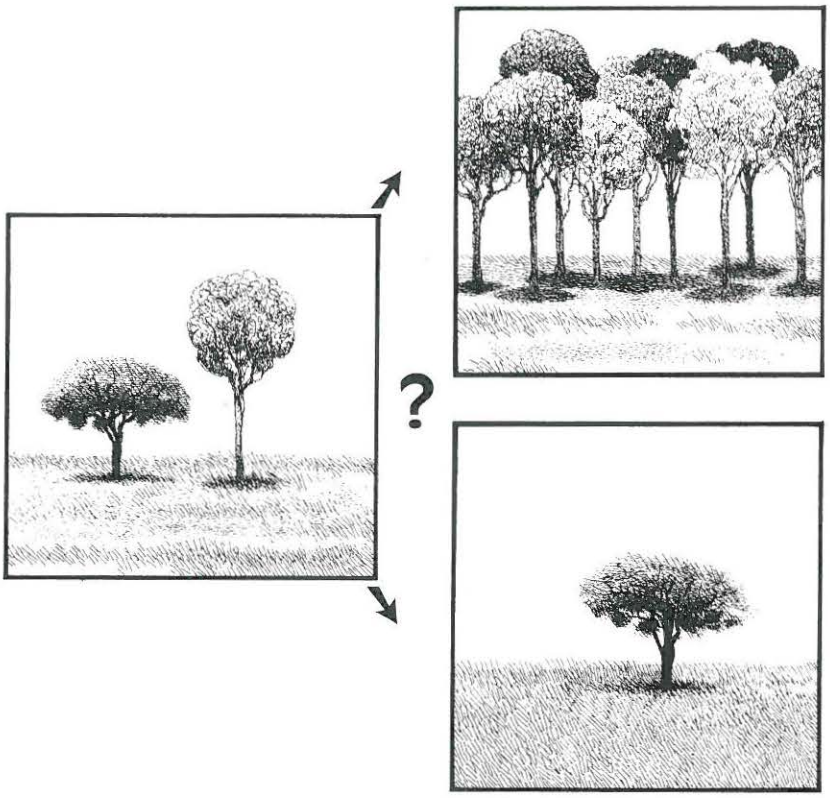
GLOBAL IGBP CHANGE

REPORT No. 5



Effects of Atmospheric and Climate Change on Terrestrial Ecosystems

The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP)
of the International Council of Scientific Unions (ICSU)

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REPORT No. 5

Effects of Atmospheric and Climate Change on Terrestrial Ecosystems

Report of a Workshop organized by the
IGBP Coordinating Panel on
Effects of Climate Change on Terrestrial Ecosystems

at CSIRO, Division of Wildlife and Ecology
Canberra, Australia
29 February–2 March, 1988

Compiled by
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The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP)
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PREFACE

In this report we summarize the discussions and deliberations of a small (36) group of scientists attending an especially convened workshop in Canberra, Australia. The workshop was held in the week following the first Australian national IGBP meeting "Global Change", sponsored and organized by the Australian Academy of Sciences. The findings of the workshop were presented to the first Scientific Advisory Committee of the IGBP, in Stockholm, October 24-28, 1988, and the main points emerging from the discussion at this meeting have been included in this report.

We wish to thank everyone who contributed their time and expertise to the Workshop. It was a difficult task to 'think globally' throughout the course of the workshop. Nonetheless we believe that this report will fulfil its objectives in making a useful contribution to the goal of formulating the IGBP and in specifying the critical issues in a research programme on the effects of climate change on terrestrial ecosystems.

The individual contributions by working groups had to be edited and merged by us. The information is credited to the participants and we accept any responsibility for misrepresentation.

Financial support for the carriage and reporting of the workshop was provided by the IGBP.

February 1989

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INTRODUCTION

The Special Committee of the IGBP has established four Coordinating Panels to develop proposals for research in areas where the requirements for primary data are a prerequisite for understanding "Global Change".

These four areas are (IGBP, 1987):

1 Terrestrial Biosphere-Atmospheric Chemistry Interactions
2 Marine Biosphere-Atmosphere Interactions
3 Biospheric Aspects of the Hydrological Cycle
4 Effects of Climate Change on Terrestrial Ecosystems

This report presents the findings of a workshop on the last of these topics, held at the Division of Wildlife and Ecology, CSIRO, in Canberra Australia, from 28 February to 2 March, 1988. A summary of the findings presented to the first Scientific Advisory Committee of the IGBP, in Stockholm, October 24-28, 1988, and the comments of the SAC have been included in this report. The list of workshop participants is given in Appendix I. Background information for the workshop, prepared by members of the SC-IGBP Coordinating Panel, is presented in Appendices II and III.

Objectives of the Workshop

The overall objective of the Panel is to develop a research programme which will generate a predictive understanding of the effects of climate change on terrestrial ecosystems where climate change includes changes in both climate and atmospheric composition.

This capacity is required to forecast (primarily) the consequences of climate-driven ecosystem change for land use and biotic conservation and (secondarily) to determine the potential feed-back of these changes on further atmospheric and climate change. Aspects of the secondary objective, the feedback, will also be addressed by IGBP Coordinating Panels 1 and 3 above.

As a consequence, the objectives of the workshop were:

1. To establish the scientific issues involved in developing a predictive understanding of the reciprocal interactions of climate change on terrestrial ecosystems;
2. To debate and explore these issues thoroughly and to afford them a relative priority;
3. To identify the major gaps in knowledge and understanding, and/or where there is a need for a synthesis of existing knowledge;
4. To develop specific research proposals, in terms of i) key questions to be answered and/or specific data sets that are required, ii) recommendations on how the research should be approached (e.g., observation and data analysis, field experiments, remote sensing, controlled environment research, etc.), and iii) appropriate locations where this research might be undertaken. The last of these was not attempted.

The participants were divided into eight working groups, each of which produced a list of the scientific issues involved in their topic, and the key questions or kinds of information which would require research. The reports have been amalgamated and the results constitute the basis of this report.

The direct and indirect effects of climate change are considered first (section A) under four main headings:

Soil and landscapes
Vegetation dynamics and distribution
Vegetation function
Higher trophic levels

The implications of these changes for the maintenance of biological diversity and, very briefly, for agriculture and managed forest crops, are then considered in section B.

In section A we have attempted to follow a consistent framework. We begin with an introductory account of the relevant processes involved in the effects of climate change. Emerging from this is a section highlighting the major scientific issues which need to be resolved, and these in turn are followed by a listing of research needs and recommendations.

Owing to the variable styles in which the working group reports were submitted it has not been easy to cast each section into this mould. Nevertheless, any loss in the impact of the individual reports is more than compensated for by the increase in comprehension of the overall document.

SUMMARY OF RESEARCH NEEDS AND RECOMMENDATIONS

The following is a summary of the research needs and recommendations compiled from all six sections that follow in the report. They are numbered 1-40 and listed under section headings. Each recommendation is supported in detail in the main text. All are considered important. Those marked by an asterisk (*) are for the immediate attention of IGBP.

One particular observation was made by several of the groups, and because it is of fundamental importance, it is included here, as an introductory comment and recommendation.

> There is no body of ecological theory adequately integrating environment, energetics, dynamics, distribution and abundance. The gap looms large in both plant ecology and in animal ecology, and it hinders our general understanding of the effects of climate change on the distribution and dynamics of populations. It is a high priority that such a theory be developed, using existing data, and that it be tested and refined experimentally.

Landscape and Soils

* 1. Establish the requirements for the mechanistic modelling of the relationships between precipitation regime and the spatial redistribution of water and soil materials. Which existing models most closely meet these requirements?

* 2. What will be the qualitative and quantitative changes in the following soil properties as a consequence of climate induced change in soil processes:
i) soil nutrient pool size and transfer rates;
ii) soil water regime including ground-water recharge and salinity;
iii) soil structure?

3. What are the requirements for models of organic matter accession and decomposition that predict levels of N, P, S, ionic exchange chemistry, and pH under climate change? Which existing models can serve as starting points?

* 4. Enhance existing water balance models to relate the dynamics and interaction of soil water in the rooting zone, ground-water recharge and salinity to the climatic factors of precipitation (P) and temperature (T). What are the minimum data sets for these models? Do such compatible data sets now exist and is there a suitable international interchange procedure already in existence?

Vegetation Function

* 5. What are the relationships between vegetation structure, dynamics and composition and the albedo, evapotranspiration and surface roughness characteristics of a landscape? Will potential climate-driven change in vegetation structure, dynamics and composition significantly alter these energy, mass and momentum exchange characteristics? (See also # 15)

* 6. Within the major biomes, develop mechanistic models to relate atmospheric composition, climate and vegetation to the exchanges of the trace gases, CO_2, H_2O, NO_x, etc. between the biosphere and the atmosphere.

7. What is the relative importance of changes in vegetation structure, dynamics and composition compared with changing cloudiness in determining the energy, mass and momentum exchange characteristics of landscapes?

* 8. There is a need to determine, at a landscape level, within a representative set of vegetation types, the influence of increased atmospheric CO_2 on soil organic matter and litter decomposition, water use efficiency and primary productivity and litter fall.

9. Establish the differences in CO_2 responsiveness of different life-forms, the mechanisms of response, and the limits to genetic and phenotypic plasticity.

* 10. A major problem in measuring functional attributes of vegetation is that of scale. The research need is how to aggregate output from individuals to 'homogeneous' communities, which together constitute a mosaic in the landscape. A fundamental part of this aggregation must be the simplification of landscape description through the use of a new functional taxonomy at species- (Plant Functional Types) and community level (Vegetation Functional Types).

Vegetation Dynamics and Distribution

* 11. Develop an efficient hierarchical structure of inter-linked statistical and mechanistic models, which together predict changes in vegetation structure, dynamics and composition in response to climate change. Which existing models can contribute to this IGBP model structure?

* 12. Establish the availability of, and further requirements for, data sets appropriate to the modelling development outlined in # 11 above. There is a need to develop co-ordinated data-bases of climate, soil and biotic data, from the same localities because this lack is currently more limiting than model development as such.

13. With respect to statistical models, the capacity to incorporate transients (as functions), and situations where analogues of the new environmental conditions do not now exist, is critical. Therefore the contribution of mechanistic models is imperative to overcome this limitation.

* 14. Use statistical models to indicate important areas in which the most significant effects of climatic change may occur and where more detailed process-oriented work should be concentrated. This must include secondary effects such as changed fire regimes.

* 15. Establish the most appropriate classification of Vegetation Functional Types (VFTs) for the feed-back effect of vegetation on climate, and determine what conditions are required for vegetation to change from one type to another. (See also # 5)

* 16. Is there a need for a classification of Plant Functional Types (PFTs) reflecting the characteristic features of plants which determine their responses to climate? What is the most appropriate classification for IGBP purposes?

* 17. Vegetation will, most probably, respond to climate change via changes in the frequency of extreme climatic events. Consequently, IGBP models must include these secondary climatic characteristics as primary determinants of vegetation composition. The research need is to identify and characterize such events and include them in models subject to validation.

18. For the major biomes, determine the relationships between climate and fire regimes (frequency and intensity). How will human modification of fire regimes influence the potential climate-driven changes?

* 19. With respect to past climate/vegetation changes, is it possible to define periods of past climate variation and vegetation response which are analogous or homologous to those expected in the future? Is it possible to adequately test models of long-term ecosystem behaviour with these historic data? A synthesis of existing tree ring and pollen data sets would be most relevant here; particularly those from tropical lowland areas.

Similarly is it possible to document the effects of CO_2 fertilization during prehistoric periods of known CO_2 variance (e.g., full glacial atmospheric CO_2 concentrations of 180-200 ppmv)? For example an examination of late Quaternary leaf macro-fossil data to correlate stomatal densities, isotopic composition with the atmospheric CO_2 data would be most instructive. (See also # 9)

What specific kinds of rare events do we expect to be both of interest in vegetation response to climate change, and recorded in fossil pollen and tree ring records (i.e., frost frequency and drought frequency in tree rings; vulcanism and flood intensity in fossil pollen records), and what is the "palaeo-ecological fingerprint" of each? Research is needed to define the measurement characteristics of these palaeo-ecological tools.

Are there potentially-useful and little-used or poorly-developed sources of quantitative data on interrelated long-term climate and biotic patterns? An analysis of historical climatic and agricultural data sets would be of value; for example some in China may be millenia-long.

Lastly, many of the above tasks could be facilitated by the development of faunal palaeo-environmental indicators (e.g. beetles, ostracods, molluscs, corals) and species-level identification capabilities for pollen grains.

Higher Trophic Levels

* 20. Because of their significance to human welfare, an urgent research need is to analyze the likely responses of important pest species to a range of future climate scenarios and, of equal importance, to investigate how we might identify those species not presently pests but which will become so under particular climatic conditions.

21. Identify and adapt the available data bases and models for use in projecting distributional changes of a range of animal species (invertebrates, reptiles, mammals).

* 22. There is a need to establish the value of using animals as indicators of climate change. If the conclusion is positive, it is suggested that a set of indicator species be designated on each major land mass and their distribution and dynamics closely monitored.

Maintenance of Biological Diversity

23. There is a need to establish the extent to which persistence of some species will be a problem. Since a complete inventory of the distribution of all organisms in relation to extrinsic variables is impossible, it is necessary to select data subsets. The biological parameters are species, communities and functional groups, and the environmental parameters (predictors/scalars), are temperature, precipitation, etc. The research problem is how to select the subsets.

* 24. Determine the predicted distribution patterns of selected species, communities, etc. as a consequence of existing climate change scenarios. Based on how different they are from present patterns, identify the kinds of organisms and/or the kinds of habitats that are most seriously affected.

25. What are the ecological criteria for the design of a nature conservation reserve system on a regional basis that will incorporate the biota now and in the future? What ecological information is required to redress the inadequacies in existing reserve systems that are projected as a consequence of climate change?

* 26. Develop the ecological criteria to support the management of off-reserve areas in order to complement and supplement reserve systems, recognizing that it is impossible to conserve the complete biota in a reserve system, and that under a changing climate the existing global network of reserves will become progressively less able to conserve the species they currently contain.

* 27. Determine likely land-use patterns under the range of climatic change scenarios and identify potential areas of conflict with nature conservation objectives.

Agricultural and managed forest crops

* 28. Research effort should concentrate on the development of generic growth and yield models for all of the major crops (and varieties), including tree crops. The models should be tested across the full range of existing climatic conditions under which they are grown.

* 29. The effect of increasing CO_2 levels on the performance of different crops (and therefore on the predicted model outputs under changed climates) needs to be experimentally determined under field conditions, at an appropriate scale. The results should be incorporated in the generic growth and yield models.

30. The period of significant climate change may correspond with the period when current developments in genetic engineering reach their phase of application in crop breeding. The two developments should interact strongly, and research in these two areas should incorporate each others' developments.

Animal Production from Rangelands

31. Significant shifts in temperature may influence breeding and growth in different types and breeds of domestic livestock. As in the case of crops, equivalent generic models for livestock breeds need to be developed.

* 32. Determine the changes in vegetation on rangelands that are important for livestock production. As an example, a shift from predominantly winter to predominantly summer precipitation in semi-arid rangelands would be likely to induce a vegetation shift from shrubs to perennial grasses. The former favours sheep, the latter cattle.

* 33. What will be the influence of secondary effects on rangelands? Where the primary effect of climate and CO_2 change is increased production (through increased precipitation and increased water use efficiency), the secondary effects of changed fire regimes are likely to strongly re-enforce even quite small changes in vegetation. Before including such effects in models of rangelands, it is necessary to assess the role of man in controlling fire regimes.

Predictive Understanding: Modelling and Scaling

Scaling Down

34. For planned field sites the precipitation regime needs to be characterized. In particular, within an area equivalent to a global circulation model (GCM) cell size, i.e. 200 x 200 km, determine the average (and its meaningfulness), class/frequency precipitation distributions for time intervals (eg. months) and precipitation types (eg. convective vs system). What is the most appropriate measure of spatial variability or patterning that can be applied to precipitation events? Is there an equivalent to the beta diversity index used by ecologists? The relationships between spatial patterning and precipitation type need also to be determined.

* 35. Models of landscape functioning at a spatial scale of a GCM cell are required to relate the temporal and spatial characteristics of precipitation to measured hydrological and ecological response. In particular, where the data and understanding are best, models predicting the consequences of changes in either or both of the precipitation characteristics are required.

* 36. What to do about extreme events? The discussion of precipitation, etc. above concentrated on the functioning of ecosystems or landscapes, ie. a tendency to consider the 'average' conditions. It is of equal importance to consider the rarer events, particularly the extremes of precipitation (P) and temperature (T), for these shape the environmental envelope and determine the limits of the distribution of ecosystems. While the importance of extremes or rare events is recognized by terrestrial ecologists it remains largely a qualitative appreciation that cannot yet be explored with the output of GCMs. The topic probably requires a workshop of its own to come up with specific research recommendations that would enable, within a GCM cell, for any biome, quantitative determination of what constitutes an (ecologically) extreme event in terms of P, T and the coincidence of P and T, and the consequences of such an event. In addition attention should be directed to determining the correlation between the extremes of P and T, understanding the mechanisms that generate and preserve this correlation, and characterizing the spatial patterning of this correlation as a function of precipitation regime and climate type.

37. Develop models relating ecological response to both the temporal and spatial pattern of extremes and use these to forecast vegetation change.

Scaling Up

* 38. Refine, or develop and test, models to forecast the primary productivity of landscapes from P and T for the major biomes. The opportunity exists to use readily available satellite data as part of this modelling process.

* 39. Examine the methods of spatial description of landscapes to determine if statistically based measures (frequency distributions, fractals) can be used to determine natural or intrinsic scales to be exploited in stratification and sampling for ecological and hydrological measurements.

40. Determine whether roughness is of significance to GCMs in forecasting precipitation (P) and where in the biosphere this significance is greatest. Determine the response surface of roughness as a function of vegetation vertical and horizontal structure (patchiness) and the response surface of albedo and ET as a function of the vertical and horizontal vegetation structure, given that these two parameters are everywhere important in GCMs.

A. Direct Effects of Atmospheric and Climate Change

I. Landscapes and Soils

Processes

It is useful to separate the direct impact of climate change on landscapes from the impact of climate change on the soils that clothe them. The former is largely physical, the latter largely chemical.

Landscapes

The topographic characteristics of landscapes - ruggedness, dissection, etc., - control the spatial and temporal patterns of soil and water distribution, solar radiation and therefore plant composition and plant productivity. The spatial patterns of water, soil and nutrient distribution span several orders of magnitude of scale; from the topographic controls of drainage at scales of 104m or so, down to very local scales determined by and affecting individual plants. Such patterns are most apparent in arid environments where the response of plants to small changes in water availability is marked. However, homologous patterning of plant distribution and productivity, with characteristically different scales, can be found even in the most mesic and topographically subdued landscapes. Landscapes therefore can be viewed as determining a basic, characteristic spatial patterning in the distribution of water resources (soil and nutrients) and plant community composition and productivity. The distribution and productivity of higher trophic levels is coupled to this pattern; the strength of this coupling being determined by the relative importance of water as a limiting resource for plant growth.

Landscapes determine the patterns of plant distribution and productivity through the processes of water distribution (run off/run on) and concomitant relocation of soil materials and solutes (erosion/deposition). Both of these processes are controlled by climatic factors; most strongly by the factor of precipitation and to a lesser extent by the factors of temperature and wind. Control is not completely climatic, however. There are, for example, the feedbacks of vegetation cover on run off, which vary in sign, strength and influence according to characteristics of the precipitation regime. Changes in the intensity and duration of precipitation characteristics eventually will lead to changes in vegetation cover and thence to changes in the temporal pattern of infiltration and run off, etc.

Therefore, climatic changes which involve changes in precipitation regime, e.g., intensity/duration and/or time, sequence and amount, will for a given unchanging landscape result in changes in the spatial and temporal patterns of hydrological processes and biological productivity. The feedbacks of vegetation on water movement may be both positive and negative. Because of the kinetic energy of moving water (approx 1000 times that of wind), conditions of a positive feed back of vegetation on run off can generate rapid change as water redistribution amplifies more subtle vegetation changes. One such example would be a climate change that involved an overall small (10%) decline in annual precipitation, which would result in lower plant production and thus less litter cover, but a marked change in the precipitation intensity/duration giving less frequent, but high intensity storms. These storms would produce high runoff and soil erosion thus reducing the potential for plant growth. Reduced plant growth would further exacerbate the runoff/soil erosion cycle. Such positive feedback interactions explain the non linear relationships between mean annual precipitation or runoff and denudation (erosion) from landscapes, Figure 1.

Soils

A useful framework within which to consider the processes involved in possible soil changes is one that recognizes the direct interactions of climate with the three key processes that together determine the soil profile, Figure 2. Climate directly influences the soil zonation, texture differentiation and the role of organic matter in soil formation (eg. Corbett, 1969).

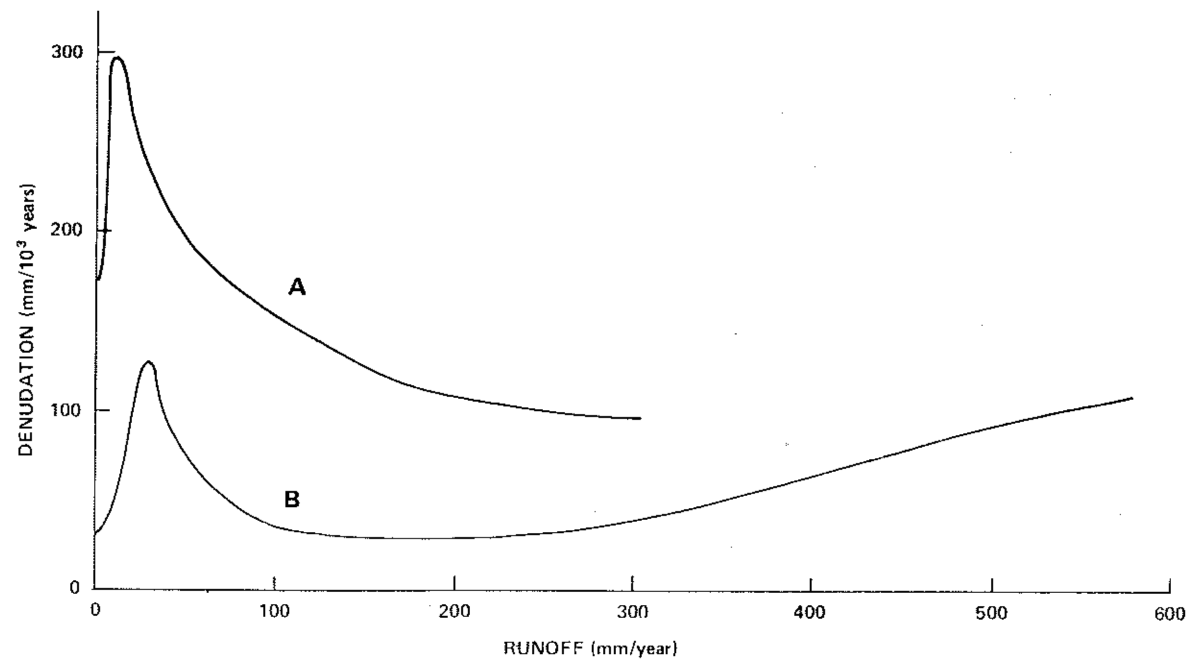


Fig. 1. The non-linear relationship between mean annual runoff and the mean rate of denudation (erosion) of landscapes. Curve A was derived for catchments in the USA; B for Australian and Asian catchments. As mean annual rainfall, and therefore runoff, diminishes, the rate of denudation rapidly peaks. Relatively small shifts in rainfall near these critical areas will catalyse a very large change in erosion through the positive feedback loop involving vegetation cover. After Williams (1978).

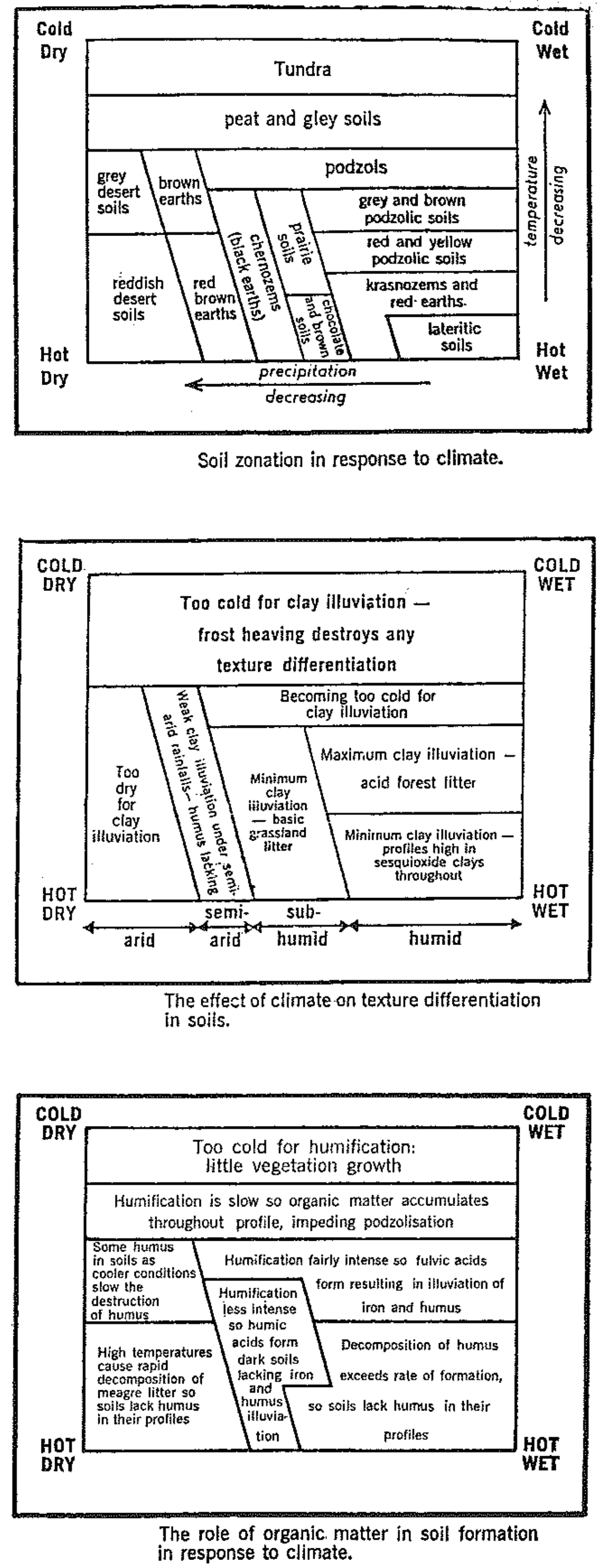


Fig. 2. A framework for relating the direct interactions of climatic factors (rainfall, temperature, etc.) with the three processes that determine the characteristics and dynamics of soils

Scientific Issues

Landscapes

The concepts of intrinsic scaling are not new but the appreciation of their utility and the extent of their applicability has grown amongst hydrologists and ecologists alike. The research issues in the effect of climate change on landscapes are:

1. field hydrological/ecological investigation recognize explicitly and account for the implicit spatial scaling imposed by the landscape at any one site;

2. any stratification of the landscape must be made at some recognized level within the hierarchy of landscape functioning, e.g. catchments, erosion cells, canopy drip zones, etc.;

3. the temporal scaling and extrapolation of hydrological and ecological investigations will be determined by the frequency distribution of the key processes of run on/run off and erosion/deposition.

That is, we reiterate that the landscape provides the spatial and temporal context of field investigation and modelling. The response of vegetation and processes to climate change has to be integrated or synthesized to the level of aggregation of landscapes. Man in his management of terrestrial ecosystems is, slowly, recognizing and accepting this task.

Soils

The scientific issues involved in the influence of climate change on soils can be specified even though there is relatively little information available on soil response to climatic change.

The response times of the properties and profiles of most soils to climate change are estimated to be very slow compared with the landscape processes of run off, etc., or the biological species and community responses discussed in the following sections (Table 1, Figure 3). Noting particularly the different shapes of response in Figure 3, response times of soil processes and profiles can be classified into short (<50 years), long (50-1000 yrs) and very long (>1000 yrs).

Nevertheless, a number of soil types will respond significantly within the IGBP time-frame, as suggested in the following scenarios (W. Sombroek, V. Targulian, W. Scharpensal and Yaalan, pers. comm.).

The deeply weathered reddish loamy to clayey soils of the forest-savanna transition zones of Eastern Africa, which are stable under their present-day natural vegetation, may start to be leached to an extent that a relatively dense clay-illuviated horizon develops below an unstable topsoil of low organic matter content (changing the soil from rhodic or orthic Ferralsol into an orthic Acrisol or Lixisol). This in fact happens already under present-day land clearing in parts of the region, because of the sudden diminution of the homogenizing action of soil biologic life. Similar effects may occur in the drier parts of Sumatra.

Certain silty sedimentary deposits in the wide riverine valleys of the Sudan-Sahelian zone of West Africa ("fadama's") may develop from Fluvisols into saline and/or sodified soils following even a minimal change in precipitation/flooding regimes - as exemplified by human actions with the same soil-hydrological implications.

In general, however, changes in soil development will be more rapid and profound in the younger or less weathered sediments of the glaciated or desert fringe region of the northern part of the northern hemisphere, and slower or less profound on the stable, continental shields of the equatorial regions.

TABLE 1

A grouping of soils according to the relative persistence of Soil Horizons and Features. After Birkeland (1984), p 305.

Easily Altered	Relatively Persistent	Persistent
Mollic epipedon	Histic epipedon	Oxic horizon
Ochric epipedon	Umbric epipedon	Placic horizon
Salic horizon	Albic horizon	Argillic horizon
Gypsic horizon	Cambric horizon	Natric horizon
Mottles	Argillic horizon	K horizon
	Spodic horizon	Plinthite
	Calcic horizon	Duripan
	Fragipan	

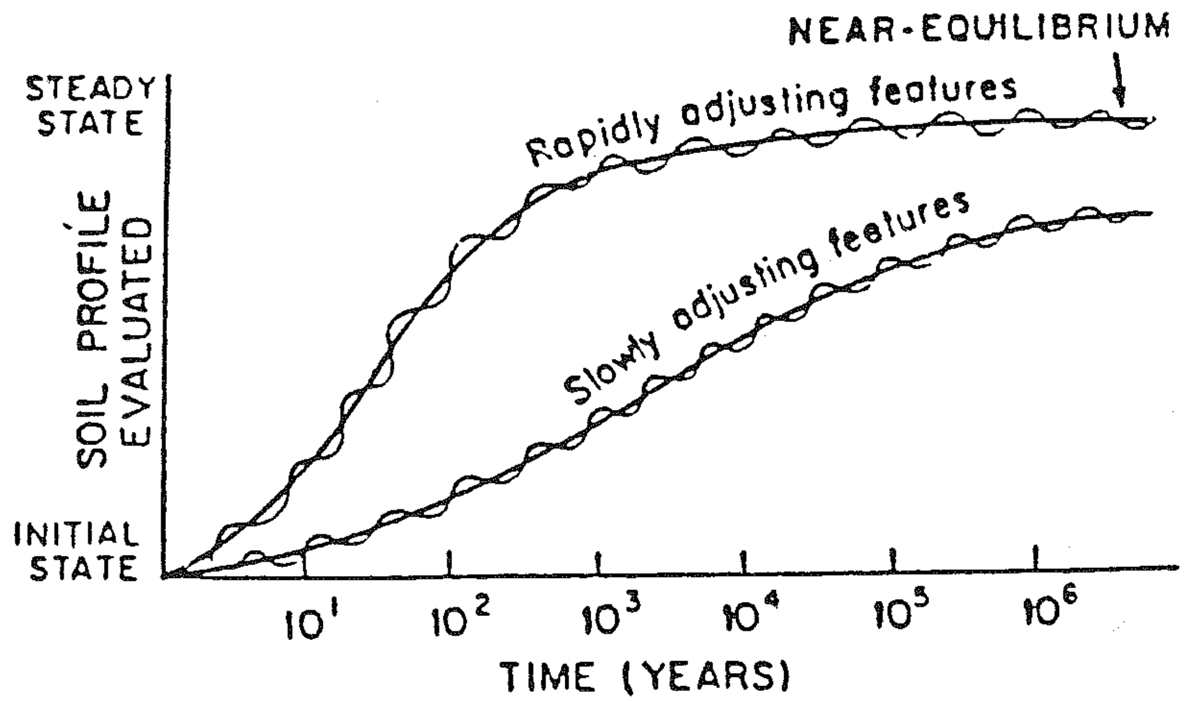


Fig. 3. A diagramatic representation of the time taken to achieve steady state in generalized soil properties after the initiation of soil development. The response of various soil properties to climate change will range between these two extremes.

If temperatures increase, a warming-up of the northern Eurasian and North American perma-frost plains with their loamy to silty sediments, all the shallow, imperfectly to poorly drained soils (Gleysols) of the tundra and the northern boreal forest biomes, will be radically changed by the melting of huge amounts of ground ice. The peat soils (Histosols) of the polar and boreal zones will shrink or disappear due to increased rates of decomposition of the organic matter. The podzolised soils of the tundra and boreal forests (Podzols, spodic cambisols) which derive from oligomictic sands and coarse crystalline rocks will turn into more acid and more leached variants.

If precipitation increases, the heavy textured soils of present-day tundra, boreal and humid temperate regions (some Luvisols, Podzoluvisols) will develop gleyic features in their topsoil, turning them into pseudogleyic/stagnic variants. It may be pointed out that about 50% of the increase in the CO_2 in the atmosphere over the past 150 years is attributed to changes in land use. Also the increase in the second major greenhouse gas, CH_4, is due in large measure from paddy soils with increasing percentage of fully irrigated soils, with their ever-intensifying fertilization as needed for the new high-yielding varieties. Climate-induced changing land use, and associated changes in soils are therefore likely to have effects on the climate.

Because of the paucity of published relevant experimental or observational data on the ways in which climate change might affect soil it was difficult to confidently set down generalizations that will hold globally. The following are considered informative:

northern and southern Hemisphere soil assemblages are distinctively different from each other;

very little information is available on soil responses to climatic change;

some soil properties will respond faster than others, but few will respond in the short term and the nature of the response will differ between soil types;

pedogenic inertia will cause different time-lags and response rates for different soil types.

Given the above provisos, the overall effect of climatic change on soils could be most usefully dissected by individual climate factors. Table 2 contains the interactions of the climatic factors of precipitation, etc., with various soil properties and processes. The climatic factors are dealt with in order of importance; precipitation was ranked the most important, vegetation the least. Vegetation is of course not a climatic factor but it is an indirect, important effect of precipitation and temperature change.

The soil processes on which climate and atmospheric CO_2 change are predicted to exert an important effect are: litter accession, decomposition, organic matter turnover; proton/nitrogen accession from the atmosphere, leaching, exchange chemistry, relocation of salts and bases; ground-water recharge; erosion/deposition regimes.

The scientific issues in regard to soil changes are listed in priority order in Table 3.

Research Needs and Recommendations

* 1. Establish the requirements for the mechanistic modelling of the relationships between precipitation regime and the spatial redistribution of water and soil materials. Which existing models most closely meet these requirements?

* 2. What will be the qualitative and quantitative changes in the following soil properties as a consequence of climate induced change in soil processes:

i) soil nutrient pool size and transfer rates;
ii) soil water regime including ground-water recharge and salinity;
iii)soil structure?

3. What are the requirements for models of organic matter accession and decomposition that predict levels of N,P,S, ionic exchange chemistry, pH under climate change? Which existing models can serve as starting points?

* 4. Enhance existing water balance models to relate the dynamics and interaction of soil water in the rooting zone, ground-water recharge and salinity to the climatic factors of precipitation (P) and temperature (T). What are the minimum data sets for these models? Do such compatible data sets now exist and is there a suitable international interchange procedure already in existence?

TABLE 2

The interaction of climatic factors, ranked in order of importance for soil related processes. A research priority rating High, Medium and Low) is also applied

Priority	Property/Process	Parameter
	1. PRECIPITATION	
H	Erosion/deposition	Intensity/duration
L	Weathering	Time, sequence and amount
M	Leaching Relocation of salts and bases	"
M	Ground-water recharge/ Salinisation	"
H	Soil Decomposition/ O.M. turnover	"
H	Soil moisture regime	"
	2. ATMOSPHERIC ACCESSION	
H	Acidity	
H	Nitrogen	Total amount and spatial distribution
L	Sulphur	
L	Aerosols (cyclic salts)	

TABLE 3

PRIORITY OF SCIENTIFIC ISSUES IN REGARD TO SOIL CHANGES

1. PRECIPITATION
   - Erosion/deposition
   - Litter/decomposition/O.M. turnover
   - Soil moisture regime
   - Leaching/relocation of salts and bases
   - Ground-water recharge/salinisation
2. ATMOSPHERIC ACCESSION
   - Acidity of rain
   - Nitrogen in rain
3. TEMPERATURE
   - Litter decomposition/O.M. turnover
   - Soil moisture regime/evapotranspiration
   - Permafrost limits
4. WIND
   - Erosion/deposition
   - Soil moisture regime/evapotranspiration
5. VEGETATION
   - Litter
   - Soil moisture regime/root extraction
   - Soil permeability/biopores
   - Earthworms and termites
6. FIRE
   - Greenhouse gas flux
   - Litter level
   - Nutrient loss

II. Vegetation Function

Processes

Vegetation function represents the combined effects of the constituent individual plants in capturing and releasing resources. To understand and predict the effects of climatic change on the way vegetation functions, some general propositions relating to the processes involved in vegetation/atmosphere exchanges need to be examined. These are:

- Production and general growth patterns are in the main driven by average climatic conditions (means), whereas survival (presence/absence) of particular species is determined mostly by extremes, modified by past production patterns and the frequency of extremes;

- The sensitivity of vegetation to changes in atmospheric conditions will be reflected by trends at the margins (boundaries) of areas to which the vegetation type is well adapted. The detection of trends and analyses of the mechanisms responsible for them are best done on the basis of observations made at the margins. (This proposition is based on the interpretation of vegetation as discrete types with defined geographic ranges.)

- Fluxes of entities (e.g. water vapour, heat, CO_2) between vegetation and the atmosphere are determined by the vegetation type (e.g. forest, grassland, woodland) as well as by atmospheric conditions. Studies of such fluxes must take place within large areas of vegetation, avoiding edges.

- A particular vegetation type occurs within a climatic envelope, the limits of which may be readily defined by the limits of tolerance of the vegetation to extremes of low temperature and to the balance of precipitation and evapotranspiration (Woodward 1987). Over much of the globe sensitivity to low temperature is a collective and stable physiological property of vegetation. Climatic change will immediately change the occurrence and degree of extremes of low temperature and therefore the geographical limits of a vegetation type. The hydrological balance will also respond immediately to climatic change but transpiration will, in addition, be sensitive to changes in the atmospheric concentration of CO_2. The limits of vegetation distribution and functioning will therefore be most sensitive to climatic change.

- The response time of vegetation functioning to climatic change will be dependent on the growth and developmental responses of individual plants. These responses are measured as the fluxes of entities between the atmosphere and vegetation (irradiance, water vapour, heat, CO_2) and the soil and vegetation (water, nutrients).

- Owing to vegetation-level processes (e.g. microclimate modification, competition) the responses of individual, isolated plants to environmental factors will be poor predictors of vegetation responses.

These propositions provide the framework for the establishment of the major scientific issues in this area, for identification of the gaps in our knowledge and understanding and for the development of research proposals.

Scientific Issues

Photosynthesis is the primary process involved in the growth of vegetation and the factors governing it are well known. Additional research on photosynthesis per se, as a biochemical process, or at leaf level, has low priority in relation to possible changes in climate and their effects on vegetation. For IGBP purposes attention should be confined to the effects of atmospheric and climatic factors on processes at the level of the plant community and ecosystem.

The factors which will likely undergo significant change in the next few decades are atmospheric CO_2, temperature, plant available moisture (PAM), nutrition and, perhaps, light. The unresolved scientific issues in regard to how these factors will influence vegetation function are as follows:

1. On a Global Scale

- How vegetation change will affect albedo (especially hot, water-limited environments and cold, snow/tundra environments). Note that the present predictions of greater temperature change at the poles have ignored albedo change at low latitudes.

- How CO_2 and climate change together will affect C-storage in ecosystems and how C/N ratios will affect decomposer cycles.

- The characteristics of cloudiness and its effects on evaporative demand.

- The role of vegetation in the fluxes of N and trace gases.

- Responses of different vegetation biomes to changes in temperature regimes.

2. On Regional Scales

- How CO_2 flux responses vary between major vegetation types. (Best studied within large areas.)

- How extreme events will affect regional-scale changes in vegetation function.

- How genetic variability will modify regional responses.

3. On Local (community) Scales

- Mechanisms of CO_2 interactions with water, light, nutrients and temperature, and the quantification of these responses.

- How plant populations will respond to CO_2 enrichment, at all stages of their life cycle.

- Mechanisms of response of different life forms; reason for genotypic differences in CO_2 responsiveness.

- Limits to genetic plasticity as CO_2 concentrations change.

- Interactions of soil water and root function.

Research Needs and Recommendations

* 5. What are the relationships between vegetation structure, dynamics and composition and the albedo evapotranspiration and surface roughness characteristics of a landscape? Will potential climate-driven change in vegetation structure, dynamics and composition significantly alter these energy, mass and momentum exchange characteristics? (See also # 15)

* 6. Within the major biomes, develop mechanistic models to relate atmospheric composition, climate and vegetation to the exchanges of the trace gasses, CO_2, H_2O NO_2, etc. between the biosphere and the atmosphere.

7. What is the relative importance of changes in vegetation structure, dynamics and composition compared with changing cloudiness in determining the energy, mass and momentum exchange characteristics of landscapes?

* 8. There is a need to determine, at a landscape level, within a representative set of vegetation types, the influence of increased atmospheric CO_2 on soil organic matter and litter decomposition, water use efficiency and primary productivity and litter fall.

9. Establish the differences in CO_2 responsiveness of different life-forms, the mechanisms of response, and the limits genetic and phenotypic plasticity.

* 10. A major problem in measuring functional attributes of vegetation is that of scale. The research need is how to aggregate output from individuals to 'homogeneous' communities, which together constitute a mosaic in the landscape. A fundamental part of this aggregation must be the simplification of landscape description through the use of a new functional taxonomy at species- (Plant Functional Types) and community level (Vegetation Functional Types).

III. Vegetation Dynamics and Distribution

There are two, quite distinct issues relating to climate-induced changes in vegetation dynamics and distribution:

Problems which might arise in connection with individual species. These are likely to be either in the form of species extinctions and local losses of species, or invasions and/or explosions of species. The approach to these problems must clearly be based on an individual species assessment. It will be addressed to some extent in this section, but will be dealt with more fully in section B.

Problems arising from changes in vegetation community structure and function. These may concern particular species or groups of species, but will also (mainly) involve changes in community function, both in terms of feed-back on climate and in terms of the value or effect the community has for humans (primary production, value to herbivores, supply of fuel or fibre, cover, etc.). This class of problems may therefore involve treating vegetation in different ways; as a single unit, as a community of plant functional types (PFTs) or guilds, or as selected species.

Whether we are dealing with species or PFTs, changes in community composition are brought about by changes in the following processes.

Processes

Five processes (in phenological sequence) determine the dynamics of vegetation on a site, and therefore the changes which occur in the distributions of plant species and communities:

i) Germination and establishment (G/E)
   - in the presence of established vegetation
   - in gaps or extensive bare areas following mortality of established vegetation

ii) Growth and competition (G/C)

iii) Seed production (SP) (including dormancy and seed longevity).

iv) Dispersal or removal of seeds or other propagules (D)

v) Mortality (M)
   - age-specific mortality
   - age-independent mortality

Scientific Issues

1. Determinants of Community Dynamics

The primary issue is to determine how climate (and therefore a change in climate) influences the five processes in either individual species or plant functional types (PFTs). This reduces to establishing the following four relationships, which express the processes as functions of those climatic and other variables which together determine the rates or levels of the processes concerned.

As discussed in section II on vegetation function, there is an important distinction between the nature of the climatic variables which determine the functioning of a given plant community and those which bring about a change in the species composition and the physiognomic structure of a community: Community function (primary production, evapotranspiration, etc.) is determined largely by mean climatic conditions; community change (demographic processes resulting in species change) is brought about largely as a result of episodic, extreme events, i.e., the variance rather than the mean. Obviously, both the mean and variance play a role in both function and composition, but the relative importance differs. Furthermore, the relative importances change from one type of vegetation to another, and in general increasing emphasis is placed on extreme events with an increase in aridity.

The first of the four relationships, therefore, includes the two most important demographic processes in plant communities, namely germination/establishment and mortality (especially age specific mortality).

i) G/E and M = f_1 {1. absolute limiting conditions(e.g., min/max temperatures, threshold levels of nutrients)
2. time for which plant available moisture (PAM) = 0}

In addition there are other variables which, in turn, will be affected by a change in climate and will influence G/E and M. Three such variables which will need to be taken into account are:

3. fire frequency and intensity
4. herbivores, pathogens and seed predators/dispersers
5. influence of CO_2 on all of the above, especially 1 and 2

We can express all this tautologically by posing the question: for each species or plant type, what is the minimum sufficient model which allows prediction of change in G/E and M as a function of 1-5? This model must include their interactive effects, because these define the nature of particular events or combinations of conditions which result in significant, episodic change. The "minimum sufficient model" is the key phrase and the challenge to IGBP. In order to avoid the inclusion of too many complicating factors, it was suggested by some participants that we should rather ask: "What is the single most important thing to introduce into our existing models, to make them better?" One step at a time.

ii) G/C = f_2 {1. PAM, CO_2, light, temperature
2. soil nutrients
3. herbivores and pathogens}

iii) SP = f_3 (season length, temperature, light, CO_2?)

iv) D = f_4 (animals, wind, surface hydrology, micro-organisms, i.e., vectors, predators and pathogens) Dispersal will also be influenced strongly by barriers induced through land-use changes.

In determining these four relationships, problems and questions arise at different scales, from global to continental/regional to landscape and, finally, community. The importance of the variables in each of the equations therefore varies and (fortunately) not all of them will need to be included in each analysis. Again the emphasis must be on keeping complexity to a minimum.

2. Initial screening and the use of statistical models

An initial screening procedure is needed to reduce the complexity of the problem, by identifying places/vegetation types where change is likely to be great or easy to determine. The screening should consist of using the relationships between present day distributions of species or PFTs and present climate, to make projections of changes in their distributions as a consequence of future climate scenarios. These statistical models include no ecological or biological mechanisms.

It is possible that in some places, and for some questions at particular scales, a simple correlative model will be all that is required to provide a satisfactory prediction of vegetation change.

There are various correlative models which relate either species, species groups or vegetation types to sets of climatic parameters. They all suffer from the following major limiting assumptions:

- The difference between realized and fundamental (or potential) niches of species is ignored.

- Assumption of equilibrium. There are no time lag effects built in to such models, and a major factor in determining whether particular species or PFTs will a) persist on a site or b) be able to move to new sites, will be the rate of change in climate relative to such attributes as longevity and dispersal. We need to understand the transients to predict the impact of climate change.

- The direct effects of increased CO_2 on, e.g., plant water use efficiency (in the field) are ignored, and these potential effects, if present, will alter the existing statistical relationship.

- The scale of most models of plant distribution is such that differences in soil type are ignored. Where soil is important it will be necessary to predict a set of plant community mixes, the number in the set being equal to the number of ecologically distinct soil types.

- Analogues of the new environmental conditions may not exist, either because of new climatic combinations which may occur, or because of secondary effects such as new fire regimes.

Bearing in mind these limiting assumptions, research into the use of statistical models should proceed as follows:

Problem definition. What are the appropriate scales and domains for statistical models?

	Scale	Domain
Temporal	Seasonal but with an annual harmonic	100+ yr
Spatial	Point models, but the aggregation problem will still have to be solved	Globe
Biological	Depends on purpose; ranges from physiognomic to age/size structure and includes animal, especially pest, populations (see list of biological descriptors)	Biosphere

Biological descriptors for such models might include one or more of: Physiognomy, biomass, diversity, composition, productivity, age/size structure, C:N ratios, GCM input set.

Model conceptualization and techniques. There have been few thorough attempts to resolve the issue of how much complexity needs to be incorporated in the statistical models - i.e. how many climatic variables and which ones should be used to predict vegetation change; what source of climatic data should be used; how should it be corrected for regional/local variation? How many state variables should one attempt to predict within a particular model?

The workshop was not unanimous in the views expressed on these questions. Two views emerged. The majority view of those who addressed the issue is that there is a need for improved techniques for statistical models, involving two highly complementary approaches:

i) Improved statistical methods
ii) Improved estimation of independent variables which incorporate/summarize relevant processes.

i) Requires substitution of methods like generalized linear modelling for simple linear least squares regression, incorporation of factors, variables and their interaction; use of CART procedures (Classification and Regression Trees, Breiman et al. 1984) for recognition of threshold effects; the use of non-linear techniques rather than linear methods, and the incorporation of methods to estimate the statistical frequency distributions with their extreme values.

ii) Requires the substitution of process-oriented indices (e.g., annual evaporation/annual precipitation) for simple state variables with no necessary physiological relevance such as mean annual precipitation, altitude, etc. Similarly, biological processes must be incorporated, e.g. competition, role of nitrogen fixing organisms and pathogens, by using summary indices based on processes which are biologically more relevant than abundance of other species or life forms.

The alternative view is that we should restrict ourselves to a rapid screening, using models that already exist. After that, go immediately to process models which deal with particular parts of the world.

3. Classification of Plant Functional Types

It is necessary to establish whether, for IGBP purposes, there is a need for a PFT classification. The need has been expressed (e.g. Appendices 2 and 3), but the full implications of developing such a classification, and the way in which it would be used, have not been considered in detail.

For the feed-back effect of vegetation on climate, it is likely that a fairly broad classification of Vegetation Functional Types (as opposed to plant types) is all that may be necessary. The research requirement would be, firstly, to establish the minimum set of such types to adequately represent the feed-back effect (albedo, surface roughness, evapotranspiration and CO_2 flux) and, secondly, to determine the conditions required for a change in vegetation from one type to another.

For the effect of climate on vegetation, it may be necessary to develop a PFT classification. However, it may, alternatively, be more useful and efficient to miss out the PFT step, and to develop instead a "classification" of the characteristic features of plants which enable them to respond (via the five processes described above) to a shift in climate variables (particularly PAM and T). Given this information, it would be possible to go directly from a change in climate in any one region to a forecast of the species which would be likely to increase, decrease or remain unaffected (based on their sets of the characteristic features, and assuming that the climate shifts would not significantly alter the nature of the interactions amongst species).

4. Mechanistic models of Dynamics and Distribution

In view of the serious limitations of statistical models beyond their use for initial screening, there is a need for the development of appropriate mechanistic models. There are two main approaches.

i) Generally applicable (mechanistic) models. Generic models, or generally applicable models should be developed, for the major biomes and perhaps for the globe (e.g. the Universal Vegetation Model, UVM, currently being developed at IIASA). These models should, again, incorporate the minimum, but sufficient, set of biological and ecological mechanisms required to predict change in vegetation within a defined set of possible rates and magnitudes of changes in climatic conditions.

There are already a number of models which may provide a framework for such IGBP models. Some may even claim to have achieved such status. However, they all differ considerably in their output and they will need to be modified after it is decided exactly what they are required to predict. In all cases, careful peer review and acceptance is a necessary step. Some examples are:

Forests.	The FORET model has been widely used and modified for different situations (Shugart 1984). The Vital Attributes model of Noble and Slatyer (1980) has been used to predict forest composition change, mainly in response to fire regimes, but the approach could include climatic and other variables.
Grasslands.	A number of IBP-originated models exist. The generality of the mechanisms, and the level of species or even PFT detail needs to be determined. Few of them explicitly include fire. There are also more specific models for grassland production (e.g. McKeon et al. 1982).
Savannas.	Models range from simple, physiognomic models based on changes in the ratio of top-soil to sub-soil water (Walker and Noy-Meir 1982, Eagleson 1986), up to complex simulation models with more detail on species and function. Again the effects of fire are not explicitly included.

Research in this area needs to be co-ordinated with the activities of other groups working on the topic, such as the SCOPE Scientific Advisory Committee on "Ecosystem Response to Climate Change: The Effects of Climate Change on Production and Decomposition in Coniferous Forests and Grasslands", and the IIASA programme on modelling global vegetation change.

In the development of these models it is important to note that there are two scales which need to be considered; a) individual community models and b) models at the scale of the landscape, which include a mosaic of patches (communities) and which take into account the connections between the patches that dictate landscape level properties - total species, biomass, etc. These connections may be vulnerable to climate change just as they are to human interference

In considering the synthesis and further development of existing models, there is a need to pay particular attention to a) demographic aspects and associated time lags (possible rates of change), and b) identification of 'extreme' events or event driven processes (G/E, M) in the biome concerned. These should include combinations of climatic features (such as potential and actual precipitation) and secondary effects such as changes in fire regimes, insect irruptions.

ii) Palaeo-ecological models. A considerable advance in developing a predictive understanding of vegetation change in response to climate can come from investigating past biotic and climatic change.

The major scientific issues which this approach addresses are:

- The development and testing of models of climate change
- The development and testing of models of vegetation change, including an examination of hypotheses concerning succession, diversity/stability, and multiple equilibria.
- A search for carbon fertilization effects in past and present vegetation
- The separation of intrinsic from climate and human induced vegetation behaviour over long time periods
- Documenting the frequency distributions of rare events
- Development of fine resolution biotic palaeo-environmental indicators

Examples of appropriate methods to achieve this are:

(a) Collect and analyse appropriate fossil leaf data of stomatal densities and of stable isotope composition at fine resolution to determine CO_2 responses of the pre-industrial period.

(b) Construct international tree-ring data sets to define pre-industrial climate-growth and CO_2-growth relationships. (Note: An International Tree ring data-set is being slowly collected, collated and maintained at the University of Arizona Tree Ring Laboratory.)

(c) Identify and analyse new tree-ring series from seasonally dry tropical locations which are free from atmospheric pollution.

(d) Continue development of Accelerator Mass Spectrometry for ^{14}C dating and develop ^{32}Si dating method. (This will be explained and developed further in the report of IGBP Working Group 3).

(e) Document at fine resolution vegetation and climatic change at high sedimentation sites in tropical lowlands and very high latitudes near climatically sensitive ecological boundaries. Concentrate mainly on the Holocene with special emphasis on the last 6000 years, in order to document frequencies of rare events and long-term characteristics of transient responses by vegetation communities.

(f) Collect parallel tree ring and weather data from sites which include the entire circumpolar boreal forest, with which to modify and verify growth models and to document temperature versus CO_2-induced growth changes. These high latitude forests are likely to be impacted heavily by CO_2 concentration changes and by climate change and the forest structure and composition are simple enough to allow modelling of transient climate effects with mechanistic models. This initial boreal forest work would serve as a test-bed for modelling the more complex vegetation at lower latitudes.

Research needs and recommendations

* 11. Develop an efficient hierarchical structure of inter-linked statistical and mechanistic models, which together predict changes in vegetation structure, dynamics and composition in response to climate change. Which existing models can contribute to this IGBP model structure?

* 12. Establish the availability of, and further requirements for, data sets appropriate to the modelling development outlined in # 11 above. There is a need to develop co-ordinated data-bases of climate, soil and biotic data, from the same localities because this lack is currently more limiting than model development as such.

13. With respect to statistical models, the capacity to incorporate transients (as functions), and situations where analogues of the new environmental conditions do not now exist, is critical. Therefore the contribution of mechanistic models is imperative to overcome this limitation.

* 14. Use statistical models to indicate important areas in which the most significant effects of climatic change may occur and where more detailed process-oriented work should be concentrated. This must include secondary effects such as changed fire regimes.

* 15. Establish the most appropriate classification of Vegetation Functional Types (VFTs) for the feed-back effect of vegetation on climate, and determine what conditions are required for vegetation to change from one type to another. (See also # 5)

* 16. Is there a need for a classification of Plant Functional Types (PFTs) reflecting the characteristic features of plants which determine their responses to climate. What is the most appropriate classification for IGBP purposes?

* 17. Vegetation will, most probably, respond to climate change via changes in the frequency of extreme climatic events. Consequently, IGBP models must include these secondary climatic characteristics as primary determinants of vegetation composition. The research need is to identify and characterize such events and include them in models subject to validation.

18. For the major biomes, determine the relationships between climate and fire regimes (frequency and intensity). How will human modification of fire regimes influence the potential climate-driven changes?

* 19. With respect to past climate/vegetation changes is it possible to define periods of past climate variation and vegetation response which are analogous or homologous to those expected in the future? Is it possible to adequately test models of long-term ecosystem behaviour with these historic data? A synthesis of existing tree ring and pollen data sets would be most relevant here; particularly those from tropical lowland areas.

Similarly is it possible to document the effects of CO_2 fertilization during prehistoric periods of known CO_2 variance (e.g., full glacial atmospheric CO_2 concentrations of 180-200 ppmv)? For example an examination of late Quaternary leaf macro-fossil data to correlate stomatal densities, isotopic composition with the atmospheric CO_2 data would be most instructive. (See also # 9)

What specific kinds of rare events do we expect to be both of interest in vegetation response to climate change, and recorded in fossil pollen and tree ring records (i.e., frost frequency and drought frequency in tree rings; vulcanism and flood intensity in fossil pollen records), and what is the "palaeo-ecological fingerprint" of each? Research is needed to define the measurement characteristics of these palaeo-ecological tools.

Are there potentially-useful and little-used or poorly-developed sources of quantitative data on interrelated long-term climate and biotic patterns? An analysis of historical climatic and agricultural data sets would be of value; for example some in China may be millenia-long.

Lastly, many of the above tasks could be facilitated by the development of faunal palaeo-environmental indicators (e.g. beetles, ostracods, molluscs, corals) and species-level identification capabilities for pollen grains.

IV. Higher Trophic Levels

Processes

Climate has two main direct effects on animals. It influences their energetics, and therefore determines which kinds of animals (size, shape, metabolism) can survive and/or prosper; and it influences their reproduction. The combined effects determine the potential distribution of animal species, and the interactions with other species determine their actual distribution and abundance. The influence of a change in climate on a species will therefore be both direct and indirect, through the influence on other species.

Changing weather patterns will therefore have no general effect upon the dynamics and distribution of animal species. The ranges of some will expand and those of others will contract. Data bases such as the CSIRO CLIMEX (Sutherst and Maywald 1985) are available to model projected distributional changes where sufficient biological data are available.

The ranges of the majority of animal species reflect specific habitats. For some the nature of the habitat is the overwhelming determinant of their performance and distribution, and prediction of the fate of those species is a simple corollary of the fate of the plant communities upon which they depend. No additional prediction is required in these cases.

Scientific Issues

There are three kinds of issues concerning changes in higher trophic levels in response to climate change:

1. The conservation of adversely affected species, especially those with restricted geographic ranges and narrow climatic tolerance and habitat requirements. The consequences to one sub-set of such species - the topographically stranded relicts on mountain tops - can be predicted as a group: most will go extinct as mean temperatures continue to rise.

2. The dynamics of pest species. They will exhibit no general reaction to a change in climate. Their inconvenience to people will be amplified in some cases and dampened in others. Some species not presently pests will undoubtedly become so when their climatic ranges are changed. The ecology of a large number of economically important pest species is presently known well enough to specify the likely effect of a climate change upon their dynamics and distribution. Where that knowledge is not available it can be made available by standard ecological research. Note however that the specification of climatic change leading to a prediction of biological outcome must be more precise than simply "mean temperature will rise by 3oC and precipitation by 10%", or some such. As emphasized in the section on vegetation dynamics, the specification must include at least such additional projections as changes in seasonality and in year-to-year variability of weather.

3. Livestock performance and breeding. This will be dealt with in the next section.

4. One issue which generates controversy is the use of animals as "early-warning" indicators of the speed and direction of climate change. The workshop failed to agree on this point and two, strongly contested views emerged. One group of scientists are firmly convinced that there will be too much confounding with factors other than climate, and that in any case our ability to measure climate change directly is more than adequate. The other group, the proponents of the notion, suggest that the ranges of a carefully chosen sub-set of animal species should be pressed into service as early warning indicators of the speed and direction of change of those components of climate that are biologically meaningful. Indicator species would thus be used as bio-assaying agents, the movement of their range boundaries integrating these shifts in weather patterns. Those range boundaries are likely to be considerably more sensitive to biologically important shifts in climate than is time series analysis on standard weather records. Standard weather stations do not record data allowing detection of changes in, for example, diurnal distribution of precipitation, diurnal distribution of temperature, and intensity of precipitation events. Such changes have important biological consequences. They can be detected early from movements in the range boundaries of indicator species, and those movements can be interpreted to identify the component(s) of climate involved.

Research Needs and Recommendations

* 20. Because of their significance to human welfare, an urgent research need is to analyze the likely responses of important pest species to a range of future climate scenarios and, of equal importance, to investigate how we might identify those species not presently pests but which will become so under particular climatic conditions.

21. Identify and adapt the available data bases and models for use in projecting distributional changes of a range of animal species (invertebrates, reptiles, mammals).

* 22. There is a need to establish the value of using animals as indicators of climate change. If the conclusion is positive, it is suggested that a set of indicator species be designated on each major land mass and their distribution and dynamics closely monitored.

In the above recommendation the set chosen should, as far as possible, meet these criteria: they should utilize a broad range of food items or utilize a food item that is widely distributed; their habitat preferences should be catholic (i.e., they are not habitat-sensitive); the position of the range boundary, and the population dynamics within the distribution, should be relatively insensitive to non-climatic perturbation, particularly that caused by people; they should be highly mobile, capable of jumping gaps in habitat; their ranges should be capable of expanding at both ends of an environmental gradient (e.g. a gradient of temperature, of seasonality or of precipitation); the relationship between their ecology and weather should be known in some detail so that an expansion of range can be interpreted unambiguously in terms of one or more components of climate; their distribution should have a long circumference such that a change in the range boundary can be seen to reflect regional rather than local influences; the current distribution should reflect the current climate.

Researchers in each region would be expected to make their own choice of appropriate species, and the following are offered simply for illustration:

North America:	mule deer, whitetailed deer, horn fly
Africa:	the suite of tsetse fly species
Asia:	screw worm fly
Antarctica:	the Pygoscelis group of penguins

Essential to the exercise is a detailed knowledge of the relationship between weather and the ecology of an indicator species. A study on the ecology of each is needed to fill the gaps in knowledge. Since the questions to be addressed would be tightly constrained by the use to which the indicator species are to be put, it is anticipated that such studies would not be long term but would run for approximately five years. Concomitantly and after that study the range of species would be monitored closely.

B. Implications of Climate Change

The underlying processes are the same as those described for the effects of climate change, in Section A. Therefore, in assessing the implications of the changes for conservation, and for agriculture and forestry, we consider only the scientific issues involved, and the recommendations.

I. Maintenance of Biological Diversity

Scientific Issues

1. Biological diversity is likely to change in unknown ways in response to climate change. Species will move at different rates, altering their present distributions, and some will change genetically, at least ecotypically.

2. Because the once continuous ranges of many species are now fragmented, and especially in the light of the relatively very fast rate at which the climate change will occur, it is likely that some species will be left in areas climatically unsuitable for them, without being able to disperse into new, suitable areas.

Research Needs and Recommendations

These two issues lead to five questions:

i) What are the current distributions and abundances of species?

ii) How will species respond to climate change, by moving or evolving?

iii) Where should reserves be sited to encompass the most species now and in the future?

iv) Are there widely applicable guidelines for off-reserve management to maintain species diversity?

v) Will the effects of land use change override those due to climatic change alone?

The research needs are considered in relation to these five questions.
Question i)

23. There is a need to establish the extent to which persistence of some species will be a problem. Since a complete inventory of the distribution of all organisms in relation to extrinsic variables is impossible, it is necessary to select data subsets. The biological parameters are species, communities and functional groups, and the environmental parameters (predictors/scalars), are temperature, precipitation, etc. The research problem is how to select the subsets.

A first approach would include the selection of subsets of species using the two criteria of climatically sensitive and vulnerable. Climatically sensitive species are those with very narrow tolerance ranges for one or more climatic variables. A vulnerable species has one or more of the following attributes; geographically localised, with small total population, specialised (especially where part of the life cycle is linked to some climatic factor), poor dispersers, restricted to rare and/or threatened environments. A second requirement is to collect data for the study of impacts of extreme events on distribution patterns of selected species. An important part of the research concerns the identification and characterization of "extreme events". Recognizing practical constraints, a minimum data set for the first iteration of this study involves use of climate variables that are averaged over years but that include whatever measures of variability are available. The minimum data set comprises:

- geographic location (provides elevation), and climate data,
- time of observation, reliability, etc.,
- presence/absence of selected species (if necessary, collect abundance data by class),
- response characteristics of species - minimum data set as appropriate for particular organism,
- site disturbance history,
- functional characteristics.

Having sampled the selected biological parameters, statistical models (see Section II.1) can be developed at regional scales to define present distributions (e.g. Austin, Cunningham and Fleming 1984) . They may be for species, communities, or other groups with similar functional attributes. Resolving this problem will also require access to the data from the long-term monitoring sites of the IGBP's Geosphere-Biosphere Observatories and determining what are the impacts of extreme events on individual species, assemblages of species (communities) and on organisms grouped by functional attributes.

Question ii)

* 24. Determine the predicted distribution patterns of selected species, communities, etc. as a consequence of existing climate change scenarios. Based on how different they are from present patterns, identify the kinds of organisms and/or the kinds of habitats that are most seriously affected.

The problem can be addressed using the statistical/correlative models. The limiting assumptions of such models discussed earlier apply here, and their validity is confined within the envelope of variables used.

Question iii)

25. What are the ecological criteria for the design of a nature conservation reserve system on a regional basis that will incorporate the biota now and in the future? What ecological information is required to redress the inadequacies that are projected as a consequence of climate change?

Criteria for design of the ideal system should include at least one viable population of each taxonomic entity, e.g. species, community, etc. This raises the following subsidiary research questions. What is a minimum viable population size? How many populations are sufficient to ensure persistence? Finally, are key environmental processes going to respond to climate change in the same way (in the same direction) as the taxonomic entities?

Recommendation 25 spawns the following subsidiary research questions:

- What are the inherent dispersal abilities of the various taxa and how are these affected by existing physical constraints (e.g. patterns of other land uses)?
- What is the capacity of species to adapt without moving?
- What is the role of corridors of habitat in the dispersal of species?
- Given that conservation management (theoretically) involves maintenance of processes, what are the likely consequences of atmospheric changes on those processes?

Question iv)

* 26. Develop the ecological criteria to support the management of off-reserve areas in order to complement and supplement the reserve system, recognizing that it is impossible to conserve the complete biota in a reserve system, and that under a changing climate the existing global network of reserves will become progressively less able to conserve the species they currently contain.

To establish these criteria we need the results of long-term experiments on the effects on conservation values of different intensities of land use in different land use zones (e.g. pastoral, arable, forests, etc.) Such experiments could, and should, be established now so that in 10 years time, some guidelines might be available. It is possible that a careful selection of existing experiments and land-use patterns, for which historical data are available, may provide valuable information.

Question v)

* 27. Determine the likely modified land-use patterns under the range of climatic change scenarios and identify potential areas of conflict with nature conservation objectives.

To achieve this it is necessary to work in conjunction with the agriculturalists and foresters (see following section), to generate a range of potential land-use scenarios using mechanistic tree and crop models together with the forecast environmental parameters provided above.

Appropriate locations

Criteria for the optimal selection of research locations include access to long-term meteorological data, experiencing the greatest impacts of climate change, existing compatible biological data sets, and proximity to refugia. Additional criteria would be sites of species richness, steep environmental gradients, management security for long-term studies and buffering against land use change. Regions close to the tropics which cover a range of climatic gradients, such as north Queensland in Australia, meet some of these criteria. Mountain tops (especially with tree-lines) and boreal regions are forecast to experience the greatest impact of climate change and are therefore target sites. Many of these same criteria are involved in the selection of the IGBP Geosphere-Biosphere Observatories, and wherever possible the same sites should be used.

II. Agriculture and Managed Forest Crops

The implications of climate change for agriculture (including silviculture) were addressed but not developed by the workshop. The topic is obviously of very great significance, and must be treated as an issue in its own right. The expertise of the working groups was (by design) largely in the areas of natural ecosystems.

Research Needs and Recommendations

Agricultural and managed forest crops

* 28. Research effort should concentrate on the development of generic growth and yield models for all of the major crops (and varieties), including tree crops. The models should be tested across the full range of existing climatic conditions under which they are grown.

* 29. The effect of increasing CO_2 levels on the performance of different crops (and therefore on the predicted model outputs under changed climates) needs to be experimentally determined under field conditions, at an appropriate scale. The results should be incorporated in the generic growth and yield models.

30. The period of significant climate change may correspond with the period when current developments in genetic engineering reach their phase of application in crop breeding. The two developments should interact strongly, and research in these two areas should incorporate each others' developments.

Animal Production from Rangelands

31. Significant shifts in temperature may influence breeding and growth in different types and breeds of domestic livestock. As in the case of crops, equivalent generic models for livestock breeds need to be developed.

* 32. Determine the changes in vegetation on rangelands that are important for livestock production. As an example, a shift from predominantly winter to predominantly summer precipitation in semi-arid rangelands would be likely to induce a vegetation shift from shrubs to perennial grasses. The former favours sheep, the latter cattle.

* 33. What will be the influence of secondary effects on rangelands? Where the primary effect of climate and CO_2 change is increased production (through increased precipitation and increased water use efficiency), the secondary effects of changed fire regimes are likely to strongly re-enforce even quite small changes in vegetation. Before including such effects in models of rangelands, it is necessary to assess the role of man in controlling fire regimes.

C. Predictive Understanding: Modelling and Scaling

The functioning of the geosphere-biosphere is characterized by scale-dependent processes. The issues involved in modelling and scaling have been considered at some length by both ecologists and climatologists. As reported by earlier meetings, e.g. Risser (1986) and Rosswall et al. (1988), the central role of scaling in the design, integration and synthesis of field experiments in the forthcoming IGBP is acknowledged but no useful, widely applicable theory presents itself. A functional approach is required and we believe the following will contribute to such an approach.

I. Scaling Down

Scientific issues

Scaling down includes all of the steps involved with the application and interpretation of the output variables from GCMs to terrestrial ecosystems. This is the most pressing issue in the whole modelling process because it is only through GCMs that quantitative forecasts of future weather and climate regimes will come. Without a quantitative and dynamic link to this forecasting capacity, future research on and, more importantly, management of terrestrial ecosystems will be blind. The output of GCMs must be coupled to ecological models that are scaled at landscape and/or management level or else the substantial scientific investment in global modelling will have no influence on the direction of terrestrial ecosystem research.

The problems involved in linking GCMs to ecosystem or landscape models derive from the great disparities in scale that currently characterize each research field. Because of computational limits existing GCMs are modelled on an appreciably coarser scale than most ecological models. Typical spatial cell sizes (100-200 km on a side) and time steps of 30 minutes are meaningless in terms of the scales of the micrometeorology of terrestrial surfaces.

Precipitation, which is a key ecosystem variable, provides a good illustration of the mismatch between GCM forecasts and basic ecological requirements. For almost all biomes the ecological and managerial consequences of a given rain fall will be determined by its time (frequency and intensity) and space (patchiness) characteristics. However, precipitation within GCMs is currently generated and represented as a 'uniform drizzle' - a space/time precipitation pattern that does not, in fact, occur. Thus, forecasts of the ecological effect of this modelled precipitation smeared over a GCM cell are meaningless for most of the world's landscapes.

The problems of scaling down can only be solved by practical considerations. That is, terrestrial ecologists must specify to the climate modellers exactly what is required to interface the output of GCMs to realistically scaled ecosystem models. At this stage we need to explore the possible ways in which scaling down can be approached.

One possible, though not necessarily easy, approach is to devise and build 'nested' models to effect this linkage as an exercise separate from the 'global' running of the numerically intensive GCMs. This pragmatic and empirical approach can be illustrated using precipitation again. Ecologists need to specify what the 'structure' of the precipitation is at the localities of interest. The structure can be characterized by locating it along an axis of precipitation mechanism, the poles of which are precipitation regimes dominated by 'convective rain' and 'system rain', respectively. A 'convective rain' regime would be very variable in space (patchy) with stochastic, high-intensity showers. Conversely 'system precipitation' would be characterised by low intensity showers that are spatially uniform and persistent in time. As far as the authors are aware such a classification is not either well defined or widely accepted.

The second aspect of the structure of precipitation is a statistical description of events. This description should allow a rapid appreciation of the relationship between precipitation depth and the probability of its occurrence. The class/frequency diagram is adequate, Figure 4.

The information flow in a hypothetical empirical model that scales a GCM output to that more appropriate to what is required for ecological or hydrological modelling is set out as Figure 5. The input is the forecast precipitation output from just one cell of a GCM. This total precipitation depth is then given a spatial variation dimension by the mechanism parameters, in turn determined by geographic location, time of year and other weather variables, e.g. temperature, generated by the GCM. Lastly, the precipitation depth is given a temporal (intensity) dimension determined by the empirical distribution for that location at that time of year.

Another approach is the use of meso-scale circulation models (MCMs) nested with GCMs to examine the more localized effects of topography on precipitation and temperatures.

Research Needs and Recommendations

34. For planned field sites the precipitation regime needs to be characterized. In particular, within an area equivalent to a global circulation model (GCM) cell size, i.e. 200 x 200 km, determine the average (and its meaningfulness), class/frequency precipitation distributions for time intervals (eg. months) and precipitation types (eg. convective vs system). What is the most appropriate measure of spatial variability or patterning that can be applied to precipitation events? Is there an equivalent to the beta diversity index used by ecologists? The relationships between spatial patterning and precipitation type need also be determined.

    It is recognized that for much of the world, the existing network of rain gauges is far too sparse. Therefore, where possible, satellite image data should be used as a surrogate or co-variate either by observing the extent and persistence of clouds or the direct effect of precipitation in the form of lowered surface temperatures or vegetation greening.

* 35. Models of landscape functioning at a spatial scale of a GCM cell are required to relate the temporal and spatial characteristics of precipitation to measured hydrological and ecological response. In particular, where the data and understanding are best, models predicting the consequences of changes in either or both of the precipitation characteristics are required.

    The other climatic variables, temperature and radiation, are secondary in importance to precipitation. Because they are continuous and spatially relatively insensitive variables, their incorporation into finer-scaled surface models would be a simpler matter than for precipitation.

* 36. What to do about extreme events? The discussion of precipitation, etc. above concentrated on the functioning of ecosystems or landscapes, ie. a tendency to consider the 'average' conditions. It is of equal importance to consider the rarer events, particularly the extremes of precipitation (P) and temperature (T), for these shape the environmental envelope and determine the limits of the distribution of ecosystems. While the importance of extremes or rare events is recognized by terrestrial ecologists it remains largely a qualitative appreciation that cannot yet be explored with the output of GCMs. The topic probably requires a workshop of its own to come up with specific research recommendations that would enable, within a GCM cell, for any biome, quantitative determination of what constitutes an (ecologically) extreme event in terms of P, T and the coincidence of P and T, and the consequences of such an event. In addition attention should be directed to determining the correlation between the extremes of P and T, understanding the mechanisms that generate and preserve this correlation, and characterizing the spatial patterning of this correlation as a function of precipitation regime and climate type.

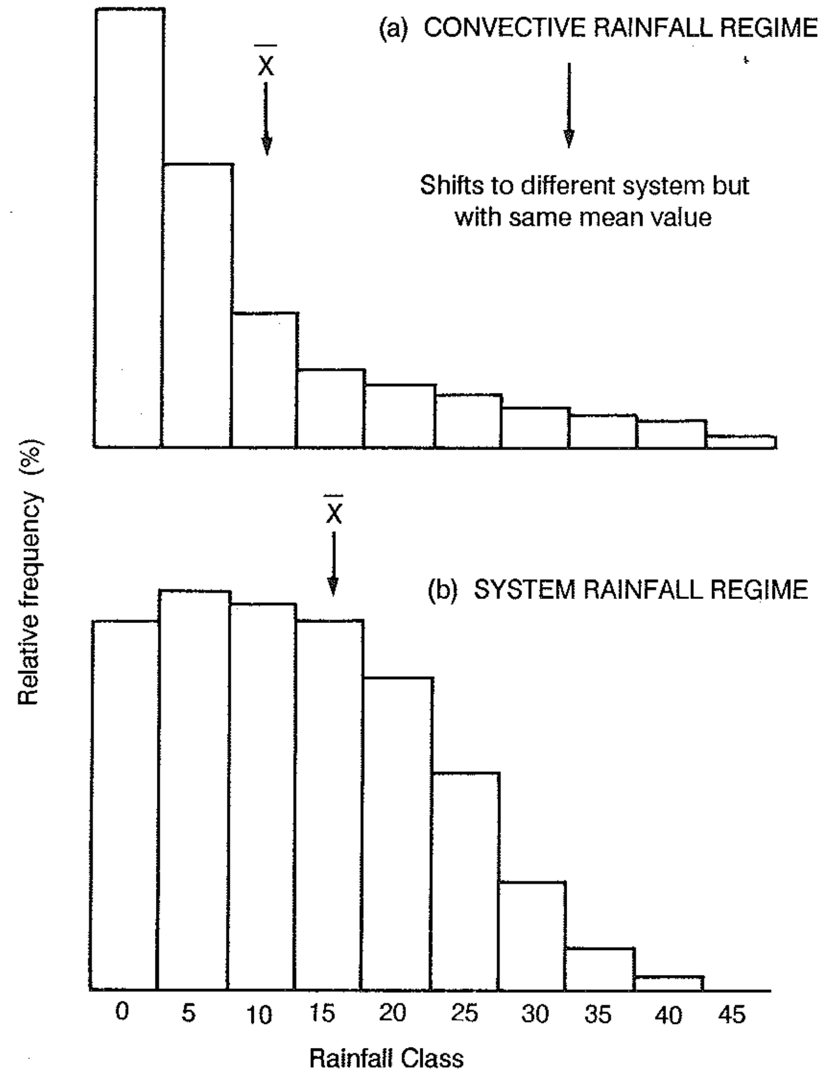


Fig. 4. The frequency distribution of all recorded rainfall events at a hypothetical arid site experiencing (a) a largely convective rainfall regime and (b) a shift to a system rainfall regime for the same site. The biological and hydrological changes that could be expected as a consequence of this change in rainfall regime can be appreciated readily.

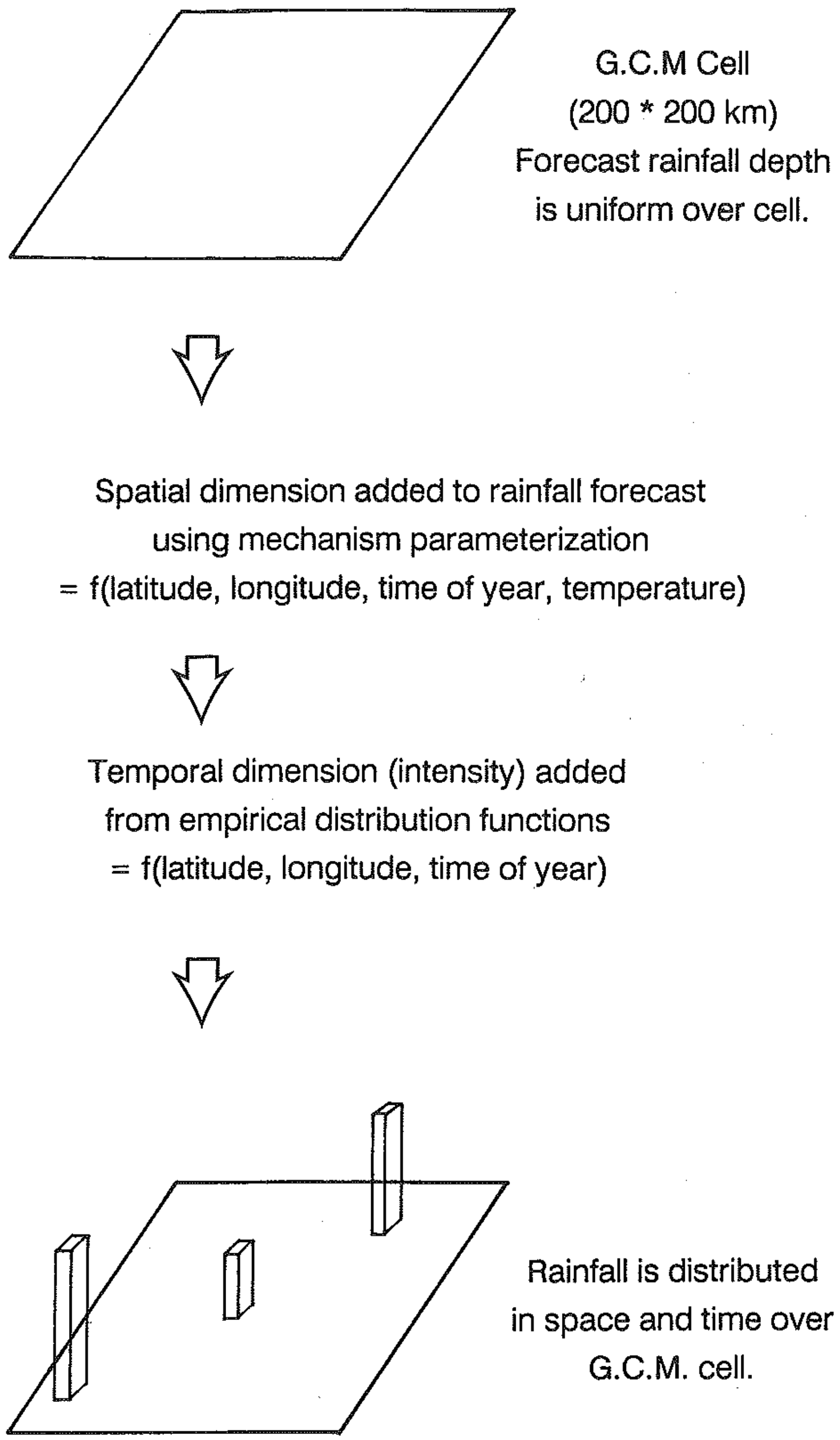


Fig. 5. The flow path envisaged in a simple empirical model that generates temporal and spatial characteristics for the rainfall depth forecast within any one cell of a GCM

37. Develop models relating ecological response to both the temporal and spatial pattern of extremes and use these to forecast vegetation change.

As with precipitation, the frequency distribution of rare or extreme values of temperature cannot be derived from the GCM output directly. Nested models or meso-circulation models considerably more complex than that envisaged for precipitation will need to be developed.

II. Scaling Up

Scientific Issues

Scaling up includes all the steps required to parameterize the land surface to provide the interactive (feed-back) link between it and GCMs. The surface parameters currently required by GCMs are albedo (A), evapotranspiration (E_T), surface (aerodynamic) roughness (Z_0) and CO_2 flux (productivity). The question that must be faced by both terrestrial ecologists and climate modellers is how to represent accurately landscapes aggregated over a cell size of 200 x 200 km, or 40,000 km_2. The recommendations that follow are derived from very pragmatic considerations. It is recognized that these empirical suggestions are just a beginning, but the beginning is all important. The sooner realistic parameterization of landscapes is incorporated into GCMs, the sooner the strength and dynamics of the feed-back loop, and the relative contributions of surface components to this loop, will be studied.

How to represent the 'mixture' of landscape components that will be contained within one GCM cell, e.g. Figure 6. There is a considerable literature dealing with either determining the aggregate properties of a mixture or inferring the composition of a mixture from its aggregate properties. However the application of this theory is dependent on the ability to spatially define the components by boundaries, and on the nature of the parameter to be averaged. For example, given the boundaries, it is a relatively simple task to compute a weighted mean:

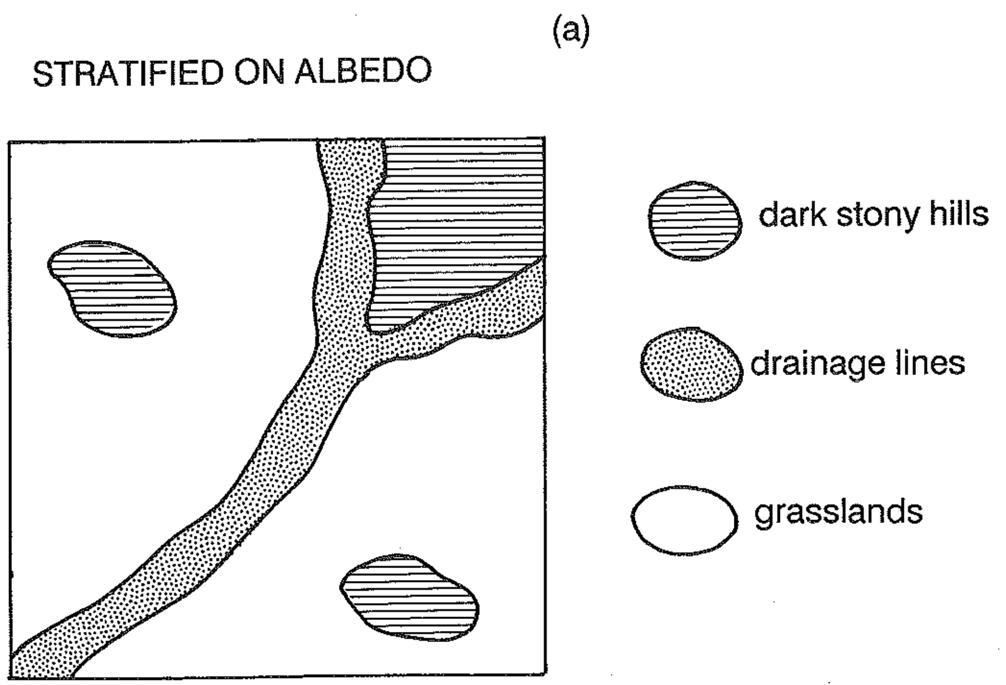
$$\text{xbar} = p_1.x_1 + p_2.x_2 + p_3.x_3 + \text{etc.}$$

where x_1, x_2 etc. are the mean values for each of the components (areal units) and p_1, p_2 are the relative proportions of the total area occupied by each component, i.e. all p values sum to 1.0.

This is not the difficult step; it is the location of the boundaries of the various components or landscape strata. This must be done to produce a meaningful mean for each of the strata by observing the criterion of minimizing the variance within a stratum while maximizing the variance between strata. Sampling within a stratum, to obtain a valid estimate of the stratum mean, requires the reverse criterion - i.e. selecting a scale which minimizes the variance between sample units, and therefore maximizes the variance within each unit.

It follows then that the stratification of a given area will vary according to the parameter under consideration. A hypothetical example is provided as Fig 6.

Given a relatively flat semi-arid savanna grassland at the end of the rainy season the stratification of the GCM cell on the basis of albedo (A) might appear as Figure 6a with relatively high albedos (25%) for the dry treeless grasslands and lower albedos for the trees growing along the drainage lines (15%) and the dark bare stoney hills (10%). The same cell stratified by evapotranspiration (ET) would present a different pattern where the highest ET comes from the woodlands along the drainage lines and the lowest from the bare stoney hills, Figure 6b.



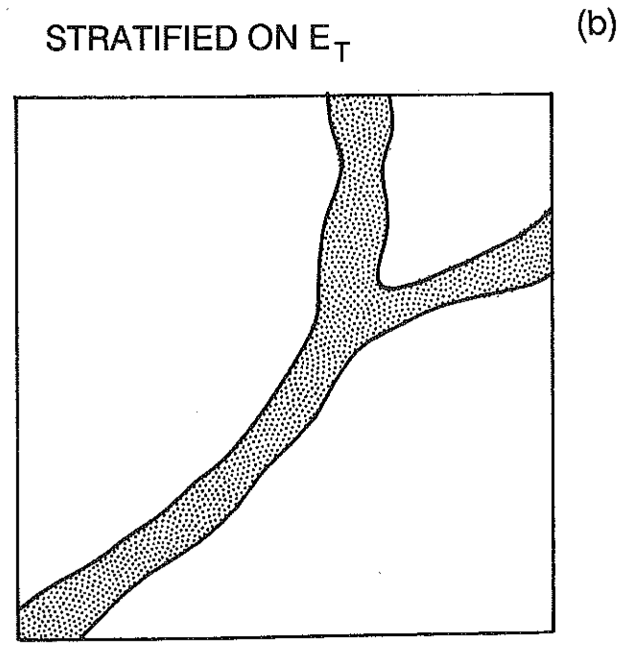


Fig. 6 a. Example of stratification of GCM sized area as on basis of albedo (a) and E_T (b)

b. Hypothesized relationship between vertical vegetation structure and roughness (Z_0)

Two additional points must be made. Parameter values for GCM cells will change over time as a result of changes in both the absolute values of A, E_T, etc., for strata and the relative changes in area of each stratum. As far as the authors are aware the relative importance of the dynamics of the key parameters for heterogeneous landscapes are not well appreciated. The only recent experimental programme that explicitly addresses some of these issues is the International Satellite Land Surface Climatology Project (ISLSCP) FIFE on the Konza National Prairie, USA.

The second point concerns the general applicability of the weighted mean approach outlined above. This is a linear, additive mixture model and it assumes that there is no interaction between components. Even though interaction can be explicitly included in mixture models, it represents an appreciable increase in complexity. For this landscape problem two possible kinds of interaction between strata would involve E_T via advective effects as well as Z_0. This interaction would, most likely, not be significant other than along the strata boundaries.

If there are no interactions between them, then weighted mean regional values can be obtained using the standard procedure of stratified sampling. Obtaining such regional values will be greatly facilitated if, for the region concerned, there exists a characteristic frequency distribution (CFD) of the proportions of any part of the region made up by each 'type', or stratum. One requirement, therefore, is to determine whether a characteristic frequency distribution does exist at some particular scale. If so, that is the appropriate scale at which to sample the landscape in order to obtain regional estimates. The next step is then to investigate whether a change in climate will induce a change in CFD.

If there are significant interactions between the components of the catena or mosaic, then estimating regional values of vegetation function using a stratified sampling approach based on CFD's is not possible.

Three of the surface parameters (A, E_T, Z_0) can be measured for representative landscape components using standard micro-meteorological methods. The fourth, net CO_2 flux, is less readily quantified directly. Interpreted as primary productivity, it can be modelled as a function of P and T (e.g. Pittock & Nix, 1986) as a first attempt to provide an interactive landscape for GCMs. Development beyond this simple function requires inclusion of soil data (depth, texture) and vegetation or crop type. This will involve a very considerable cost in time and effort and should therefore proceed on the basis of sensitivity analyses of GCMs to variation in CO_2 flux.

Research Needs and Recommendations

* 38. Refine, or develop and test, models to forecast the primary productivity of landscapes from P and T for the major biomes. The opportunity exists to use readily available satellite data as part of this modelling process.

* 39. Examine the methods of spatial description of landscapes to determine if statistically based measures (frequency distributions, fractals) can be used to determine natural or intrinsic scales to be exploited in stratification and sampling for ecological and hydrological measurements.

40. Determine whether roughness is of significance to GCMs in forecasting precipitation (P) and where in the biosphere this significance is greatest. Determine the response surface of roughness as a function of vegetation vertical and horizontal structure (patchiness) and the response surface of albedo and E_T as a function of the vertical and horizontal vegetation structure given that these two parameters are everywhere important in GCMs.

REFERENCES

Austin, M.P., Cunningham, R.B. and Fleming, P.M. 1984. New approaches to direct gradient analysis using environmental scalars and statistical curve-fitting procedures. Vegetatio 55: 11-27.

Birkeland, P.W., 1984. Soils and Geomorphology, Oxford University Press, New York.

Box, E.O. 1981. Macroclimate and Plant Forms: an Introduction to Predictive Modelling in Phytogeography. The Hague: Junk.

Corbett, J.R., 1969. The Living Soil, Martindale Press, West Como.

Eagleson, P.S., 1986. Stability of tree/grass systems. In C. Rosenzweig and R. Dickinson (Editors), Climate-Vegetation Interactions. OIES/UCAR, Boulder, Colorado, pp. 106-109.

McKeon, G.M., Rickert, K.G., Ash, A.J., Cooksley, D.G. and Scattini, W.J.,1982. Pasture production model. Proceedings of the Australian Society of Animal Production, 14: 201-204.

Noble, I.R. and Slatyer, R.O., 1980. The use of ital attributes to predict successional changes in plant communities subject to recurrent disturbances. Vegetatio, 43: 5-21.

Pittock, A.B. and Nix, H.A., 1986. The effect of changing climate on Australian biomass production - a preliminary study. Climatic change, 8: 243-253.

Risser, P.G.(Compiler), 1986. Spatial and temporal variability of biospheric and geospheric processes. ICSU Press, Paris.

Rosswall, T., Woodmansee, R. and Risser, P.G., 1988. Scales and Global Change: Spatial and Temporal Variability in the Biospheric and Atmospheric Processes. SCOPE 35., Chichester: John Wiley & Son.

Shugart, H.H., 1984. A theory of forest dynamics: an investigation of the ecological implications of several computer models of forest succession. Springer-Verlag, New York.

Sutherst, R.W. and Maywald, G.F., 1985. Computerized system for matching climates in ecology. Agriculture, Ecosystems and Environment, 13: 281-299.

Walker, B.H. and Noy-Meir, I. 1982. Aspects of the stability and resilience of savanna ecosystems. In: B.J. Huntley and B.H. Walker (Editors) Ecology of Tropical Savannas, Springer-Verlag, Berlin, pp. 556-590.

Wigley, T.M.L. 1985. Impact of extreme events. Nature, 316: 106-107.

Williams, M.A.J.. 1978. Water as an eroding agent. In K.M.W. Howes (Ed) Studies of the Australian Arid Zone III. Water in Rangelands, CSIRO, Australia, pp. 79-92.

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Appendix II

DRAFT REPORT OF THE IGBP COORDINATING PANEL ON EFFECTS OF CLIMATE CHANGE ON TERRESTRIAL ECOSYSTEMS

PREFACE

The members of the Panel are R. Herrera, V.M. Kotlyakov, J.S. Singh, B.H. Walker (Chairman) and D.Z. Ye. This draft report was prepared by me, with inputs from V.M. Kotlyakov and D.Z. Ye. I am grateful to them for their contributions, but accept responsibility for any inconsistencies or errors, and for its present biases. The report follows on previous IGBP documents and the discussions at the first SC-IGBP meeting in June, 1987, and is intended only as a basis for discussion. It will be developed further at a workshop to be held February 29-March 2 in Canberra, Australia.
B.H. Walker
January 1988

Introduction

There are two perspectives for the problems associated with the ways in which changes in climate will bring about changes in ecosystems: A local and regional perspective, concerned with changes in ecosystem properties which involves changes in those properties and processes which will feed back on the atmosphere and further influence climate change.

The research required to resolve these two issues may well require different approaches and involve different sorts of models, and they may therefore need to be kept separate. If it turns out that they can be dealt with in the same models, so much the better. But it would be unwise to try to force a single model approach from the beginning.

In both cases there are direct and secondary effects. In order to simplify the problem, and to make the required research tractable, we consider, in this panel, primarily the effects on vegetation. Although changes in higher trophic levels will also occur, directly, as a result of climate change (e.g. temperature effects on insect development), most of the important changes in animals will be a result of changes in habitat. For this first stage it is therefore valid to focus our initial consideration on changes in vegetation and soil.

Direct Effects

The direct effects of climate on ecosystems fall into two main types:

1. Effects on the performance of the existing vegetation, reflected as changes in such organism and community processes as net primary production, uptake or loss of nutrients, evapotranspiration.

   These processes are determined mainly by changes in the mean values of the plants' environment.

2. Effects on the composition and structure of the vegetation. These effects are brought about through changes in both the mean values and (more importantly) their variance - including the frequency and timing of particular, episodic events which influence demographic processes such as fecundity, dispersal, germination, seedling establishment and age-specific mortality.

In both cases we are concerned with determining the changes in the three, or perhaps four, primary environmental axes which determine the growth and distribution of plant species, namely plant available moisture (PAM), available nutrients (AN), temperature (T) and, perhaps, the quantity and quality of light (L). The direct effects of increased CO_2 in the atmosphere can be considered as one component of the changes in AN. It has already been shown that CO_2 will increase net photosynthesis and also water efficiency under controlled conditions. It is much less clear whether or not there will be significant effects in natural ecosystems which are subject to many interactively limiting environmental factors. We need better empirical evidence, and further discussion of CO_2 is deferred to the last section of this report. We will focus here on soil nutrients.

We therefore need to know how climate change will be reflected in the mean values of PAM, AN, T and L, and in the variance of these values - in particular the frequencies of important, rare events such as major droughts, exceptional wet periods, frequency of frosts, etc. Having determined the changes in the PAM/AN/T/L environment, we then need a predictive model which relates the performance and the composition of vegetation to this environment.

Secondary Effects

Assuming the successful development of the predictive model, the next requirement is to include the secondary effects of climate change. There are numerous possible such effects, but three will immediately need to be considered:

i) Effects on frequency, intensity and extent of fire

ii) Effects on the patterns of land use, including conversion from pastoral to arable, dryland to irrigated farming, etc.

iii) Effects on soil, in particular on organic matter decomposition and nutrient cycling, which will in turn require a knowledge of effects on soil fauna. There will also be longer-term changes resulting from changes in pedogenesis (leaching, rates of laterization in response to temperature changes, etc.)

Scale Effects

All of the above effects are scale-dependent, in both time and space. The scale we must use in regard to predicting the changes in ecosystems that will be significant for Man's use of these ecosystems is much finer than any existing models of predicted climate change. In terms of feed-back on climate the scale is much smaller.

Appendix III

IGBP SPECIAL COMMITTEE MEETING - JULY 1987

VEGETATION - CLIMATE INTERACTIONS

B.H. Walker

1. The findings of the ICSU working group in regard to this topic are summarized as Sub-Appendix I.

2. The working group is to be complimented on a clear and succinct analysis of the problem, and their recommendations, based on careful deliberations, must be acted on by the IGBP.

3. Most of the recommended research is clearly needed and there can be no disagreement as to its potential value. With regard to a few of the recommendations, however, before they are given strong support by the IGBP there is perhaps a need for further consideration of how the results of such research will actually be incorporated into integrated projects, such as the Global Biosphere Models, or how they will contribute to IGBP's objectives in other ways. As examples, following brief discussions with other ecologists, I have some reservations about the potential value of two approaches:

   i) Within the development of GBMs, it is not clear how an increased understanding of transpiration, photosynthesis and respiration at molecular or plant organelle levels can aid in scaling up to landscape level parameterization. It needs to be spelled out in terms of specific mechanisms or relationships which need research.

   ii) I am in favour of an experimental approach to ecosystem function. However, the proposal to initiate large-scale ecosystem experiments will require careful guidelines. IGBP must avoid becoming involved in a wide array of experiments which will not lead to an improved capacity to predict the consequences of global climate change.

   A particular problem is the interactive effects which will occur as the climate changes. For example, will experiments in which water is manipulated without simultaneously increasing ambient temperatures produce appropriate results?

4. In terms of developing an IGBP programme of research, there is a need for three kinds of input from those involved in the area of vegetation-climate interaction:

   i) Integration of existing and forthcoming information into development of the global biosphere models

   ii) Studies of the influence of vegetation on climate at
      - biome level, with global/regional influences
      - regional/landscape level, with local influences

   iii) Predicting the changes in vegetation STRUCTURE and FUNCTION, resulting from changes in climate.

5. In addition to the recommendations of the ICSU working group which covered details of changes in function (mainly changes in production processes), successful models of change will require improved knowledge in the following areas:

i) Predictions of how climate change will in turn alter, at a regional scale, the three primary determinants of vegetation structure and function
   - plant available moisture (PAM)
   - available nutrients (AN)
   - temperature (T)

ii) Predictions of changes in variability as well as in the mean values of environmental parameters. From what we know of plant demography, it is not the change in the mean values of these parameters, but rather the changes in variation and frequency of extreme events, seasonal patterns, etc., that determine change in plant communities. We therefore need estimates of changes in such parameters and properties as:
   - the seasonal pattern of precipitation
   - frequency of "droughts"
   - likely absolute maximum temperatures
   - frequency of frosts (length of growing season)
   - rate of fuel accumulation (fire frequency)

6. In order to translate the predicted changes in PAM/AN/T (including the predicted changes in extreme or other particular events) into changes in vegetation we need to develop the following

i) Application and further development of existing bio-climatic models. These models already demonstrate a fairly close relation between climate and the distribution of both individual species and vegetation types. This is the simplest and most direct approach and the first step should therefore be an attempt to further refine and use such models so as to be able to predict the structure, composition and productivity of vegetation based on climatic and soil parameters. The assumption is that existing vegetation types will shift in accordance with spatial shifts in climate, within the same basic soil types.

ii) In the event that the bio-climatic models are not sufficiently accurate, there may be a need to develop a hierarchical system for classifying vegetation on the basis of plant functional types - i.e. based on characteristics of plants that respond, functionally, to the sorts of predicted climatic changes. As an example, at least in Australia winter rains (low temperatures and high soil moisture) generally favour shrubs and forbs, whereas summer rains generally favour grasses. In place of Latin binomials, plants will be classified as perennial vs annual, deciduous vs evergreen, woody vs herbaceous, etc.

   We will then need models relating the predicted changes in climate to changes in the relative amounts (proportions) of the various functional types of plants.

   Some preliminary ideas on this approach are contained in my presentation to the SCOPE meeting in Bangkok this year (circulated).

iii) For the development of the climate models we need, for each vegetation type, models which relate vegetation structure, composition and function (production) to those characteristics which feed back on climate, viz. seasonal CO_2 fluxes, evapotranspiration, albedo, surface roughness (momentum). To start with we need to ask where in the world changes in each of these three parameters are most probable and most likely to have a significant effect. For example, a decline in leaf area index from 3 to 2 in a forest will induce little change in albedo, but a drop in aerial cover from 66% to 33% in a semi arid rangeland will result in a considerable change.

7. It is important to note that despite any time frame the IGBP might set, the climate will continue to change and the vegetation will consequently, also continue to change. We are therefore analyzing a system that has no equilibrium state and in which the vegetation change is lagging behind the changes in climate. The amount of the lag will differ between vegetation types. Therefore, in order to predict vegetation changes there is a need to estimate the likely lag times associated with each vegetation type and functional group of species, in response to particular degrees and rates of climate change.

IGBP

TERRESTRIAL ECOSYSTEMS AND ATMOSPHERIC INTERACTIONS

Summary of the ICSU Working Group Report

Four research areas are proposed:

1. Large scale modelling of global change
2. Atmospheric chemistry
3. Ecosystem processes
4. Survey, Monitoring and Inventory for Terrestrial Ecosystems

1. Large Scale Modelling for Global Change

Development of Global Biosphere Models (GBM): combined surface-temperature models. Need to extend General Circulation Models (GCMs) to allow study of global biosphere dynamics and feed-back on climate. This requires estimation of

- albedo (radiation fluxes)
- surface roughness (momentum)
- evapotranspiration

These in turn require research at 2 scales:

(a) community or ecosystem functions, general models of plant functioning and ecosystem function to generate variation in (eg) LAI, canopy structure, metabolism as a function of climate dynamics and soil

(b) physiological models, at the plant leaf scale, of transpiration, photosynthesis, respiration and allocation, based on an understanding at the biochemical and biophysical level.

[Note: This approach concentrates on physiology and functioning of existing vegetation. There is an equal need for demographic models which enable prediction of change in mortality, dispersal, germination, establishment, etc. of different functional types of plants under different climatic conditions - e.g. the changes from evergreen to deciduous, perennial to annual, woody to herbaceous, etc.]

2. Changes in Atmospheric Chemistry associated with Modifications of Terrestrial Vegetation

The main issues are production of CH_4, NO_x (NO, NO_2) and CO; which all strongly affect the amounts and distribution of O_3 and OH radicals in the troposphere. The main requirement is for studies of:

i) CH_4 from rice paddies, natural wetlands, and biomass burning
ii) CO from biomass burning and from natural hydrocarbon oxidation
iii) N_2O from biomass burning, natural and agricultural soils (and ocean)
iv) NO_x from lightning and from natural and agricultural soils

These measures need to be used in extending existing GCMs to include transport and transformation of these compounds.

3. Ecosystem Processes

How will ecosystem processes respond to, modify and interact with the changing global environment? Suggested approaches:

i) Improving estimates of ecosystem distribution and of their rate of change

ii) Improving estimates of short-term changes in fluxes through systems over large units
   (- gas flux rates by aircraft over landscape units
   - satellite imagery combined with process studies
   - bio-geochemical cycle studies, over landscape units)

iii) Improved estimates of long-term functional changes in systems
   - a few carefully selected stations with detailed measurements of environmental parameters and of ecosystem functional properties

iv) Improved understanding of system functioning and capacity to predict the impact of the changing environment
   - whole ecosystem experiments: Would include manipulating CO_2, temperature, water balance, atmospheric oxidants, system structure (e.g. species removal), and would be done over scales from m^2 to landscape units.

4. Survey, Monitoring and Inventory

Development of a data base of change in terrestrial ecosystems including information on:

i) Historical records of change (pollen, tree rings, trapped gases, etc.)

ii) Quasi-static conditions - considered to be static for practical purposes, e.g. geology, topography, soil, major vegetation formations

iii) Dynamic conditions - meteorological conditions, biomass, photosynthetic capacity, albedo, etc.

IGBP should concentrate on (iii); and this requires development of appropriate remote sensing techniques and techniques for analysing and integrating the data.

IGBP Reports

No. 1. The International Geosphere-Biosphere Programme: A Study of Global Change. Final Report of the Ad Hoc Planning Group, ICSU 21st General Assembly, Berne, Switzerland 14-19 September, 1986 (1986)

No. 2. A Document Prepared by the First Meeting of the Special Committee, ICSU Secretariat, Paris 16-19 July, 1987 (1987)

No. 3. A Report from the Second Meeting of the Special Committee, Harvard University, Cambridge, MA, USA 8-11 February, 1988 (1988)

No. 4. The International Geosphere-Biosphere Programme. A Study of Global Change (IGBP). A Plan for Action. A Report Prepared by the Special Committee for the IGBP for Discussion at the First Meeting of the Scientific Advisory Council for the IGBP, Stockholm, Sweden 24-28 October, 1988 (1988)

No. 5. Effects of Atmospheric and Climate Change on Terrestrial Ecosystems. Report of a Workshop Organized by the IGBP Coordinating Panel on Effects of Climate Change on Terrestrial Ecosystems at CSIRO, Division of Wildlife and Ecology, Canberra, Australia 29 February - 2 March, 1988. Compiled by B. H. Walker and R. D. Graetz (1989)

No. 6. Global Changes of the Past. Report of a Meeting of the IGBP Working Group on Techniques for Extracting Environmental Data of the Past held at the University of Berne, Switzerland 6-8 July, 1988. Compiled by H. Oeschger and J. A. Eddy (1989)