase in the semi-arid areas on the low latitude side of the deserts. With a complicated chain of events occurring in the climate system and with
uncertainty about their inter-relationships, it is at this stage not possible to draw any
definite conclusions about how the climatic conditions in these areas would change
with global warming.

However, certain indications about possible consequences to agriculture from
fluctuations of climate in such areas may be obtained from Parry et al. (1988, Vol. 2),
where a thorough study of climate impact on agriculture in semi-arid areas of Kenya
is presented. The region under study belongs to three different agroclimatic zones
where precipitation conditions vary from a maximum of 1 500 mm per year in the
wettest regions to only 550 mm per year in the driest zone. According to general
experience from dry land farming in semi-arid regions in the tropics, an average of
750 mm per year is required for relatively stable dry farming conditions as long as
annual variability does not exceed 40 per cent. This implies that with present
climatic conditions dry land farming is possible in the two wetter zones while
agriculture is limited to cattle raising on rangelands in the drier one. Present
variability of rainfall during the long rainy season varies from about 30 per cent in
the wetter zones to 50 per cent in the drier zones. During the short rains variability
lies between 50 and 70 per cent in all regions. For the agricultural year, rainfall
variability lies between 25 and 40 per cent in all regions.

The region selected in Kenya, can be considered as typical for the situation in
semi-arid lands on the low latitude side of the desert regions. If global warming were,
for instance, to increase variability to say 50 per cent there is no doubt that, even
with an expected increase of mean precipitation due to higher temperatures, farming
in these areas would suffer, implying that agriculture would have to shift increasingly
to rangeland cultivation and cattle raising. This is quite clearly confirmed by the
agricultural conditions in the Sahel during the recent long periods of drought.

5.1.6.1.2
Semi-arid regions in the southern hemisphere

5.1.6.1.2.1
Australia (20–30°S)

In areas bordering the Australian desert on the high latitude side, i.e. areas
influenced by the temperate latitude westerlies, it is expected that a displacement
southwards of the westerlies might cause a decrease of winter rainfall. However, it is
also possible that convective summer rainfall will increase in these regions because
such a trend has been noticed during the recent decades of warming of the southern
hemisphere (Pittock and Salinger, 1990).

If warming continues, it is not likely that the trend towards increasing
summer rainfall will persist because gradually the region will come under the
stronger influence of subsidence. As in temperate latitudes, the above tendencies
will lead to deteriorating conditions for all agriculture dependent on winter rainfall
and in the long run, also to more problems for crops cultivated in the summer
period.

In northern Australia the situation in the semi-arid regions is not very
different as far as recent trends are concerned. There are no strong changes in either
winter or summer rainfall patterns. A continuous warming is, however, likely to
influence the summer rainfall positively, which would mean improved conditions for
tropical agriculture.

5.1.6.1.2.2
South Africa (20–30°S)

There are no clear indications that global warming will affect the semi-arid areas on
the borders of the deserts in Botswana and Namibia any differently from other semi-
arid areas bordering deserts created by the sub-tropical high pressure systems. Areas
bordering the deserts on the south side will most likely become drier and areas on
the northern side are likely to receive more rainfall. Some deterioration of
conditions for agriculture will then be encountered in southern Africa while both
crop growing and cattle raising would be enhanced in the drier parts of Angola and
Zimbabwe.

5.1.6.1.2.3
South America

If the high pressure system in the Pacific moves towards higher latitudes, the deserts
of north Chile and south Peru are likely to spread further south implying
deteriorating conditions for agriculture in the northern part of Chile in the area
from Santiago to Antofagasta. On the low latitude side of the deserts, it is not likely
that the desertic situation will change along the coast of Peru with global warming,
unless the frequency of El Niño situations in the general circulation increases. In
fact, there are indications that the opposite would be more probable. In the semi-arid inland areas of southern Bolivia it is likely that rainfall would increase rather than decrease, so that agricultural conditions would improve.

In the semi-arid areas of Argentina on the leeward side of the Andes, conditions would probably deteriorate in the north but become slightly better in the southern regions. Slightly improved cattle raising conditions could also be expected over the southern pampas.

5.1.6.2 Monsoon climates

Regarding the likely climate development with global warming in the monsoon regions, it has been predicted that summer monsoons would be strengthened due to an increased difference in temperature between a warmer continent and the oceans. Consequently, the winter monsoons would be weakened (Das, 1985).

As a further consequence it could be expected that precipitation during the summer monsoon seasons would be enhanced to the benefit of agriculture, for instance in the rice-growing regions of southern and southeastern Asia.

Analysis of 80-year (1900–80) data of surface air temperature over the northern hemisphere and large-scale rainfall activity of the summer monsoon over India has given the following indications about the relationship of temperature with monsoon activity.

On decadal and longer time scales, the epochs of relatively cooler and unstable climate over the northern hemisphere (1901–20 and 1960–80) were associated with less than normal decadal averages of monsoon rainfall, larger rainfall variability and greater frequency of monsoon failures. The relatively warmer and stable climatic epoch of the period from 1921–60, on the other hand, was associated with favourable monsoon rainfall activity (i.e. decadal-scale above-average monsoon rainfall, less variability and very low frequency of monsoon failures). The mean temperature (or the mean climatic state) of a particular epoch, appears to have influenced differently the variability of large-scale atmospheric circulations like monsoons over the globe, through significant changes in the frequency of occurrences of extremes.

In areas like west Africa and east Africa as well as in northwest India, wet monsoon climates are bordering on very dry climates. In these areas it is unclear what will happen with global warming as the consequent climate developments will depend upon how the general circulation mechanisms involved will be affected by the change in the temperature difference between the equator and the poles. If the monsoon mechanism dominates, precipitation is likely to increase to the benefit of agriculture. If the subsidence mechanism over the arid regions is strengthened and spread, precipitation is likely to decrease. In the monsoon regions in both west and east Africa, the models give contradictory results with increases in some regions and decreases in others, perhaps indicating the conflict between the impacts on the rainfall mechanisms operating. In the Asian regions, the results are also contradictory. In south Asia one model indicates a strong increase in precipitation while another gives a small decrease in the same area. A third model indicates a complicated picture with increases in some areas and decreases in others. It seems that the conflict stems from the fact that the impacts on different rain mechanisms are not sufficiently well parametrized in the models, which therefore give contradictory results. However, it seems reasonable to pay more attention to the results of the models that indicate a strong increase in precipitation amounts than to the others, as such a result is consistent with what can be expected from the physical processes involved. It should be mentioned in this context that an increase of precipitation could lead to much higher frequency of floods and similar disasters, which could have a serious and devastating regional impact on agriculture.

Another climatic issue which is likely to be influenced by a global warming and would have considerable impact on agriculture, particularly in south Asia is the date of the onset and withdrawal of the southwest monsoon (Rao, 1976). Considering the fact that present agriculture is based, to a large extent, upon recent climate statistics, it is clear that a problem could arise if a warming of the Asian continent led to an earlier onset of the monsoon, with present planting dates becoming obsolete. It is difficult to say in which direction any change in the onset
date will occur, but it seems most likely that the date of onset will be earlier in the year and the monsoon will last longer than at present. The impact on agriculture of these and other changes in the monsoon circulation will depend very much on the rate of warming. The slower the change of temperature, the easier it will be to adapt agriculture to new circulation conditions and to new dates of the onset of the monsoon.

There are no monsoon climates of any significance in the southern hemisphere.

The increase of temperature in the above regions from a global warming by the middle of next century is estimated to be between 0.5 and 2.0°C, somewhat lower than the global average. It is expected that this could lead to an increase of precipitation in these regions of between 5 and 20 per cent. This enhanced rainfall may occur largely through increases of rainfall intensity. The higher temperature will also be accompanied by increased potential evapotranspiration which may imply more drought stress in regions already exposed to such stress or bordering on semi-arid and arid areas. Tropical storms may increase in frequency and spread into areas where they do not exist at the moment. Rising sea levels and tropical storm surges are expected to have a detrimental impact on agriculture in coastal regions and river estuaries (Jager, 1988).

As both heat and water are generally sufficient for agriculture in tropical and equatorial humid regions, it is the excess of both that may become detrimental in the future. Floods must be expected to occur more frequently in many areas and agriculture will suffer, in particular, from too intense rainfall and increased soil erosion. In areas which have been opened up through cutting down tropical rain forests, soil degradation will be greatly increased by a combination of higher rainfall intensity and increased soil temperature. Regions of infertile soils in the uplands may also become increasingly vulnerable.

It must finally be realized that the impact of global warming in the equatorial and tropical wet regions may also result basically from the changes induced on the general circulation conditions. These altered conditions may cause more changes in rainfall patterns and drought stresses than the increased temperature. Such changes, which at this stage cannot be predicted, may in many regions become of greater importance to agriculture than the general implications mentioned earlier.

Some indications of what may happen with global warming in some humid tropical regions are given below.

The most obvious problem in Amazonia connected with global warming is the likely increase of its vulnerability to harmful environmental effects of deforestation and the opening up of the rainforest for settlements. Increased radiation effects cause increased soil temperatures leading to soil degradation. It is likely that this effect will be further enhanced by global warming. In coastal zones, rising water levels will increase the chances for tropical storm surges and rising peak runoff in estuaries and deltas.

A recent study by GEMS/GRID by UNEP has shown that coffee cultivation in the higher areas of Uganda would be vulnerable to global warming. Large areas where coffee is now being grown with great success would be wiped out by an increase of annual mean temperature of 1–2°C. Although this study does not go into the detailed impact of changes of other climatic parameters which are certain to complicate the picture, it is evident that growing industrial crops in the humid tropics could be in considerable danger through an increase of temperature in many regions (GRID/GEMS, 1988).

As in other humid tropics, it is likely that rainfall in this region will increase and the summer rainfall regime will push southwards over the Australian continent so that improving conditions are expected for tropical agriculture in the borderline zone to semi-arid conditions in northern Australia.
Another phenomenon likely to be affected by global warming is the frequency of tropical storms in the oceans off the Southeast Asian mainland. As water and air temperatures increase, the frequency of tropical storms will rise and the area where they will be formed will be enlarged. This could become a serious problem to human settlements and activities (including agriculture) in the region.

5.2 FORESTS*
by E. Choisnel

Before analysing the results of the GCM simulations as a consequence of the enhanced greenhouse effect and their possible implications for forests, we must redefine the concept of climate variability as fluctuations of the climate above and below a mean state.

The currently observed mean climate and variability are both characterized through a statistical analysis of 30-year time series (1951–1980), such a period being seen as a compromise between a sufficiently long period to provide a proper statistical distribution of climatic variables, and a sufficiently short one to filter, as it were, the climatic fluctuations over longer periods.

Using GCM simulations with a doubled CO$_2$ concentration, we can diagnose a change in the given level of the mean climate, while remembering that it is still climatic variability which causes the new mean state. Moreover, there is as yet no proven confirmation of a change in the range of climatic variability (Rosenberg, 1986).

The above points are fundamental and must be taken into account when making an evaluation of the impact of climate changes on forests, especially as regards the following three crucial aspects:

1. A new mean state is defined in relation to the current global climate, but the path leading from one state to another is not known;
2. As a corollary to the above, during this passage from one mean state to the other it is not known what will be the rate of increase in mean air temperature, a factor which is crucial to the forest ecosystems' adaptability to the climate change;
3. Analyses of the impact of climate changes can only be done, as we shall see, at the level of local climate. Otherwise, how can microclimatic changes be linked with those predicted on the scale of the general circulation of the atmosphere?

What conclusions can be drawn from these global climate simulations with a doubled CO$_2$ concentration? All the models agree in predicting an increase in the Earth's mean temperature. This increase is within $3^\circ$C ± $1.5^\circ$C, which leaves a wide margin of uncertainty. The latter is due both to the differing projections of the future increase in the various greenhouse gases, and to the response of the oceans' surfaces, which is still poorly known. This increase is also distributed differently according to latitude and season, the maximum being predicted in winter in the high latitudes of the northern hemisphere ($-6^\circ$ to $-7^\circ$)

The various models differ when it comes to regional modifications of precipitation. In general, allowances are made for an increase in evaporation linked to the increase in temperature which would entail, as it were, a speeding up of the water cycle. There is also much uncertainty about modelling of the cloud cover which is not only linked to the water cycle but also operates on the atmosphere-land radiative transfers. All of these uncertainties lead us to reason more in terms of probable scenarios than of a definite evolution.

Among these different scenarios, various points should be considered in more detail, such as:

1. Changes during winter, especially a possible drop in rainfall around the subtropical latitudes in the northern hemisphere;
2. Increasingly early summer drought.

* The author thanks G. Aussenac, J.M. Guehl, M. Becker and C.C. Wallen for their important contributions to this section.
CHAPTER 5

5.2.1 FOREST STANDS AND ECOSYSTEMS

An inventory and detailed description of the various forest zones around the world are outside the scope of this report, but it is important to envisage a certain typology of the various forest ecosystems encountered on the different continents.

Forest ecosystems are reputed to be more vulnerable than agricultural systems to the possible impact of global climate changes, mainly because of their slower adaptation (range of species, spatial structure of the cover, time needed for natural evolution of the cover). The need is also stressed to preserve these ecosystems since their over-hasty destruction through human activities or the changing environment, without an immediate new land use for a new annual or perennial crop, can lead to increased greenhouse gas effects through the release of CO2 (unrestrained deforestation and forest fires).

A second aspect of forest ecosystems to be examined is the fact that they generate their own microclimate which contributes to the conditions of their own growth.

5.2.1.1 Different types of tree cover

The typology of the various forest stands should take account of both the spatial structure of the tree cover and the species composing this cover.

As regards structure, we must distinguish between closed cover and open cover, which correspond to different ways of intercepting solar radiation and to differences in the sensitivity of their internal microclimate to the external climatic conditions. In determining the stand's composition we must distinguish between monospecific cover, broadleaved cover, softwood cover and multispecific cover.

Closed cover has the peculiarity of intercepting all the solar energy through its foliage and the underlying soil is protected from wide diurnal ranges in the microclimatic elements. Depending on their specific composition (broadleaved or softwood), this closed nature of the cover is maintained for all or part of the year. Most forests throughout the world form closed cover. Natural renewal of the trees is possible without change of the cover if the spatial distribution of trees is dense.

With respect to species composition, the main distinction to be made is obviously between softwood and broadleaved trees or between evergreen and deciduous species. Mixed softwood/broadleaved systems are relatively infrequent worldwide. Perrier (1982) distinguishes four main types of closed evergreen forests:

1. Equatorial forest in zones with high annual rainfall (more than 2 000–2 500 mm/year). These are mainly broadleaved forests, and the understoreys include a wide range of species which maintain a permanent leaf index;

2. Rainforest, mainly containing eucalyptus and limited to small areas with warm, humid climates in the southern hemisphere. It may evolve quickly in cases of lower rainfall;

3. Boreal evergreen forest in the high latitudes of the northern hemisphere, where it covers a large part of the continental area and is frequently almost monospecific;

4. Mediterranean evergreen forest.

Perrier also distinguishes three types of deciduous tree cover, namely: monsoo forest, mixed boreal forest and temperate deciduous forest. A distinction should also be made between natural and production forests, the latter undergoing periodic clearing. There is a need to determine more accurately the range of a species in relation to the climatic variability which it can accept.

The range is often characterized by a range of mean annual rainfall values and supportable temperature extremes.

5.2.1.2 Adaptability of the various species

The adaptability of certain species is not known. It is estimated that wild species generally have considerable intraspecific genetic diversity. In the case of associations of species, a climate change risks favouring one species to the detriment of the others, but from the point of view of maintaining tree cover to protect the soil from the effects of the sun and erosion, a multispecific forest has greater resistance than a monospecific one because of the different adaptabilities of the various individual species.

In the case of mountainous regions, compensating for climate warming through a shift towards a higher altitude will be limited by the wind speed, which may become a strict limiting factor for the timberline.
Current opinion among forest researchers on the definition of a state of balance between an ecosystem and its environment is that a forest ecosystem is never really in balance. It evolves in time and its current pseudobalance is the result of its own history.

5.2.2 Method for analysing the possible impact of local climate changes on the main physiological functions and various ecological processes

This sub-section analyses the results of experiments in forest bioclimatology on interactions between each elementary physiological function and the climate, bearing in mind the complexity of the problem since climate change will not affect only one variable (temperature or rainfall alone) but the effects will be combined.

The maintenance of good growth conditions is linked to thermal conditions and water availability. A general rise in temperatures may have a favourable impact in reducing late frosts which damage young plants.

5.2.2.1 Growth

Growth in general increases with temperature but distinction must be made between growth in height and growth in diameter. In temperate regions, there seems to be no upper thermal limit for growth in height. The latter occurs earlier in the year in cases of higher temperatures. In cases of multispecific cover, there may be more competition between the trees because of the increase in growth.

The microclimatic environment of trees can be seen to have a considerable effect on growth (shelter cutting, clearing and clear felling). There seems to be an optimum thinning which is about 50 per cent of that carried out for clear felling. This is connected with a lower level of potential evapotranspiration than on cleared land (Aussenac, 1984).

Growth in diameter has been studied within dendroecological studies. It has been deduced that water supply plays the major role in comparison with temperature. In the Vosges, France, a positive effect on the silver fir was noted from the potential water budget (rainfall/evapotranspiration) during the spring and summer of 1989 as well as during the previous six years, which indicated the after-effects of drought. During this study a specific effect of temperature was observed only for February, with a slowing effect in the case of very low temperatures (Becker, 1989).

5.2.2.2 Photosynthesis

A distinction must be made between spring and summer photosynthesis, and winter photosynthesis. Photosynthesis depends on both temperature and light. The optimum temperature is between 20 and 25°C for most species, and temperature increases may or may not have a beneficial effect depending on the latitude and the season (period at optimum or beyond). Negative thermal effects are observed in summer, with temperatures higher than the optimum for the species.

The role of light is linked more to local microclimatic conditions (role of thinning (Helms, 1964)), but it must be remembered that the evolution of cloudiness in the case of a climate change is still problematic. Photosynthesis may also be limited when growth is slow since there is then an accumulation of assimilated substances, with a negative retroactive effect on photosynthesis.

As regards winter photosynthesis, it has been shown (Guehl et al., 1985) that softwood trees could have photosynthetic activity to temperatures of -3°C, and that there was considerable production potential for the Douglas fir (Choisnel et al., in press).

An increase in winter temperatures, in the absence of any moisture stress, would have a favourable effect on softwood photosynthesis which varies according to species.

5.2.2.3 Water availability, evapotranspiration

If climate changes result in less rainfall in certain regions, the water conditions will obviously change too. Even if there is no significant drop in rainfall, the increased temperature will result in higher potential evapotranspiration. In general, even short episodes of climatic drought disturb the functioning of trees and limit growth.

In the case of drought, regulation of transpiration varies from one species to another. With an increase in moisture stress, reduced transpiration affects first the Austrian pine, the Scotch pine and balsam fir, then the Douglas fir and spruce, and finally the cedar and evergreen oak (Aussenac, 1987). Unfortunately, little is known of the reaction of tropical species to moisture stress. Some species, such as
the beech, have very low stomatal regulation capacities and can survive only in conditions of good water supply. Drought affects growth in diameter before growth in height.

An increase in temperatures can also affect the stomatal regulation which depends on the air saturation deficit: stomatal resistance increases with this deficit, for example when air temperature increases and unchanged partial atmospheric water vapour pressure remains unchanged.

Here we shall note only that a rise in temperature accelerates the completion of the development cycle during the year. For example, Aussenc (1975) linked the budding date of various conifers to cumulative (from 1 January) temperatures above 0°C.

In trees, reproduction is dependent, among other things, on daylight hours. As in the case of the annual development cycle, it is estimated that an increase in temperature will generally accelerate the plant's life and impair the tree regeneration rate. Tree ageing will therefore take place more quickly, with the lethal threshold for most tree species being about 40°C. The risk of death will clearly have to be examined separately for production forests.

This subject is currently being studied within the IGBP programme. With regard to the physical processes, it should be remembered that evolution of the soil conditions will depend considerably on the precise evolution of the tree cover itself and the latter's possible death rate, since, as the tree density per hectare diminishes, the solar radiation penetrating to the soil surface will increase and affect the evolution of temperature in the litter and the humus layer in the first soil horizons.

There are several different types of humus in the soil and, in general, an increase in temperature will accelerate the process of nitrogen mineralisation and the release of CO₂. The latter effect may be combined with direct effects of atmospheric CO₂ increases. It is still too soon to evaluate impacts on tree nutrition.

Seed migration is another ecological process affecting the forest's potential development, and must be taken into account since it may be a limiting factor to natural regeneration. Indeed, seed migration is the natural process which may permit a species to adjust its range in the case of a climate change. However, it is estimated that the migration rate of most plant species through seed dispersal is of the order of 25-50 km per century. This is why it is crucial to know what the rate of increase in temperature will be during the transitional period which will occur in some 20 years according to estimates, when average temperatures will start to increase.

In the mid-latitudes in the northern hemisphere, the mean annual temperature decreases by 1°C when one moves 100–150 km northwards. If the temperature actually increases by more than 1°C in less than a century, which is a low hypothesis, it will be impossible for natural regeneration by seed migration to permit a readjustment of the forest's range through a latitude shift. Warming will therefore probably cause a dying-out phase. Hence the urgent need to preserve seeds of the currently present forest species.

A rise in temperature could favour the proliferation of certain types of insect, which is an additional factor increasing the fragility of the forest ecosystems. A greater frequency of prolonged drought may also lead to an increase in the number of forest fires.

It is difficult to evaluate the combined effects because of uncertainty regarding the concomitant evolution of temperature, rainfall and cloud amount in the case of global climate change. The description of impacts on the various physiological functions and ecological processes listed above shows the complex overlapping of the phenomena. In particular, there is a strong interaction which exists between growth and water supply. Moreover, these combined effects must be examined in relation to microclimatic effects whose modifications depend on projected global climate changes and are difficult to perceive.
5.2.3
POSSIBLE EFFECTS OF WARMING IN DIFFERENT FOREST ZONES

A general rise in temperature is predicted, with modulations according to latitude and season. It is also estimated that the northern hemisphere will undergo greater variations than the southern hemisphere.

Beyond these temperature aspects, the crucial question is whether or not the temperature increase will be accompanied by increased, stable or reduced precipitation. Regional scenarios in this respect vary from one model to another. This is clearly a difficult task, especially since the direct impact of the increased CO_2 concentration on forests must be taken into account (Eamus and Jarvis, 1988).

Before considering possible regional scenarios, it must be stressed that account must be taken primarily of modifications during the two extreme seasons. Moreover, it is for winter that the most distinct temperature and precipitation changes are predicted, particularly in the high latitudes in the northern hemisphere.

In estimating the impact on forests, possible modifications of the characteristics of regional hydrological cycles must be considered. Any tendency towards increased winter precipitation, increased liquid precipitation and less solid precipitation (snow) would reduce the temporary storage of water returned to the hydrological cycle during the spring snowmelt. This is crucial for mountain regions.

5.2.3.1
Forests in the high and middle latitudes in the northern hemisphere

5.2.3.1.1
Boreal forests in the high latitudes

These are the forests north of 45°N on the American continent (USA and Canada) and north of 60°N on the Eurasian continent (Sweden, Norway, Finland, Siberia and the northern Russian Federation).

The effect of a temperature increase should result in a northward shift of the forest's range. The scenario used is one of increased rainfall in winter. Manabe and Wetherald (1987) predicted a reduction in summer soil moisture caused by earlier snowmelt in spring. In order for the increased winter precipitation to be beneficial to the forest, the soil must be deep and completely occupied by the trees' root system. The winter water storage in the soil under tree cover will be very high if the soil has been deeply desaturated during the summer. However, this aspect introduces considerable uncertainty because of the great variability of soil conditions encountered. Species with shallow root systems presumably suffer most. Manabe and Wetherald also predicted a period of intense springtime evaporation which could be fairly favourable to growth.

An increase in temperatures should affect the southern limit of the northern forest, with an unfavourable effect on species already occurring at the limit of their natural range with regard to temperature and soil moisture conditions. The rise in temperature during winter should also cause an increase in evapotranspiration and photosynthesis.

5.2.3.1.2
Temperate forests in the mid-latitudes

These forests are situated in the west and southeast of the United States as well as in central and western Europe. The greatest uncertainties with regard to changes in precipitation concern the mid-latitude belt.

The predicted increase in summer temperatures is similar to that of the mean annual temperature worldwide, while the predicted increase in winter temperatures is higher, but less than that in the high latitudes for the same season (Jaeger, 1988). If the rise in temperature during spring and summer is accompanied by a simultaneous increase in precipitation, favourable conditions for forests could occur. But an increase in temperature is accompanied by an increase in actual evapotranspiration during spring and potential evapotranspiration in summer, giving a scenario corresponding to an earlier dry summer period. In areas further south in Europe and the United States, the combination of high temperatures and summer drought could cause more deaths in trees (Bolin et al., 1986).

Woodman and Furiness (1989) predicted a reduction in the productivity and diversity of species in the low latitude forests in California and the southeast United States. In the Mediterranean forest zone in winter, a lower rainfall scenario cannot be excluded, in which case there is a risk of non-replenishment of the water reserves in the soil during the only season when evapotranspiration remains at a moderate level.
5.2.3.2 Forests in the inter-tropical zone

These are the equatorial forests in Africa, Central America and the Amazon Basin as well as Southeast Asia. It is even more difficult to project the impacts in these zones. According to climatic scenarios based on a doubled CO2, the warming in both winter and summer will be less than the mean annual warming of the Earth (by a factor of 0.7-0.9 (Jaeger, 1988)). These zones benefit from heavy precipitation. Enhancement of the hydrological cycle linked to the warming could further increase rainfall where it is already abundant.

These zones are already under risk of intensive deforestation which is a more immediate concern in relation to the preservation of forest zones (Section 6.2). As regards possible evolution of the tropical rain forest, two characteristics may be important:

(1) The fact that the species are adapted to moisture conditions which, generally, are not limiting factors;
(2) The diversity of species ensures a better adaptability.

There is an uncertainty regarding a change in the level of climatic variability in these regions which plays a major role in the general circulation of the atmosphere.

5.2.3.3 Mid-latitude forests in the southern hemisphere

Most of the works published on climate change scenarios have highlighted the forests in the northern hemisphere. This zone includes the forests in Australia, New Zealand, Chile, Argentina and southern Brazil, where the forests are primarily production forests. In New Zealand, the direct effects of increased CO2 would play a more important role than temperature increases, with an increased growth for most species (Hollinger, 1988). Similar conclusions were drawn for southern Australia.
6.1 AGRICULTURE AND GREENHOUSE GAS EMISSIONS
by M.J. Salinger

The quantification of the relative contribution of global agriculture to atmospheric trace gases has been very recent. It has now been realized that many individual sources are in combination responsible for significant emissions of trace gases contributing to greenhouse gas increases. Agricultural activities with associated changes in land use patterns are a significant and probably increasing source of anthropogenic greenhouse gas emissions. This section will consider current and potential future emissions of the greenhouse trace gases and their contribution to global warming. Regional aspects of greenhouse warming on agriculture have been considered in Section 5.1, and of climate variability on agriculture in Sections 3.1 to 3.3.

Since 1860 the area in cultivated land worldwide has increased by about 900 x 106 ha (Houghton et al., 1983). The conversion of ecosystems to agriculture has resulted in releases of 116 x 106 g C from the stocks of 696 x 106 g C available in 1860. Reductions in the global terrestrial carbon store occur from changes in both area and composition of vegetation type. The change in land use to agriculture is a significant source of CO₂ increase since 1860. For the purposes of this discussion, land use changes will not be considered as an agricultural activity, but it must be noted that land use modification contributed about 9 per cent to greenhouse warming in the 1980s.

Agricultural conversion of atmospheric CO₂ through net primary production removes carbon from the atmosphere. Human and other activities (biomass consumptions by livestock and humans, decomposition of dead agricultural organic matter) cycle the carbon back into the atmosphere. The net effect of agriculture on atmospheric CO₂ has yet to be well estimated. Its source or sink is not considered here. The agricultural activities that have been clearly identified as providing direct net emissions to the atmosphere are considered.

6.1.1 AGRICULTURAL SOURCES OF GREENHOUSE GASES

Four agricultural activities contribute directly to atmospheric emissions of greenhouse gases: livestock production, rice cultivation, biological fixation of nitrogen and the use of nitrogenous fertilizer, and agricultural biomass burning.

Significant emissions of methane are produced by ruminant animals. Methane is produced by methanogenic bacteria. These micro-organisms are strict anaerobes and are reliant on other micro-organisms for providing them with their substrates (Cicerone and Orenland, 1988). They are responsible for enteric fermentation in the gut of herbivores, a digestive process by which carbohydrates are broken down into simple molecules for absorption into the bloodstream. As a byproduct, CH₄ is released by flatulence and eructations. The gut of ruminants provides the ideal environment for the anaerobic food web and CH₄ emissions are highest from these animals (cattle, dairy cows, sheep, buffalo, and goats). Of the annual global source of 400-640 Tg CH₄ (1 Tg = 10¹² gram, or 10⁶ tonnes), enteric fermentation in ruminant animals accounts for 65-100 Tg CH₄ (Cicerone and Orenland, 1988).

In these estimates, variations in CH₄ release due to differences in diet type, food amounts and cattle age have been considered but uncertainties remain. Generally, the higher the quality of the food, the lower the fractional release of CH₄. Of these emissions, approximately 60 per cent comes from cattle and 20 per cent from dairy cows. Animal wastes are also a potentially large source of CH₄ emissions. Best estimates place enteric fermentation at 15 per cent of the annual global CH₄ flux from all sources.
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Rice paddies are another major source of CH₄. Methane is produced by methanogenic bacteria from anaerobic decomposition in flooded rice paddies. The gas escapes by bubbling through the water column, diffusing through the water/air interface, and transport through the rice plants. Most CH₄ from rice paddies is emitted through the plants themselves. Rice paddies account for 25–170 Tg CH₄ of the annual global release (Cicerone and Oremland, 1988). Numerous factors affect CH₄ production and emission in rice growing. Some of these factors include rice species, number and duration of harvests, temperature, irrigation practices and fertilizer use. Best estimates place rice paddies responsible for 20 per cent of the annual global CH₄ release.

Biomass burning, including savanna and agricultural waste, has not yet been well quantified as a greenhouse gas source. Biomass waste burning (such as grain stubble) produces a number of the greenhouse trace gases: CO₂, CO and CH₄. The ratios of these to total C burned is highly variable, and depends on types of burning, moisture content and amounts of biomass that are burnt annually. Estimates of emissions are 20–40 Tg of CO and 20–80 Tg CH₄ for the annual global release (Darmstadter and Edmonds, 1989; Greenberg et al., 1984). The latter represents about 10 per cent of the annual release of CH₄.

Fertilizer application and biological fixation by agricultural activities are major sources of nitrous oxides. In aerobic soils, the bacterial processes of nitrification and denitrification can add N₂O to the atmosphere. In nitrification, bacteria convert ammonia to nitrite which is oxidized to nitrate, and a fraction converted to N₂O. In denitrification, anaerobic bacteria convert soil nitrogen (as nitrate or nitrite) leading to the release of molecular nitrogen to the atmosphere.

Nitrogenous fertilizer application enhances N₂O flux rates, by increasing nitrogen cycling and leaching, nitrification and denitrification. Some of the applied N is converted to N₂O and released to the atmosphere. Forest clearing for agriculture increases the leaching rate and nitrogen mineralization. The amount of N₂O released depends upon a number of variables, including rainfall, temperature, the type of fertilizer applied, mode of application and soil conditions. Preliminary estimates suggest that agricultural activities emit about half the global source of approximately 10–17.5 Tg N per year (Kavaugh, 1987; Marland and Rotty, 1985). The flux of N₂O from known sources ranges from 4.6–10.5 Tg N per year. Despite these discrepancies, it is believed that the observed increase in N₂O is from human activities.

6.1.2 TRENDS IN AGRICULTURAL SOURCES

Present and future emissions of greenhouse gases from agricultural sources are dependent on present and future trends in global agriculture. Thus projected livestock numbers, area in rice paddies, biological fixation of nitrogen and nitrogenous fertilizer use and savanna burning will all affect the emissions of CO₂, CH₄ and N₂O.

Global human population has been increasing at 1.8 per cent since the 1960s. It is estimated to grow by 1.3 per cent per year, reaching 8190 million by 2025. Future food demand will depend on population levels. Livestock numbers have increased considerably during the last 100 years, with global cattle and sheep populations increasing at 2 per cent per year from the 1940s to 1960s and 1.2 per cent since. Livestock numbers are projected to increase by 45 per cent from 1990–2025. From the assumptions of global agricultural models, CH₄ emissions from livestock could increase by 35–65 per cent from 1985–2025 to 75 Tg CH₄ per year, and by about 125 per cent to 2100.

Emission of methane from rice paddies is a function of area under cultivation, rather than yield per hectare. From 1950–84 rice paddy area increased approximately by 40 per cent. Projected land area used for rice production, and thus CH₄ emissions, could increase by 15–35 per cent to 2025, and by 50 per cent to 2100. Biomass burning projections are not available for future projections, but are expected to increase.

Fertilizer application and biological fixation by agricultural activities are expected to increase by 2100. These increases occur as rises in food production are necessary to satisfy the demands of a growing global human population. The land
available is finite, but more production will be required. The main reason that North American agriculture has been able to increase its production of food and fibre over the last 50 years with little changes in agricultural area is because of increased fertilizer input. Grain yield since 1955 can be directly correlated with fertilizer use per unit area under cultivation for both developed and developing countries. Cultivation is expected to become more intensive resulting in greater fertilizer use which could increase by 70–110 per cent to 2025, and by 160 per cent by 2100. As well as increased land area used for agricultural activities, the contribution of N₂O emissions from these sources should continue to increase.

The previous two sections have considered the agricultural sources of greenhouse gas emissions to the atmosphere and their trends. To estimate the effect on climate from last century to the present and future, calculations are required on the effects of these on the Earth's atmosphere radiation budget.

The present agricultural emissions account for approximately 45 per cent of the CH₄ release, about half of the N₂O release and an unquantifiable proportion of the CO₂ release. The atmospheric concentrations of CH₄ and N₂O are much lower than CO₂. However, these trace gases have a Global Warming Potential (GWP), molecule for molecule, much higher than that of CO₂ (IPCC, 1990). The GWP is a result of the effectiveness of a gas in absorbing infrared radiation, their atmospheric residence time and the time period over which the climate effects are considered. The GWP for CH₄ is 9 and N₂O 190, compared with a CO₂ GWP of 1 over a 500 year time period.

Presently the greenhouse gas forcing contribution of CH₄ is 20 per cent and N₂O 6 per cent of the total forcing. The greenhouse forcing as a consequence of agricultural emissions is 10 per cent from CH₄ and 3 per cent from N₂O, with a residual 3 per cent from other activities producing CO₂ and CO. Agricultural practices therefore contribute in the range of 15 per cent of the greenhouse forcing.

Total greenhouse forcing has increased by 2.2 W/m² (Wigley, 1989) since the late 18th century, making the share of agriculture 0.3 W/m². As the forcing change has been about half that due to greenhouse gas doubling, the equilibrium warming should be about one-half of the climate model estimates. Depending on the climate sensitivity (the equilibrium response of climate to greenhouse gas forcing and how rapidly this is achieved), the equilibrium warming due to greenhouse gases to date would be about one half of the greenhouse gas doubling value of 0.8°–2.3°C. The actual warming is substantially less because the thermal inertia of the oceans dampens the response, and is estimated to be 0.6°–1.3°C. The agricultural contribution to this is 0.1°–0.2°C.

Future effects of agricultural greenhouse emissions are dependent on the trends in activities discussed in Section 6.1.2. Emissions of CH₄ from enteric fermentation are assumed to increase in most projections as livestock numbers increase. The requirement for higher crop production from only a moderate expansion of area means higher fertilizer application and thus an increase in N₂O emissions. Growth in rice paddy sources of CH₄ is projected to be lower. The relative contribution of CH₄ and N₂O at 2030 AD, which is the best estimate for doubling of greenhouse gas forcing, is projected to be similar to now (Wigley, 1989). The assumption made is that the total share of production of greenhouse gases from agricultural activities is similar to the present (15 per cent), although the distribution from specific agricultural activities may change in emphasis.

Global mean warming over the next 40 years or so is expected to be between 0.9° and 2.5°C with a best estimate of 1.5°C. This places the contribution from agricultural activities in the range of 0.1°–0.4°C. If effective greenhouse gas concentrations in the atmosphere stabilize at double their pre-industrial levels, equilibrium warming is not reached until some time later. The global warming commitment for effective doubling is from 1.5°–4.5°C, with agricultural emissions accounting for 0.2°–0.7°C.

In summary, agriculture is a significant source of greenhouse gas build-up since 1800, and will continue to be so in the future because of growing human population demand for growth in food production. The main agricultural sources are
enteric fermentation from the global livestock population and rice paddies for CH$_4$, and the application of nitrogenous fertilisers for N$_2$O. The first and last sources (livestock and fertilizer) are projected to continue growing to maintain increased food production. Only modest increases in rice paddy area are expected. Estimates, which at the moment are rather uncertain, place the contribution of agricultural activities to the enhanced greenhouse effect since 1800 at 0.1°–0.2°C by 1990, and 0.2°–0.7°C when a doubling of the greenhouse effect occurs.

6.2 FORESTS*  
by E. Choisy

The Earth’s surface, and its plant cover, are in a state of continual interaction with the atmosphere. This interaction involves both surface energy exchanges and mass exchanges, the latter generally concerning water in liquid or gaseous state. The particular characteristics of forest cover give rise to unique Earth/atmosphere exchange mechanisms. This section will deal with the Earth/atmosphere interaction from the point of view of the forest’s effect on the climate. Regional aspects of the effects of climate variability and greenhouse gas warming on forests have been discussed in Sections 3.4 and 5.2.

6.2.1 SPACE SCALES  

In climate studies, the following space scales are generally recognized, each being associated with influencing factors of greater or lesser specificity (Choisy, 1984).

1. Planetary or global scale (1 000 km);
2. Regional climate scale (100 km);
3. Topoclimate scale (1 to 10 km);
4. Microclimate scale (10 to 100 m).

These climate space scales are comparable with Orlanski’s atmospheric process space scales (Orlanski, 1975). At each of these space scales, the effect of the forest on the climate will also depend on the dimensions of the forest cover itself.

The degree to which forest-induced climate effects are open to measurement will depend on the space scale involved. While such effects are readily measurable at microclimate scale (climate in forest clearings, in the vicinity of forests or in the atmospheric layer above the forest), difficulties arise at the more distant scales; denser measurement networks are required, and measurements must be taken at a greater height above ground level. For this reason, regional scale climate studies must rely on the correct interpretation of data from existing measurement networks.

At the global scale, forest-induced climate effects can only be studied by means of modelling techniques using global climate models, which, with greater or lesser degrees of accuracy, take into account the characteristics of forest cover areas and their present or future distribution over the surface of the Earth.

6.2.1.2 SPACE SCALES FOR FOREST STUDIES

It is not easy to determine the dimensions above which forest cover begins to have a significant bearing on regional scale climates. This difficulty is compounded further by regional and national variations in the ways crop growing activities infiltrate into forest areas. Many authors consider that forest extensions of the order of square kilometres (i.e. hundreds of hectares) are necessary before significant climate effects are noticed. Here, however, it is necessary to specify which climates are being discussed.

For a long time now, the notion of forest climate has been invoked without any specification of space scale. The term in fact applies to microclimatic effects operating within the forest, including, for example, the factors which govern tree growth. It is also possible to speak of forest-induced microclimates in forest clearings or in areas adjacent to the forest. Moreover, at this space scale, forestry workers will

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attempt to influence the climate in such a way as to optimize those conditions which are favourable to tree growth and development, especially repopulation (Aussenac, 1984).

The real question of forest-induced climatic effects in fact lies on a wider scale than merely microclimatic. However, a global study into extensive forest slopes will not yield a true understanding of the physical processes involved, and it is preferable to start from measurement campaigns conducted on small forest areas (McNaughton and Jarvis, 1983). The location of such campaigns should be chosen carefully to lie well within the expanse of forest in order to minimize the effects of local advection in the surface boundary layer above the forest cover.

6.2.2 TYPES OF FOREST-INDUCED CLIMATIC EFFECTS

6.2.2.1 Relevant factors

Studies into the effects of forests on the climate form part of more general studies which seek to model the way that the Earth’s climate is affected by surface processes operating above land masses. This involves the application of what are known as general circulation models, or GCMs (Eagleson, 1982).

The climatic influence exercised by forests, or any other type of vegetation for that matter, arises out of the exchange of mass (mainly water vapour), energy and momentum between forests and the atmosphere (Thom, 1975). In evaluating such exchanges, information is required on a number of forest cover parameters, which can be considered as falling into four major categories:

1. Cover structure parameters;
2. Aerodynamic parameters;
3. Hydrological parameters;
4. Radiative parameters.

6.2.2.1.1 Cover structure parameters

For a simplified examination, taking forest cover as a whole, the essential data are canopy height, tree density (number of trees per hectare) and leaf area index over the whole area. A more detailed examination would also require information on the vertical profile of leaf area densities. A distinction must be made between coniferous and deciduous forests to take account of variations in leaf area index throughout the year. It should also be noted that cover structure parameters of both types of forest undergo slight variations with age.

An understanding of the diverse types of forest in the world and the differences between them is a prerequisite to any study into the way forests affect the world’s climate (Perrier, 1982).

6.2.2.1.2 Aerodynamic parameters

Aerodynamic parameters describe the effect of turbulence on the flux between plant cover and the atmosphere. For low canopy areas, the following two parameters are used:

1. Roughness distance $Z_0$ increases with the roughness, or roughness factor of the cover ($Z_0$);
2. Displacement height $D$ is the height at which the ($D$): vertical profile of the modulus of the wind velocity extrapolated in the forest cover cancels out. This can be considered as the vertical origin for turbulence above the forest cover.

These two parameters appear in the widely known logarithmic wind profile equation:

$$u(z) = \frac{u^*}{K} \ln \frac{z - D}{Z_0} = A \ln \frac{z - D}{Z_0}$$

where: $u(z)$ is wind velocity at height $z$; $u^*$ is friction velocity; $K$ is von Karman’s constant = 0.4; $\ln$ is natural logarithm; $z$ is height above ground; $Z_0$ is roughness factor; $D$ is displacement height, and $A$ is $u^*/K$.

However, this equation only holds true in the inertia sublayer, the lower boundary of which is located at a height of 20–50 times the roughness distance. This means that readings must be taken very high above the forest cover for roughness factors which are of the order of 1 m. This is likely to be outside the boundary wherein vertical flux conservation applies. Further, in order to minimize advection effects it is necessary to restrict investigation to extensive forest areas.
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The theory using the $Z_0$ and $D$ parameters cannot then be applied for calculating energy fluxes above forest cover from the vertical gradients of atmospheric state variables. According to Thom et al. (1975) and Garratt (1978), additional transfer processes tend to diminish the vertical gradients immediately above extremely rough surfaces. For flux calculations, the problem can be resolved by taking into account an additional resistive factor (Stewart and Thom, 1973).

Values for $Z_0$ and $D$ are given by Jarvis et al. (1976) for different types of coniferous forests and for heights from 10.4–27.5 m. Parameter values are related to the canopy height, $h$. Despite variations in the results obtained, the following average values can be used:

$$Z_0/h = 0.1$$
$$D/h = 0.75$$

From readings taken in two forests in the former Soviet Union, Rauner (1976) reports that the above ratios vary with the wind speed above the forest canopy. Perrier emphasizes the variations in roughness observed for different types of forest structure. In particular, the differences in height between individual trees in mixed forests and the distance separating trees, are factors directly related to the forest density.

Clearly, a great deal of work remains to be done to improve our understanding of the way the roughness of natural forest cover affects turbulence and flux phenomena. In modelling the wide scale climatic effects of vast forest areas such as the Amazon, the roughness factor, for want of a more accurate parameter, continues to provide essential information. The climatic effects of high levels of forest cover roughness must be examined from two standpoints. Roughness can affect the atmospheric wind and flux fields. This is discussed in Section 6.2.2.2. Roughness also affects the forest cover evapotranspiration to a degree which will depend on the heat and mass exchange coefficients. When studying this type of effect, distinction is required between sparse forest made up of isolated trees and dense forest forming a closed canopy (Seguin and Brunet, 1986). It was this second aspect which Dickinson and Henderson-Sellers (1988) dealt with first when modelling the deforestation of tropical regions.

6.2.2.1.3 Radiative parameters

Two global radiative parameters must be determined for the forest cover as a whole; albedo and long wavelength infrared emission and absorption capacities. Of these two parameters, only albedo is subject to significant variations over time and between species (see Section 6.2.2.3.1). The infrared emissivity would appear to be relatively stable and to take on a value close to 1. (This parameter has only rarely been measured independently.)

Except when considering snow covered forests, a distinction must be drawn between coniferous and deciduous trees. The albedo of coniferous forests would appear to be stable, with an average value of around 0.11. Avery and Fritschen (1971) measured albedo values of between 0.13 and 0.14 for a forest of Douglas firs (*Pseudotsuga menziesii* Murb.) and cited Miller's value (0.12) and Brooks' value (0.14) for pine forests.

As might be expected, the albedo for deciduous forests varies greatly with the season, depending on the leaf coverage. Federer (1986) reports average values of 0.18 in summer and 0.12 in winter, in no snow conditions. Spring and autumn values are less precisely known. There is a sharp increase in albedo with the appearance of the first leaves, owing to the optical properties of the new leaves which have not yet reached their maximum chlorophyll content. In autumn, the spectral reflectivity increases greatly in the red and yellow ranges, owing to the changing coloration of the leaves. The albedo of a snow covered forest (0.70) lies midway between the winter forest albedo values and the albedo value for fresh snow. Finally, Shuttleworth et al. (1984) recently measured albedo values of 12.25 (+0.2 per cent) for the tropical Amazonian forest.

6.2.2.1.4 Hydrological parameters

The two basic hydrological parameters, maximum saturation capacity ($S$) and the percentage of precipitated water reaching the soil directly ($P$) are adopted for describing the way precipitated water is distributed between the various storage
compartments of the soil/forest system. For modelling purposes it is also necessary to determine values for these parameters.

S. Rutter et al. (1971) set out a graphical method whereby saturation capacity is estimated by measuring the rain falling on the soil within the forest and the incident rainfall above the forest. The authors then use this parameter in an interception model. Rutter (1975) also gave saturation capacity values for different types of forest cover, distinguishing between winter and summer conditions for deciduous forests.

Summer values for deciduous forests are around 1 mm. Values for coniferous forest vary from 1–2 mm depending on the species. For their interception submodel, Chassagneux and Choisen (1986, 1987) take values of 1.9 mm for beech (Fagus sylvatica) and 3.9 mm for Douglas fir (Pseudotsuga menziesii). More recently, Shuttleworth (1989) reports temperate zone saturation capacity values similar to Rutter’s. Little information on saturation capacity is available for tropical forests. For winter leaf cover, Rutter (1975) suggests values of the order of 0.5 mm, while Dolman (1987) gave winter values of 0.3 mm for 9 m high oak trees.

6.2.2.1.5 Percentage of precipitation reaching the ground (P)

For coniferous forest, this value is assumed to be constant throughout the year. For deciduous forests, it varies with leaf development. Shuttleworth (1989) quoted figures ranging from 0.09–0.25 for coniferous forests in temperate regions. The upper value in this range was also adopted by Chassagneux and Choisen (1986).

For deciduous forests, these authors take winter values of 0.75 and summer values of 0.25, with a linear increase from winter to summer to account for leaf development. Dolman (1987) gave similar values for oak forests: summer 0.3; winter 0.8.

One also needs to determine values for these parameters for the tropical forest interception sub-model which appears in the general circulation model. In examining this problem, Shuttleworth (1988) emphasized the need for defining two water storage levels and for using a finer mesh in handling simulated precipitation. This is essential for a realistic representation of the atmospheric water cycle. Distributing precipitation over the basic unit sized grid will systematically overestimate the re-evaporation of intercepted water, thus producing too high simulated precipitation levels. Eagleson (1986) also brought up this problem with regard to global hydrological modelling above continental land masses.

6.2.2.2 Mechanical effects of forest cover

On the microclimatic scale, forest cover has the effect of reducing wind speed within the forest itself, in forest clearings and in the neighbourhood of the forest. In decelerating the horizontal flow of air masses, the roughness presented by forest cover tends to encourage the development of vertical heat and after vapour transfers. In this respect, the mechanical effects of forest cover are indissociable from the energy effects discussed below.

Studies into the purely mechanical interactions existing between forest and the atmosphere have concentrated on the effect of the atmosphere on the forest rather than the other way round. Owing to a lack of experimental data, little is known about the effect of the forest on the horizontal displacement of air masses.

Baumgartner et al. (1977) attempted to perform global scale estimations of the quantity of kinetic energy dissipated from January to July 1958 (IGY data). For this purpose they used a world map showing roughness factors which went from 0.01 cm above oceans to 200 cm above equatorial rain forests (Amazon, Zaire, Malaysia, etc.). By averaging roughness values over latitude bands, they found a first roughness peak between 37.5°N and 64.5°N (roughness factor 57.6 cm) and a second roughness peak in the equatorial band between 2.5°N and 2.5°S (roughness factor 46.4 cm).

6.2.2.3 Energy budget effects of forest cover

The radiative exchange budget (net radiation, Rn) of forest cover can be globally expressed by the equation:

\[ R_n = (1 - a) R_s + e R_a - e \sigma T_s^4 \]

where Rn is net radiation; Rs is global solar radiation; Ra is downward atmospheric radiation; e is emission-absorption coefficient; \( \sigma \) is Stefan-Boltzmann constant; 5.67 x 10^-8 erg cm^-2 deg^-4 sec^-1, and T\( _s \) is mean surface temperature above the forest cover (°K).
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Examination of this formula reveals a number of possible causes for differences between the radiation budgets of forested and non-forested areas:

1. Different albedo values (a) (reflection of solar radiation in the 0.25–5 mm spectrum);
2. Different emission-absorption coefficients (ε) for Earth and atmospheric radiation;
3. Different global radiative temperatures (T).

Generally speaking, forest cover would appear to have a substantial impact on the Earth's radiation budget in the solar spectrum. Forest cover has a lower global albedo than crop growing land, prairies or bare desert land. Annual average albedo values for these types of lands are: forest, a = 0.10; prairie, a = 0.20; and desert, a = 0.30–0.40 (Baumgartner, 1967). The forest can thus be seen as forming a sort of solar radiation trap. It is much more efficient in this respect than any other type of vegetation cover, although it does vary between tree species and different times of year.

The impact of forest cover on the Earth's radiation budget in the long infrared spectrum (5–100 mm) would appear somewhat less marked. Differences in emissivity here are of the order of percentage points only. Any impact in this spectrum would arise from differences in surface temperature related to radiative emission from tree crowns; here, a high rate of evapotranspiration will produce correspondingly lower temperatures.

To conclude, the energy available for evaporation is, on average, higher in forested areas. A lower albedo (capacity for reflecting solar radiation) coupled with reduced losses of upward radiation give forest areas a total radiation budget which is higher than on crop growing land or bare land. The forest can thus be seen as constituting an excellent mechanism for absorbing solar radiation. The radiative characteristics of dense forest cover are well known. However, much research remains to be done into the radiation interception characteristics and radiative exchange mechanisms of broken forest cover.

6.2.2.3.2 Energy exchange

The purpose of calculating the energy budget of forest cover is to determine the proportions in which the energy available at the surfaces which intercept solar radiation is distributed between sensible heat and latent heat. This will enable us to make a quantitative evaluation of evaporation from the forest cover. In a closed canopy forest system taken as a whole, only a very small amount of solar radiation will reach the ground. The little that does penetrate will be diffuse, and the net radiation at the ground surface will only represent a fraction of that received at the canopy; for a fully developed canopy, with a leaf area index (LAI) of 6, say, the amount of radiation absorbed in the lower levels of the forest will typically be about 5 per cent of the incident radiation striking the canopy (Jarvis and Leverentz, 1983 quoted by Shuttleworth, 1989).

Assuming an absence of conductive flux, an equilibrium occurs between the following three flux densities: radiative flux, evaporation and sensible heat. This equilibrium can be expressed thus:

\[ R_W + \psi_L + \psi_C = 0 \]

It is easy to estimate the term for radiative flux, given that the upward radiation from the canopy into the atmosphere can be calculated quite simply, knowing the downward atmospheric radiative flux and the apparent radiative temperature at the canopy surface (for very rough canopy surfaces, the intensity of the turbulence above the canopy keeps this temperature very close to the air temperature). However, it is not so easy to calculate respective proportions of latent and sensible heats, as this will depend on the degree of binding of the water arriving at the evaporating surfaces. Here, monitoring two water storage compartments is required, one representing water which is intercepted by the leaf cover and which does not fall to the ground, the other representing water which is stored in the soil and which is subsequently recovered by the tree root systems. Given identical meteorological conditions, intercepted water evaporates more readily than transpired water, as stomatic resistance will prevent transpiration rates from reaching their theoretical maximum.
As McNaughton and Jarvis (1983) showed, it is difficult to compare the evaporation of intercepted and transpired water (Gash et al., 1980) as intercepted water will continue to be re-evaporated even when it is raining or at night (Pearce et al., 1980), i.e. when little net radiation is being absorbed by the leaves and when the water saturation deficit is low. Even for widely differing available energy levels, comparable results (0.9 mm/h) are observed once raining has stopped.

When examining the energy budget of forest cover, the two limiting cases of a canopy with thoroughly wet leaves and a canopy with thoroughly dry leaves (i.e. no intercepted water) must be considered.

6.2.2.3.2.1 Consumption of latent heat by evaporation

Here, examination of the actual situation in which forest cover may be either dry or partially wet owing to the presence of intercepted water is required. The total evaporation from the canopy is made up of two components, actual evapotranspiration and re-evaporation of intercepted water. To evaluate the actual evaporation flux giving rise to the emission of water vapour into the atmosphere, two energy budgets must be established, one for transpiration and one for re-evaporation of intercepted water, and weighting between the two resulting values for evaporation flux must be determined (Chassagneux and Choisy, 1986).

To carry out accurate weighting between the two evaporation components, the proportion of time that the canopy is partially or thoroughly wet is estimated. The content of the intercepted water storage compartment will depend on the maximum saturation evaporation (S) and potential evaporation, which will increase with the saturation deficit in the air above the forest canopy. Ultimately then, the balance over a year will depend on the overall rainfall conditions, i.e. the frequency with which rain occurs and the duration and intensity of rainfall events. The main problem here is how to forecast the saturation deficit in the air above extensive forest areas, where the total flux of evaporated water will certainly be an important factor (see Section 6.2.2.4).

6.2.2.3.2.2 The effect of tree physiological processes on transpiration

The internal physiological processes of trees exercise their influence on energy exchanges mainly via the mechanism of stomatic regulation. This involves contracting the leaf pore openings in order to reduce the amount of water vapour transferred from the stomatic cavity into the atmosphere by transpiration.

Stomatic regulation is known to depend on a number of internal and environmental factors. Internal factors include the leaf water status and plant water reserves, the latter related to soil water reserves. Environmental variables include solar radiation, water saturation deficit in the air, and CO₂ concentration. Full quantitative data on the effects of these individual factors are not yet available.

The relationship between stomatic resistance and light intensity, common to most plant species, is well understood. The effect of air saturation deficit on stomatic resistance was first observed on Douglas fir forests in temperate regions (McNaughton and Black, 1973). In coniferous species, stomatic resistance is seen to increase as the air's saturation deficit increases over the day. Also, minimum values of stomatic resistance are found to be higher for coniferous species than for deciduous species (Jarvis et al., 1976). Similar results have also been obtained in tropical forests (Shuttleworth, 1989).

These results, which concern the stomatic resistance of individual leaves, are confirmed by studies into the global stomatic resistance of forest cover, making it possible to obtain a transpiration model for the forest canopy as a whole (Tian and Black, 1976; Lohmann et al., 1980; Singh and Steiitz, 1980; Chassagneux and Choisy, 1986; Stewart, 1988). In deciduous species, the stomatic resistance is inversely proportional to the leaf area index (LAI) and decreases from winter to summer.

6.2.2.3.2.3 Forest heat storage effects

The heat storage effect in forests mainly takes the form of heat build-up in the trunks and branches of trees. (The heat stored in the air within the forest can be considered as negligible.) This effect is studied in terms of a daily energy flow cycle. Heat storage is at its highest in the early morning (when it can reach 13 per cent of net radiation) and heat restitution (negative storage) is at its highest in the early
evening (Jarvis et al., 1976; McCaughey and Saxton, 1988). A number of authors have attempted to evaluate the heat storage phenomenon (Baumgartner, 1956; Gay, 1972; Stewart and Thom, 1973; Gay and Stewart, 1975). Heat storage fluxes of 40 W/m² are commonly observed after sunrise.

The restitution of heat from the forest upwards into the atmosphere can increase local convective instability and thus contribute to initiating storms in the presence of moist air masses (Cholinel, 1985). Moore and Fisch (1986) gave estimates of heat storage in tropical forests.

6.2.2.3.3 Mass exchanges

Evaporation is regulated by the presence and the degree binding of water at the evaporating surfaces. The proportion of precipitated water intercepted by the canopy and the proportion falling into the undergrowth and onto the ground must be established by considering an intercepted water compartment and a soil water compartment. Raindrops falling onto the forest canopy can reach the ground in one of three possible ways:

1. Falling directly onto the ground or into the undergrowth. The proportion of rain falling onto the ground in this way is measured by the factor, p, a geometric parameter describing the number of gaps in the canopy cover (see Section 6.2.2.1.4);

2. The drops can be intercepted on the canopy, to fall off when the amount of water on the leaf surface reaches the threshold value, S, or maximum saturation capacity (see Section 6.2.2.1.4);

3. Drops can trickle down the tree trunks. The proportion of rain reaching the ground in this way can be measured using the appropriate apparatus. In fact, it accounts for only about 2 per cent of the total incident rainfall.

The model described by Rutter et al. (1971) estimates the variation over time in the level of the intercepted water compartment and also the amount of water which trickles down the tree trunks and into the soil storage compartment.

The water budget of forest soils differs from that of crop growing soil in a number of aspects. Forest soils generally have a very high water infiltration capacity. This is because the forest cover protects the soil, both from intense solar radiation (i.e. it attenuates thermal shocks) and from the mechanical effects of raindrops, which can batter bare ground and lead to caking phenomena when the soil dries out.

Because of their deep reaching roots, trees are able to extract large quantities of water during the spring and summer seasons. With the higher rainfall and lower evaporation of the winter season, water reserves are recharged, with rainwater being fixed in the soil before surface and sub-surface runoffs begin, and before water seeps down into the groundwater reserves. This retention of water in the soil provides substantial reserves which will be available to the trees for the next summer season. In certain forest areas, however, there is obstructed drainage, caused by lower level impermeable layers. This has been observed both in temperate and tropical regions.

It is often very difficult to evaluate the level of useful water reserves in forest soils. Difficulties stem both from the uncertainty which surrounds the structure and penetration depth of tree root systems, and from the fact that forest areas are not always easily accessible to tree specialists and forest bioclimatologists. However, neutronic sounding techniques have been used to obtain moisture density profiles in certain types of forest (Aussenac and Granier, 1979).

The forest's water input can also be increased by dew formation and fog filtration, especially in mountainous regions. Fritzchen and Doraiswamy (1973) used lysimetric methods to measure dew formation on Douglas fir in a forest in Washington State (northeast United States). Over two dewy days, dew was found to contribute 20 per cent of the tree's daily water consumption.

Few quantitative data are available on fog filtration (Aussenac, 1980, and Rutter, 1975), though this phenomenon can be highly significant in mountainous regions, especially in winter and in coastal areas. For example, in the mountainous regions of western Europe, condensation takes place at an average altitude of around 800 m, under which circumstances fog filtration can be expected to represent a
substantial water input. In the coastal forests in China and Japan, advection fogs coming in from the sea are frequent at certain periods of the year (Hirata, 1929, quoted by Rutter, 1975).

Finally, rainfall readings are needed to measure the incident precipitation on forest canopies. Actual on-site measurement is very difficult owing to the heavy turbulence generated above the canopy by virtue of the forest roughness, so baseline measurements must be taken in clearings, adequate dimensions for which will depend on the average height of the forest (Choisnel, 1985).

The flux of water vapour from the forest into the atmosphere depends heavily on mass exchanges, the distribution of precipitated water, and other factors such as condensation phenomena. This flux will affect both local and regional scale climates, and on a wider scale, the flux associated with extensive boreal and equatorial forests may even have an impact on the general atmosphere circulation.

Therefore efforts are required to evaluate the flux of water vapour, not forgetting that the forest generates its own climate in the surface layer immediately above it. Few studies have been conducted into water vapour storage (which would amount to latent heat storage) in the forest, though McCaughey and Saxton (1988) showed that this phenomenon was negligible and was not governed by a regular daily cycle.

6.2.2.4 Forest areas and the hydrological cycle

On a wide scale, large forest areas can be expected to affect the climate through the changes they bring about in the hydrological cycle. The climatic effects of the hydrological cycle, especially the atmospheric part, are widely known: ready availability of rainwater input for evaporation off landmass surfaces will tend to limit thermal amplitudes. Here then the forest exerts an indirect impact on the climate.

On a smaller space scale, the presence of forest cover will have a direct effect on the vertical structure of the atmosphere directly above the forest. This effect is more difficult to measure owing to the lack of data on the vertical atmosphere above forests and on the variation in this structure over small time increments throughout the day. The discussion which follows will deal with this point first.

6.2.2.4.1 Forest water vapour exchanges, atmosphere and vertical atmosphere structure

Water vapour which is released into the atmosphere by evaporation from the forest cover undergoes vertical transfer processes. The planetary boundary layer (PBL) above the forest may be either stable or unstable, and at the same time the surface energy budget during the day may represent either a heat source, the most frequent case, or a heat sink for the atmosphere.

It will represent a heat sink when the energy flux from evaporation off a thoroughly wet forest canopy exceeds the net radiation input, in which case heat is taken out of the air to be used as latent heat of evaporation. A downward flux of sensible heat can only reinforce the stability of the planetary boundary layer, and this in turn has the effect of restricting subsequent vertical transfers of water vapour.

Aspects that account for the origin of the heat used include the dimensions of the forest, the distance from the edge of the forest, the wind speed, the altitude of the boundary layer, and advection. McNaughton and Jarvis (1983) made the assumption that the air saturation deficit above the forest canopy would be directly related to the air saturation deficit observed in the upper layers, owing to the fact that turbulence would provide efficient vertical air mixing. A low but non-negligible air saturation deficit would be maintained even above a wet forest, since, if this were not the case, fog formation above forests would presumably be much more frequent. A number of possible mechanisms were suggested to explain the permanent saturation deficit.

In the field of modelling, simulations have been carried out using three dimensional mesoscale models. The case of a transition between forest and farming land was examined by Andre et al. (1989) in the HAPEX-MOBILHY project, which took a 100 km square area with 40 per cent forest cover. In calculating surface fluxes, this model took into account albedo, roughness and the global stomatic resistance of both forest cover and crop growing land.

Two sorts of result were obtained. In good weather, with a dry forest canopy but high soil moisture content, the model predicted a circulation of breeze: the flux
of sensible heat into the atmosphere from the forest cover would be higher than from the crop growing fields, as forest cover offers a higher resistance to the transfer of water vapour by transpiration. This has an effect on the development of cumulus. With an initially wet forest cover, the model predicts a high re-evaporation of intercepted water immediately after passage of a cold front. This would have the effect of increasing the local rainfall downwind.

6.2.4.2.2 The impact of such mass exchanges is only considered significant for extensive forest cover. For certain countries, flux is expressed as a proportion of incident rainfall, data which are assumed to be accessible by measurement or estimation. Also, the effect of forest cover on the hydrological cycle is described with respect to what would be observed if the area in question were completely deforested. For reasons of clarity, different water fluxes will be examined in turn, adopting the same terminology and cycle breakdown suggested by Anderson et al. (1976) i.e. interception, infiltration, transpiration and runoff.

6.2.4.2.2.1 In temperate oceanic climates, authors emphasize the difference between coniferous and deciduous forests (Aussenac, 1980, and Rutter, 1975), quoting values of 15–30 per cent for deciduous forests and 15–45 per cent for coniferous forests.

For forest slopes in Great Britain (Calder and Newsom, 1979; Gash et al., 1980), this proportion is found to decrease as the rainfall increases from 50 to 100 mm. For coniferous forests, the proportion of intercepted rainwater decreases by 30–33 per cent, displaying an approximately asymptotic tendency.

For equatorial and tropical rain forests, the proportions of intercepted rainwater are generally lower. The most recent values are 13–15 per cent for forest slopes in the Ivory Coast (Monteny, 1987; measurements taken from 1981–83), 10.5–12.5 per cent for forest in Java (Lloyd et al., 1988; measurements taken from 1981–84, and 8.9 per cent, 3.6 per cent for the Amazon (Manaus) (Lloyd et al., 1988; measurements taken from 1983–85).

It is more difficult to estimate the proportion of intercepted water in non-closed forest areas. The few data available on snowfall interception concern the maximum saturation capacity, which would appear higher than for rainfall.

6.2.4.2.2 Infiltration

Difficulties in measurement mean that few data are available on infiltration. However, it is generally considered that infiltration will be high under forest cover, with humus playing an important role in storing water before seepage (Aussenac, 1980). On sloping ground, part of the infiltrated water may run off in the subsurface. Infiltration is generally estimated indirectly by hydrological modelling at forest slope level.

6.2.4.2.3 Evapotranspiration

Comparative studies have been conducted into various types of plant cover under the same climatic conditions. Using lysimeter techniques, Baumgartner (1970) gives ranges of values for the ratio between annual evaporation and annual precipitation in moderate latitudes. The ratio is found to vary greatly between different types of plant cover, forest cover giving a mid range value of 70 per cent. This value is only exceeded by the evaporation/rainfall ratio obtained over a surface of water, and by that obtained over waterlogged grassy land. (Baumgartner’s evapotranspiration figures include the evaporation of intercepted water.)

These initial studies have been followed by more accurate estimations, notably for equatorial rain forests in the Ivory Coast, where the evaporation/rainfall ratio of forests has been compared with that of annual crops under identical climate conditions. Moneny (1987) gives the following ranges of values, obtained by analysis of the annual water budget: annual crops and fallow land 30–55 per cent, equatorial forest 65–75 per cent. These figures show that rainwater is most efficiently recycled in equatorial forests. The difference in evaporation ratio between forest and annual crops is at least 10 per cent.

6.2.4.2.4 Runoff

Long-term experiments studying the effects of deforestation on water runoff have been conducted by the Coweeta Hydrological Laboratory (North Carolina, USA)
6.2.3 MODELLING OF ENERGY AND WATER VAPOUR EXCHANGES ABOVE THE WORLD'S GREAT FORESTS

Direct measurement techniques are only capable of evaluating the forest's impact on the climate at a local scale. Evaluation of the climatic impact of the world's great forests can only be approached by modelling techniques; the tools required here are general circulation models (GCMs). These models afford a horizontal spatial resolution of the order of 5° latitude and longitude, which is approximately a few hundred kilometres, the exact dimensions varying with the latitude (Eagleson, 1986).

Various authors quoted by Reifsnyder (1982) have tried to estimate the proportion of the Earth's land mass which is covered by forests and the distribution of forests by latitude band. There is a significant amount of uncertainty here, as the proportion of forest cover is estimated at between one-third (1/3) and one-quarter (1/4). According to Baumgartner's calculations (1979, based on figures from Lieth, 1974), the Earth's forests are divided into two groups: tropical forests (between 25°S and 10°N) and high latitude forests in the northern hemisphere (from 50–70°N).

The present-day distribution of tropical forests is the result of human action, which has brought about substantial reductions in the world's tropical forest coverage: Latin America has lost 37 per cent of its tropical forests, Southeast Asia 38 per cent, and Africa over 50 per cent (Myers quoted by Eagleson, 1986).

The present-day distribution is as follows (figures for 1978 and estimations for 2000) (Smith, 1981, quoted by Reifsnyder, 1982):

1. Industrialized countries: 14.5 million km² of forest, half of which are located within the former Soviet Union (7.8 million km²). This area is expected to remain stable.

2. Developing countries: 11 million km² of forest, about half of which are located in Latin America (5.5 million km²). This area is expected to decrease by 40 per cent before the year 2000, leaving a total surface area of 6.6 million km².

Tropical forests make up a balanced system, as a large proportion of the rainfall they receive is generated by their own evapotranspiration, which means that water is constantly being recycled above the forest. While Budyko (1974) estimated that only 10 per cent of the rain falling over the European land mass of the former USSR came from local evapotranspiration from the Earth's surface, Salati and Vose (1984) estimate a global water recycling rate of 48 per cent over the Amazon. There is the possibility of the hydrological cycle being altered by reductions in the forest area.

Deforestation mainly concerns the near equatorial areas of the Amazonian forest, the west African rain forests (Zaire) and the Southeast Asian forests (Malaysia and Indonesia (Borneo)).

6.2.3.1 Effects of deforestation in Amazonia

Amazonia was discussed by Henderson-Sellers and Gornitz (1984), Salati and Vose (1984), Shuttleworth et al. (1984) and Dickinson and Henderson-Sellers (1988). The Amazon forest today covers 5 million km², and in Brazil, Henderson-Sellers and Gornitz (1984) report a deforestation rate of 1.5–2 per cent per year, which is higher than the average global deforestation rate estimated for tropical forests throughout the world (0.6 per cent per year). The consequences of deforestation fall into two broad categories:
CHAPTER 6

(1) Local consequences arising out of alterations in water availability, surface energy budget and soil water retention. Here, "local" is taken as describing individual points throughout the area, and regional consequences are taken as the sum of these local effects;

(2) Consequences on the general atmosphere circulation, especially wind behaviour and the spatial distribution of rainfall over the South American continent.

Local consequences were examined by Dickinson and Henderson-Sellers (1988) using a general circulation model incorporating a detailed parametrization of surface processes (Dickinson, 1984).

Dickinson's study simulated the hypothetical case of the entire Amazonian forest being replaced by grazing land. The results are summarized below:

(1) Effect on surface temperature: overall increase of 3−5°C, with air temperature increase of 1−3°C;

(2) Effect on rainfall interception: sharp decrease during all months of the year except August;

(3) Effect on evapotranspiration: sharp decrease during the month of June; decrease during all other months of the year except September. This decrease would be partially attributable to the sharp drop in surface roughness;

(4) Effect on runoff: the drop in evapotranspiration would lead to increased runoff;

(5) Effect on rainfall conditions: statistically insignificant.

While control runs of the model provide quite a good reproduction of the present seasonal rain cycle in the Amazon Basin, the total annual rainfall figures that it simulates would appear somewhat high. This type of model is not capable of providing information on the wider reaching consequences of deforestation.

Salati and Vose (1984) make a number of remarks concerning the existing characteristics of general circulation in the Amazonian region. The Amazonian forest straddles the equator, and the prevailing wind direction is that of the northern hemisphere trade winds. These easterly to northeasterly winds bring with them an influx of water vapour from the ocean. During their passage over the Amazonian forest, the air masses receive further substantial inputs of water vapour owing to the intense water recycling activity over the forest. The Andes mountain range forms a natural barrier which prevents the water vapour from leaving the basin, the result being very high rainfall on the eastern slopes of the Andes (up to 5 000 mm/year).

A drop in evapotranspiration, with reduced quantities of water vapour being re-injected into the air masses crossing the Amazonian forest, could well alter the spatial distribution of rainfall in the basin. In particular, a lengthening of the dry season in the central part of the basin could have serious ecological consequences. At the same time, a higher proportion of rain falling upstream, as a result of orographic elevation, could cause considerable alterations to the flow in the Amazon river. The overall temperature rise predicted as one of the local consequences of deforestation also causes ecological stress.

6.2.3.2 Deforestation in other tropical forest areas

Sophisticated simulations using GCMs have not yet been applied to other tropical forest regions. Individual measurement campaigns have been conducted, however, and some of the results from these campaigns are mentioned above.

The forests in Indonesia and New Guinea are also undergoing heavy deforestation of more than 3 per cent of the surface area per year. The seasonal wind conditions in these regions depend on the location of the meteorological equator, and here a fuller understanding of the Southeast Asia monsoon system is required.

Finally, deforestation in west Africa also exceeds 3 per cent a year in certain regions. Again, a drop in evapotranspiration is likely to reduce the amount of water vapour reinjected into the air masses which move northwards at the beginning of the monsoon season.
CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS
by M.J. Salinger

7.1 CONCLUSIONS

Climate and climate variability have a very significant effect on agriculture and forestry, and schemes should be developed to reduce the vulnerability of climate on these activities. In turn, these activities also affect the climate on various scales.

The preceding chapters have demonstrated the many different influences that climate and climate variability have on agriculture and forestry. Generally, agriculture and forestry are well adjusted to the mean conditions in a region, but sensitive to variability, extremes and changes in the mean.

The sensitivity to climate and its variability is dependent on the type of activity. Agriculture, particularly crops, display a high sensitivity. Temperature is very important in determining crop ranges, particularly in cold latitudes. The amount of heat accumulated over the growing season between the early and late frosts often determines crop success or failure in these zones. Outside these zones, rainfall is the most important regional variable for crop production. The impact of rainfall will override the temperature effects if there is sufficient heat for crop maturity. In areas that have a high annual or seasonal rainfall variability, a change in the variability is more important than a change in the mean amount over the year. The cropping zones that are particularly susceptible to such rainfall variability occur in the arid and semi-arid subtropics, Mediterranean and monsoon regions. In those areas with lower rainfall variability, a change of seasonal or mean annual rainfall is more important.

For animal production, the most important impacts of climate are indirect. Direct effects of temperature and rainfall on metabolism, growth and performance of livestock are mainly a consequence of extreme events. High temperatures cause heat stress which can reduce reproductive performance and milk yields, and low temperatures together with strong winds cause death in newborn livestock. Indirect effects are of considerable importance to both feed production and pest and disease incidence. Here the effects of climate are felt the most, both by the deviation of conditions from the mean and by extremes. Droughts, floods and seasonal temperatures directly influence the amount and distribution of livestock feed availability and quality throughout the year. Variability of temperature and moisture are prime factors in determining disease, pest and parasite incidence which debilitates livestock.

The response of forests to climate and climate variability is different. Because most forests are complex ecosystems and have a canopy of dominant species with understorey components, they tend to form their own microclimates within the ecosystem. Forests have a range of climatic tolerance, within which a particular forest type is healthy. If climate changes, forests do not adapt rapidly because seed dispersal mechanisms only allow slow migration. The movement of climate and climate variability away from a specific forest ecosystem’s optimum has the effect of weakening the trees. Moisture stress (drought) and temperature stress (high or low temperatures at the wrong time) have the primary effect. Then extreme events such as fire, insect and disease epidemics, high winds and ice storms can change the forest ecosystem extremely rapidly.

The impact of climate on agriculture and forestry depends on the latitude zone. For cold climate agriculture, particularly in maritime climates, the influence of temperature is paramount. Examples of cropping and pastoral activities in these areas demonstrate that yields are closely linked to seasonal temperature anomalies. However, in continental climates of the cold cropping zone, such as in Canada, rainfall is more important for determining crop yields. In the temperate, subtropical
and tropical zones, rainfall and rainfall variability is the most important factor controlling variations in crop and livestock yields. Rainfall overrides temperature effects in these zones because there is sufficient heat available for crop maturity. Therefore lack of soil moisture limits crop growth in areas of rainfed agriculture. Forest yield and health are influenced indirectly because of climate effects on the species components as a result of forest fires, pests and diseases, seedling failure and other disturbances. However, temperature is the primary climate element determining latitude and altitude distribution of forest type, and moisture is the primary element determining forest existence.

The previous discussion has highlighted the effects of climate, and especially climate variability. The Southern Oscillation has recently been identified as a major source of natural climate variability. In the regions of the world where Southern Oscillation influences on climate are strong, namely the South Pacific, New Zealand, Australia, India, southern Africa and South America, all have a higher degree of rainfall variability than other regions. The El Niño and La Niña phases of the Southern Oscillation cause very significant changes in yields, and disturbances on agriculture, forestry and fisheries.

Evidence is strong for future global warming as a consequence of the enhanced greenhouse effect, with large potential impacts on agriculture and forestry. The issues facing agriculture in the various latitude zones differ. Climate warming would substantially lengthen and intensify the growing season in the cold maritime latitudes. One of the most threatened zones for agriculture occurs in the areas of Mediterranean climates. These face a production decrease in the event of the rainfall decreases and evapotranspiration increases postulated by all the models occurring. Similarly the semi-arid and arid areas of the subtropics on the high latitude sides of the major deserts face decreases in crop and livestock productivity. On the low latitude margins of the desert regions, trends in rainfall variability will be critical. The humid tropics potential difficulty is the enhancement of the hydrological cycle producing higher intensity rainfall and flooding, resulting in soil degradation of cropping land and inundation. Finally, climate warming would allow an expansion northward of the northern boreal forests but Mediterranean forests would decline. The most critical issue for forestry is the rate of climate change. Should the rate of warming be rapid, then forest ecosystems would be unable to adapt and might show widespread decline.

Agriculture and forests are both significant for the enhanced greenhouse effect, and thus affect global climate. Presently agricultural activities account for about 15 per cent of greenhouse gas emissions, and forestry another 15 per cent as a consequence of deforestation. However forests, through afforestation, can act as a significant sink for CO₂. Forests also create their own local climate, and the large areas of tropical forests in particular comprise a balanced system. In the latter, rainfall is generated as a result of evapotranspiration from the forest, which means that deforestation could lead to large changes in regional climates. A discussion of the effects of climate and climate variability should not conclude without examining measures of reducing vulnerability of agriculture and forestry. By these measures, future productivity of food and forest products, and reduced impacts on forest ecosystems can be achieved. For agriculture there is a need to identify, by agroclimatic planning, the potential of and most suitable activities for an area. Greater diversity in farming systems spreads the vulnerability and reduces the dependence on one crop. Crop and animal breeding can also be focused on plants and animals that are more resilient to variability of climate and feed supply. Farmers can also take advantage of changes in climate by changing the timing of crop planting or of livestock operation to suit the seasons. Pest and disease control is most important in preserving the resilience of crops and livestock to climate. This also decreases the vulnerability of forest ecosystems, as does the management of fire risk. Where change cannot be prevented, there is a need for emergency corridors or migration routes for the spread of natural forest ecosystems.
CONCLUSIONS AND RECOMMENDATIONS

7.2 RECOMMENDATIONS

(1) In view of the diversity of the topic, international co-operation in data collection, both basic and applied research should be encouraged.

(2) Research should also concentrate on vulnerable regions in refinement of impact studies. This research should include crop-weather models, and a comparison of different models and approaches for projections of climate and scenarios.

(3) The biosphere is an important component for influencing climate change. The effects of biospheric changes on climate, and consequent effects on agriculture and climate are matters for further attention.

(4) Close co-ordination and co-operation need to be maintained between the Commission for Agricultural Meteorology and international science programmes in this field. Those that are particularly relevant are the Intergovernmental Panel on Climate Change, the International Geosphere-Biosphere Programme, and World Climate Research Programme.

(5) Considering the need to keep abreast of both the effects of climate variability and climate change on agriculture and forestry, and the effects of agriculture and forests on climate, it is recommended that the Commission for Agricultural Meteorology continue to study this subject by re-establishing the working group with renewed terms of reference. Terms of reference should include:

(i) The impacts of climate extremes on agriculture and forests;
(ii) Southern Oscillation and other causes of natural climate variability, and their influence on agriculture and forests;
(iii) Rates of climate change resulting from both natural variability and the enhanced greenhouse effect.

Management adjustments needed in agriculture and forestry to cope with climate change include:

(iv) Identification of management adjustments in agriculture and forestry needed to cope with the rates of climate change;
(v) Measures to reduce the vulnerability of agriculture and forestry to both natural variability and global warming.

(6) A sponsor should be organized to host an international seminar/symposium on reducing the vulnerability of agriculture and forestry to climate variability.

(7) Roving seminars should be organized to disseminate the results of the conference suggested in (6) to agrometeorologists, particularly in developing countries.

(8) This technical report of the working group should be published with the least possible delay as a WMO Technical Note. In view of the importance and current nature of the topic, translation into other working languages of WMO should be considered.

(9) This final report is aimed at and can be of particular importance to planners, decision makers, agronomists and animal husbandry scientists. It should therefore be circulated widely to member countries and all authorities involved in agriculture and forestry (e.g. agricultural research institutes, agricultural universities and ministries of agriculture, etc).
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