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Effects of Global Change on Managed Forests

Implementation Plan

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GCTE Forestry Implementation Plan

Global change is anticipated to have major consequences for forestry production. A wide variety of national and international programmes has been launched to address all the scientific issues of global change impact, and, although much progress is now being made, greater collaboration and coordination would be beneficial.

GCTE

Global Change and Terrestrial Ecosystems (GCTE) is one of the Core Projects of the International Geosphere-Biosphere Programme (IGBP). Focus 3, one of the four GCTE Foci, concerns the effects of global change on agriculture, forestry and soils. One of Focus 3's five Activities deals with the effects of global change on managed forests (Activity 3.5).

In 1993 GCTE organised an international workshop in the Charles L Pack Experimental Forest, University of Washington, to consider the global change research needs of forestry. Workshop outputs included a refined Activity 3.5 Operational Plan (Appendix 1) and, following subsequent discussions, a concerted approach for bringing together existing and new programmes within an internationally agreed framework, with established priorities for coordinated experimental and modelling research. The work proposed in this present document constitutes the formal Implementation Plan for GCTE Activity 3.5 "Managed Forests".

IUFRO

IUFRO is one of the oldest international non-governmental organizations, having recently completed its first century of collaborative research among over 716 member institutions in 116 countries with 15,000 scientists. It seeks to provide a framework within which scientists attacking similar problems can cooperate, share information, reduce duplication and obtain all the other benefits of voluntary networking.

Recently IUFRO has made vigorous efforts to associate its activities with those of other relevant organizations and it will intensify these efforts after the United Nations Commission on Sustainable Development considers forestry in April 1995. At its own quinquennial Congress in August 1995 IUFRO will address specifically its responses to UNCSD recommendations and there is little doubt that among these will be a call for greater trans-disciplinary research on global environmental issues of sustainable development. One of the sub-plenary sessions of the Congress will present the findings of IUFRO's own Task Force on "Forests, Climate Change and Pollution", led by Dr Rodolphe Schlaepfer.

FUTURE ACTION

The research proposed relating to managed forests is a framework within which ongoing activities may fit and new ones may be planned, but it does not require formal commitments nor changes to existing voluntary associations; it should be noted, however, that there are advantages in being accepted into the Core Research programme of GCTE. Scientists and organizations interested in participating in the work are invited to contact the GCTE Activity 3.5 Leader, Professor Sune Linder, who is also Deputy Leader of IUFRO's Project Group on the Ecology of Sub-alpine Zones (see Appendix 2 for contact details).

Both GCTE and IUFRO acknowledge the importance of the development of this framework; this document is being jointly published by the two organizations in recognition of the wide range of organizations involved in global change research for forestry, and to help promote international action and coordination.

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EFFECTS OF GLOBAL CHANGE ON MANAGED FORESTS

A strategic plan for research on managed forest ecosystems in a globally changing environment

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SUMMARY

This report is the outcome of a GCTE-workshop on 'Global Change Impacts on Managed Forests', held at Pack Forest, Seattle, April 1993. The intention is that the report should function as a supporting document to the GCTE Operational Plan.

Studies of forest ecosystems occur in all of the four foci within GCTE. The primary aim of the forest-related research is to understand and evaluate potential effects of global change on future structure, composition, and cycling of carbon, water and mineral nutrients, in natural and managed forests and to identify resource management strategies for sustainable forestry and ecosystem management. This will require the prediction of both short-term forest responses to altered climate, disturbance and silvicultural practices, and of effects on long-term sustainable site productivity and biodiversity. The long-term emphasis will require conceptual advances in the capacity to characterise ecosystem sustainability and resilience in response to altered climatic conditions.

The research strategy underlying this plan is to sample a representative range of forest types, growing under various conditions in different parts of the world. Within these the establishment of identical, or very similar, experiments will allow evaluation of the variation of, and constraints on, the productivity and biological diversity of forests. The research plan can be summarised in terms of an overall goal and strategy, as outlined below.

Goal

- To provide a framework for planning and implementing scientific research on the impacts of global change on forests so that the research is consistent in terms of concepts, procedures and data recording, and produces results that can be compared and used to test and validate models.

Strategy

- Models and experiments should be formulated as a basis for quantifying mechanisms of forest responses to global change.

- There is a need for a range of models at different levels with different structures. Process-based production models are beginning to converge and those now available should be evaluated before decisions are made to produce new ones.

- Representative sites should be selected within the forest types considered most important both for wood production and as major ecosystems likely to be affected by global change. Sites will include boreal, temperate, wet tropical, sub-tropical and semi-arid forests, and both managed native stands and plantations.

- Identical - or at least similar - experimental or observational sites should be established along transects with a range of climatic conditions. At some sites the experiments may be simple and at others detailed manipulations and measurements may be made.

- Standard baseline measurements, providing data on site characteristics and climate, biomass and necromass and their distribution, stand characteristics (stem diameters, heights, growth rates, etc.) should be made at all sites.

- Manipulative experiments should include water and nutrition treatments and, where possible, CO_2 concentration and temperature treatments. The latter would normally be associated with detailed physiological measurements.

- Intensive site measurements should include detailed microclimatic and physiological measurements including water vapour and CO_2 flux data, stand and ecosystem carbon (including leaf area) and nutrient dynamics.

- Measurements should be made to follow community dynamics and provide data for succession models, including seed production, seedling establishment and tree mortality. There is an urgent need for good succession models incorporating mechanisms that will allow their use to evaluate the consequences of changing conditions.

- Forests are highly heterogeneous, both spatially and temporally. Geographic Information Systems (GIS) provide a tool that should be exploited to evaluate the implications of climate change for total biomass and wood production across countries and the world. Simulation models can be applied to GIS data bases, with model inputs stored as data layers, or through equations applicable to each cell or polygon, to allow calculation of changes and their implications.

BACKGROUND

Forests cover more than one third of the land surface of the Earth (Table 1). Because forests are long-lived communities the current rapidly changing atmospheric carbon dioxide concentrations [CO_2], the likely rising temperatures and other associated changes in climate will have significant impacts not only on the forests of the future but also on forests currently growing. We need focused, co-ordinated forest research programmes throughout the world to provide the information needed for accurate predictions of the effects of global change on forests and to provide the knowledge required as the basis for appropriate and adaptive management programmes.

Table 1. Estimated area of forest and other wooded land around 1990 (FAO, Forest Resource Assessment 1990 Project). The values are given in million hectares and as a percentage of the total area of forest and wooded land in the world.

Region	Area of forest	Percent of total
Europe	200	5
Former USSR	930	23
North America	730	18
Latin America	930	23
Asia/Pacific	650	16
Africa	610	15
Total	4050	100

This strategic research plan is prepared as part of the core project 'Global Change and Terrestrial Ecosystems' (GCTE) within IGBP. Studies of forest ecosystems occur in all of the four foci within GCTE (Steffen et al. 1992). Within GCTE there is one 'Activity' (3.5) specially designated to study the 'Impacts of global change on managed forests' (Appendix 1). The primary aim of 'Activity 3.5' is to understand and evaluate potential effects of global change on future structure, biomass production, and yield of managed forests and to identify resource management strategies for sustainable forestry in a globally changing environment. A managed forest is defined as any forest that is or has been subject to some form of management action, i.e. manipulation with the view of achieving some specified objective. In most cases in the past this has been wood production, but in many countries there is now a strong shift toward 'ecosystem management'. Managed forests cover the range from plantations, where management includes all silvicultural activities, through natural forests managed for sustained wood production, to natural forests exploited for timber with little or no long-term perspective.

The forest areas of the world are almost equally divided between the temperate and the tropical regions and account for 80 to 90% of plant and 30 to 40% of the soil carbon. In the temperate regions forest and wooded land account for approximately 40% of the total land area. In the tropics the coverage is somewhat lower (36%). Forest and other wooded land thus constitutes the largest component of land use in terms of area. The intensity of management and use of the forests varies both within and between regions. In a recent FAO survey an attempt was made to divide the forested areas into 'exploitable' and 'unexploitable' forests (FAO 1992). The term 'exploitable' was used for forest or other wooded land that is not only in regular and sustainable use as a source of wood, but which is also available and accessible for such use, even if not yet being so used. Using this definition more than two thirds of the world's forested area is 'exploitable' and in Europe and the U.S. more than 90% falls into this category.

Where the primary and over-riding objective of forest management is wood production exploitation may lead to loss of species diversity and alteration of the structure of the forests (e.g. from mixed to even-aged). Exploitation of native forests, without adequate knowledge of the consequences of practices such as clear-felling or "high grading" - the removal of a large proportion of the high quality, dominant trees - has been widespread in many countries. It constitutes management, in the sense that it is action towards a specified end point, but does not include any attempt to manage the producing system. However, there is now a strong move towards the management of forests as sustainable ecosystems.

Sustainability may be defined as the long-term maintenance or enhancement of the productive capacity and biodiversity of forests. Management for sustainability must take into account the physical and biological capabilities of the land, including characteristics such as species composition and the structural and functional attributes of the plant communities, and it must be based on an understanding of ecosystem functioning and processes. Economic sustainability and the implications for social well-being are not considered here, although it is recognised that economic pressures are among the primary causes of exploitive use of forests.

Evaluation of how management actions (in the broad sense used here) affect sustainability requires an appraisal of the resilience of the forest systems; resilience refers to the ability of an ecosystem to return to its pre-disturbance state. In many instances, there may be some critical frequency or intensity of disturbance that exceeds the critical threshold of resilience, resulting in non-sustainable, degraded forest ecosystems or the conversion of a forest to a non-forest ecosystem (e.g. agricultural, urban).

The research plan outlined here provides the basis for co-ordination of international research - a framework within which research directors or group leaders in forestry departments or research institutions, as well as individual scientists, can set their work, with reasonable expectation that it will be consistent and comparable with that being done elsewhere by other groups. It is axiomatic that the research done in a particular region should also provide information pertinent to the problems of management in the region. The plan clearly does not cover all aspects of the research needed to evaluate the likely effects of global change on forests, but it identifies the main areas of concern and the information needed as a basis for both management and policy decisions. It also takes into account the varying facilities, resources and skills available for research at different locations around the world and recognises that there are opportunities for great contributions even from places where access to sophisticated modern equipment is limited.

Because forests are long-lived systems with slow responses, models are essential tools for exploring the consequences of change, as well as providing valuable tools for the synthesis of research data.

The working definition of global change that underlies this plan is given in the next section, together with a series of general hypotheses about the effects of global change on forests. These are intended to indicate the important questions that arise; they will have to be formulated more precisely and explicitly for different regions and forest types. The body of the plan is divided into five main parts: 1) Study sites and transects, 2) Studies and experimental treatments, 3) Measurements and observations, 4) Simulation models, and 5) Data bases and Geographic Information Systems (GIS).

EFFECTS OF GLOBAL CHANGE ON FORESTS:
Definitions and hypotheses

Variables associated with global change, which are expected to affect forests, are: (i) increasing [CO_2], (ii) increasing average temperatures, particularly in the higher latitudes, (iii) probable changes in precipitation amount and distribution, hence changes in water balance in various parts of the globe, (iv) increasing UV-B, and (v) change in the frequency and severity of extreme events (e.g. extreme hot or cold periods, hurricanes, droughts, fires, pest and disease outbreaks).

Changes in land-use and anthropogenic disturbance in terms of pollution must be characterised and quantified so that their effects in relation to global change can be assessed.

The following hypothetical impacts of climate change on forests need to be addressed in experiments. The list is not exhaustive and hypotheses are stated in general terms, and should be re-stated in more focused and testable form (as either positive or negative statements) for particular areas and situations:

- Changes in climate (including [CO_2], temperature, and precipitation) will affect the growth patterns and rates of growth of forests, and hence will change rotation lengths in production forestry.

- The effects of increasing [CO_2] will be suppressed by ecosystem-level feedbacks associated with nutrient cycling.

- The CO_2 fertilisation effect will be detected first on water-stressed sites.

- Increased [CO_2] will affect growth patterns mainly through effects on carbon allocation, particularly increased root production and turnover.

- Increasing temperatures will increase forest growth and development through increased soil organic matter mineralisation and extension of growing seasons in cold climates.

- Increased intensity and frequency of natural disturbances such as wind, fire, pest and disease outbreaks will critically affect future forest structure through effects on tree mortality and regeneration processes.

- Global Change will cause shifts in distribution and composition of forest species.

GOAL

To provide a framework for planning and implementing scientific research concerned with impacts of global change on forest growth and production. This framework should be consistent in terms of concepts, procedures and data recording and produce results that can be compared and used to test and validate models.

STRATEGY

The research strategy underlying this plan is to sample a representative range of forest types, growing under different conditions in different parts of the world. Within these identical, or very similar, experiments should be established along transects of varying climatic conditions with the objective of evaluating the variation of, and constraints on, the productivity and biological diversity of forests. The basic minimum requirement, at each experimental or observational site, is a series of baseline (Level I) measurements and observations, preferably carried out over a long period. Where resources allow these baseline observations should be supplemented by more detailed studies on community dynamics (Level II) and, at some sites, measurements of the physiological processes governing forest growth and productivity (Level III).

All research programmes should be based on appropriate process-models. These are expected to converge towards a universally-applicable suite of forest models, for various purposes, that may have to be parameterised for particular areas but will handle most problems and analyses of forest growth in relation to climate and global change.

If agreement can be reached on standardised recording of primary data, and on their availability for exchange and comparison, progress to improve quality of information and understanding will be rapid. Models should be incorporated into geographic information systems (GIS), to deal with the heterogeneity of large areas of forest, and as a frameworks for the recording and analysis of remotely sensed information.

1. STUDY SITES AND TRANSECTS

Study sites

Selected study sites should be representative of large areas. From the point of view of assessing the impact of environmental conditions, and hence global change, on the growth and performance of forests, it is important that study sites be located in areas where significant change is expected, where there is reason to believe that the forests are likely to be susceptible to change and where forest ecosystems are of socio-economic importantance. Based on these criteria it would be desirable to have study sites in a wide range of forest types and climatic regions. However, in terms of overall priorities (i) boreal forests, (ii) northern hemisphere temperate coniferous and mixed coniferous/deciduous forests, (iii) softwood and eucalypt plantations in semi-arid and sub-tropical regions, and (iv) humid tropical and sub-tropical forests, are considered most important. The rationale for giving these forest types initial priority is:

- The boreal forest biome contains much of the world's available softwood and has high total stores of organic matter. It is predicted that the boreal areas will experience considerable warming as a result of climatic change. In those regions physiological responses to enhanced [CO_2] are likely to be limited by current low temperatures and infertile soils. Recommended study sites include southern Siberia, southern Canada (cold/dry conifers) and Scandinavia (cold/wet conifers and deciduous broadleaf).

- Northern hemisphere temperate coniferous and mixed coniferous-deciduous forests form the basis for most of the world's present timber and pulp industry. Recommended sites include northern Europe, and northern U.S.

- Humid tropical and sub-tropical forests (warm/wet) have the greatest biodiversity. These forests are under intense land-use pressures and may be highly responsive to [CO_2] except where nutrient availability is low. Recommended sites include tropical rainforests in Central and South America, south-east Asia and deciduous broadleaf and coniferous forests in the southern U.S.

- Semi-arid forests (warm/dry) are expected to be particularly sensitive to altered moisture availability, are globally extensive, and are under considerable land-use pressure. Recommended sites include woodlands in Asia and Africa, eucalypt and soft-wood plantations in Mediterranean climate zones, and semi-deciduous forests in the southern Amazon.

Transects

Experiments duplicated across transects can provide considerable amounts of information on the response of forests to environmental conditions. Transects may be relatively short, spanning steep climatic gradients - for example from coast to mountain to rain shadow - or long, across countries and continents. In either case the objective is to set up similar (if possible identical) experiments or sets of observations. Studies along transects where temperature, fertility (as reflected in different soil types) and water relations vary, provide information about the responses and constraints to forest growth. In boreal forests, threatened by rising temperatures, transects should cross the range of potential climates. Transects in humid tropical and sub-tropical forests should cover the range of land-use pressure, the major threat to these forests.

2. STUDIES AND EXPERIMENTAL TREATMENTS

Experimental work should be aimed not only at providing empirical information, but also at understanding the physiological control mechanisms and key processes underlying forest response to environmental factors. These include photosynthesis, respiration, carbon-allocation and storage, litterfall, nutrient uptake, transpiration and water use efficiency, at both the tree and stand levels.

Experiments should address the effects of environmental factors on these processes as mediated through biogeochemical feedbacks associated with the treatments themselves. An example of this might be possible changes in decomposition and nutrient cycling caused by altered litter quality under elevated [CO_2]. The emphasis on process-level understanding acknowledges the lack of fundamental understanding about forest ecosystem carbon budgets, recognizes the impracticality of studying all major forest types and supports the development of general models of forest growth.

Observational studies

Considerable information can be obtained from observational/measurement studies along transects, where a wide range of environmental conditions can be obtained naturally, but in an uncontrolled manner. This information can be greatly enhanced by conventional forestry field experiments. These may involve testing several species or provenances, manipulating tree density (either initially or by later thinning) and fertilisation treatments to vary nutrient availability. Although irrigation may not be a usual, or feasible, commercial management practice, it is desirable that, where possible, irrigation should be used to alleviate water stress in some plots, and to provide information about water x nutrient interactions. It is important that the genetic structure, including within-species variation at each site, is described and if possible quantified to enable analysis of genotype x environment interactions.

Manipulation experiments

Manipulative experiments are invariably carried out on plantations or stands of relatively simple species composition. It is recommended that they include the following factors:

[CO_2]: At sites where detailed physiological studies can be carried out it is recommended that manipulation experiments should be done to determine forest responses to temperature and [CO_2] as well as water and nutrition. Elevated [CO_2] can be achieved in open-topped chambers, open branch chambers (Branch bags) or, as a future possibility, by 'Free Air CO_2 Enrichment' (FACE). Branch bags are the simplest to use, although even these involve considerable technology to control and monitor the [CO_2], air humidity and temperature in the bags. The effects of such treatments and the extent to which the results reflect the response of trees to increased [CO_2] are not yet clear; considerable experimental work is necessary in this area. It is recommended that elevated [CO2] treatments should be ambient + 350 ppm, applied in a step change. This level is sufficiently high to detect a response in susceptible systems, but is not outside the range of predictions for future CO_2 concentrations. CO_2 should be applied day and night, but may be discontinued during certain periods of the year when tree activity is minimal due to low temperatures or deciduous habit.

Temperature: Air temperature may be varied in enclosures and soil temperature by heating. (Controlled soil cooling is technically possible but will almost always be prohibitively expensive.) Guidelines for temperature treatments should be based on the current consensus prediction of General Circulation Models (GCMs). Elevated temperature treatments should be the GCM prediction for a greenhouse forcing equivalent to a doubling of [CO_2]; this will range from relatively large (4 - 8 °C) increases at higher latitudes to minor temperature changes at low latitudes. The temperature treatments should also attempt to match the predicted seasonality of a 2 x [CO_2] climate because changes in seasonality may be of equal or greater biological importance as changes in means.

Nutrition: Whenever possible nutrient x CO_2 interactions should be included in the experimental design. Nutrient treatments should include all essential nutrient elements and repeated fertilisation to maintain "non-limited" nutrient conditions. Wherever possible current understanding of optimal nutritional requirements should be utilised both to minimise nutrient excesses and to target tree requirements accurately. Untreated stands will generally be used as the nutrient-limited condition for comparison.

Water: Supplementation to maintain field capacity should be imposed at all water-limited sites to provide a base-line for comparison of other water related treatments. Natural (rainfall supplied) water levels will generally provide the other treatment conditions. For forests in regions where GCM estimates of temperature and precipitation predict reductions in soil water, treatments might include reductions in water availability by means of throughfall diversion.

Wherever possible, experiments should be planned to run for many years. It is becoming clear that the value of carefully monitored long-term experiments, in which consistent data collection and recording procedures are used, increases steadily with time. The data from such experiments should, if possible, be made widely available.

3. MEASUREMENTS AND OBSERVATIONS

It is proposed that measurements in forest research should be based on nested experiments characterised as either:

- Level I: extensive level; baseline measurements
- Level II: medium level; community dynamics
- Level III: intensive level; process measurements.

Level I: baseline measurements

Level I measurements should be made at all sites. These would include normal measurements that can be made with simple equipment but provide essential baseline information about the state of forests and their long-term growth patterns. Level I measurements accumulated over long periods at many well-characterised sites will provide an extremely valuable data base from which considerable information about forest growth and performance, and the effects of weather and climate, may be obtained.

Models associated with Level I measurements are likely to be large-scale forest production models (see Level III) and dendrochronological models, based either on direct measurement or tree ring analysis. These will improve understanding of the role of climate change in relation to stand development and disturbance frequency (e.g. fire scars; records of extreme cold or drought). Level I measurements are not meant to be used to parameterise large-scale models, but may provide essential information for the interpretation of those models.

Level I tree measurements should include stocking, dominant species, tree diameters at breast height (dbh) and heights, changes in diameter as measured by dendrometer bands, litterfall, and mortality. They provide the basis for standard forestry estimates of wood volume, but should not be restricted - as is usually the case in forestry - to trees with stem diameters above some arbitrary minimum. Frequency of measurements may vary from daily (temperatures) to a few weeks (dendrometer measurements) to annual (mortality). The following measurements are required to characterise experimental sites and the environmental conditions: daily maximum and minimum air temperatures, precipitation, soil depth, texture and percentage organic matter. The sites should be selected to represent the most common forest type(s) in the region.

Level II: community dynamics

There is an urgent need for good successional models that include physiological controls on carbon assimilation and mechanistic descriptions of carbon allocation, nutrient and water use. There are a number of extant models that may be said to meet some of these requirements, but the area requires considerable attention. Research programmes concerned with the problems of species loss or changes in community structure should focus on such models and the measurements needed to test and parameterise them.

Level II measurements are aimed at providing additional information about the factors that cause changes in species composition. Such studies are important for all natural stands since species composition, and hence biodiversity, is considered likely to be significantly affected by many aspects of global change.

The structural characteristics of stands should be described as part of any study on species composition/community dynamics; the measurements include the factors to be measured at Level I, but should include also Leaf Area Index (LAI) and leaf litterfall. Soil temperature and soil water content should also be monitored.

To determine the effects of treatment - or environmental change - on species composition requires observations of seed production, seedling establishment, change in plant cover, and mortality.

Level III: process measurements

Process measurements are concerned with the physiological and soil processes underlying and driving the growth and production of trees; these include photosynthesis, respiration, carbon allocation, litterfall, water use, and mineralisation, uptake and utilisation of nutrients.

There are many stand-level, process-based, physiological models, written for various purposes at varying degrees of complexity (e.g. describing energy absorption and photosynthesis by canopies). Several of these models integrate plant and soil processes. There is now considerable convergence in the general structure of many of these models and it would not be advisable for new research programmes to attempt to develop new models at this level. Careful assessment of extant models is likely to show that there is one or more available that will suit the purpose, and it is likely that code will be available. It may be necessary to parameterise such models for particular stands and sites.

Process-based models are used for both detailed analysis of stand reponses to environmental conditions and as the basis for large spatial scale models driven by remotely-sensed observations (from either satellites or aircraft). The principle underlying the latter models is that net primary production (NPP) is proportional to the amount of absorbed photosynthetically active radiation (APAR), a function of LAI and incoming solar radiation. Climate, nutrients, soils and topography all affect the relationship between NPP and APAR, and this must be determined from first principles for changing climate and [CO_2]. By nesting estimates of productivity within a region, derived from detailed (fine scale) process models, with regional scale estimates of LAI and APAR, the influence of climate change on productivity can be estimated.

To allow estimates of diurnal, seasonal, and annual fluxes of carbon, water and nutrients in relation to environmental influences, Level III models require measurements with a high temporal and spatial resolution of both driving variables and key processes. In addition to measurements and observations required at Level I and II, respectively, measurements should include:

- hourly weather data above the canopy, to include but not restricted to: maximum and minimum air temperature, humidity, precipitation, wind speed, total solar, and photosynthetically active radiation (PAR);

- rates of photosynthesis, respiration, and transpiration in relation to environmental influences, on the scales of leaf, branch, and single trees;

- hourly measurements of CO_2 exchange rates and evapotranspiration for the ecosystem (by eddy covariance) and soil CO_2 fluxes;

- observations to determine phenological controls over seasonal photosynthesis and tissue production, including roots. These observations should include the seasonal variation in LAI, leaf age distribution, carbon allocation, and litterfall;

- carbon (C), nitrogen (N), and phosphorus (P) pools and annual fluxes, including above- and below-ground components;

- measurements of carbon:nitrogen ratios (C:N) in biomass, soils and decomposing litter, and studies of how rates of N and P fixation respond to increased C substrate concentrations in soils and how litter quality and soil temperature affect nutrient mineralisation.

4. SIMULATION MODELS

Models provide a framework for organising and focusing experiments. They provide hypotheses to test, and allow pre-testing of hypotheses to help suggest critical experimental tests. Predictions should be made with existing models before finalising experimental designs.

Models should be used to generate hypotheses that can be tested by experiment or observation. They should be used as experimental tools, and sensitivity analyses conducted to identify key variables and weaknesses in understanding. Model work should, therefore, be done a priori rather than a posteriori. It is not the primary role of models to 'integrate' the observations made in experiments; parameters can generally be adjusted to obtain a good 'fit' to observation without learning about the system or the model. Examples of hypotheses that may be tested are those concerning carbon allocation, phenology and nutrient uptake (see below).

Models provide the only tool that can be used to determine whether certain practices or situations will lead to, or are inimical to, long-term sustainability. Ecosystem sustainability may be evaluated in terms of maintenance of dry matter production, retention of nutrients and the maintenance of genotypic diversity and stand/community structure.

Models also provide the best means of evaluating the likely consequences of various management actions, particularly in relation to the uncertainties arising from global change. Management options to cope with change include the use of different genotypes, increased planting density, fertilisation, thinning, shorter rotations with faster growing species or growing stock with slower growing species/genotypes that are potentially more plastic and resilient. It should be noted that regression-based models - which include most of the models developed as part of traditional forest biometrical research and management - being derived from historical observations, without mechanistic basis, are unable to predict growth responses to different climatic conditions. Process-based sub-models could be employed in this context to show how existing regression-based models can be modified to incorporate climate change effects such as increasing [CO_2]. Similarly, site quality evaluation, traditionally made on the basis of observations of tree growth on a site (which is, by definition, a circular and non-predictive procedure) can only be made on the basis of process-based models driven by weather and including soil parameters.

The need for some particular classes of model has been noted earlier (dendrochronology, community dynamics/successional models, large-scale productivity models, detailed process-based production, carbon allocation, nutrient uptake and water balance models). There is an urgent need to link process-based models to tree population models and hence to produce estimates of the harvestable product, which is the information that forest managers need.

The level of detail incorporated in a particular model will vary depending on modelling objectives, and scientific hypotheses to be addressed. Where experiments are nested, a nested modelling approach is also appropriate and will make it possible to extrapolate in both time and space. Theories validated at the micro-environmental scale can be extrapolated to the stand scale using detailed canopy models which can be used to derive simplified relationships predicting annual biomass production from absorbed photosynthetically active radiation. The latter relationship can be applied to simulate growth on sites with less comprehensive data bases and to predict growth at the regional scale. Data and models at each level of the modelling hierarchy are used to parameterise and validate models at the next level. Process formulations become less complex at each successive hierarchical level. However, new processes and feedbacks become important as we scale up, e.g. soil feedbacks, which are irrelevant in simulating diurnal photosynthetic production, but critical at longer time scales.

5. DATA BASES AND GEOGRAPHIC INFORMATION SYSTEMS (GIS)

Data bases: The technology now exists to record data in computer data bases, in formats that make them accessible and understandable to all who need them. There are enormous benefits in this; the problems lie not with the technology but in the willingness of scientists and managers to agree on the data to be collected, formats and labelling, and data documentation procedures.

In the absence of international agreement it is recommended that all data be recorded in standard data bases and labelled accurately and comprehensively. For example, Level I measurements, to be of value to people other than those who collected the data, should include clear statements about the number of (individual) measurements made, methods used and estimated errors. Local classifications should be avoided, as far as possible. In the case of soils, named classifications may be of very limited value to those unfamiliar with the soils in question. The information that is required about soils, to provide a basis for most data analysis and/or modelling, is their water holding capacity, texture, probable rooting depth(s), and nutritional status. This information should, whenever possible, be stored in its primary form. It is seldom possible to disaggregate classifications into primary data; it is usually simple to derive classifications from primary data, if the classifications are needed for local purposes.

The same considerations apply to forest descriptions. The information universally needed is standing biomass, which can be derived from tree populations, tree size distributions and average height. Information about foliage mass and distribution is also essential for most analyses in terms of processes; some of this can be derived from data on canopy structure (crown size and depth). Additional information, such as the height of dominant trees, is useful. Again, the principle that primary data should be recorded, should be adhered to.

Meteorological data are generally recorded in standard forms, but in the case of forests it is important to know where the data were recorded, in relation to the forest.

The long-term objective must be to develop data bases for each forest type which provide accurate (geo)references for site location, long-term climatic data, properly documented site descriptions and standardised records of research data and observations. (See comments under "Manipulation experiments). Such records, over time and for a number of transects, will allow the refinement and testing of a complete range of models as well as providing invaluable empirical information about the productivity and growth patterns of the world's forests. Such data bases would preferably be held at a central international repository such as DIS (Data Information System). Failing that, increased use of disc-stored data, or data on CD-ROM, properly documented, will serve as an excellent substitute. These can also be used - as has happened in some instances - as repositories for large volumes of research data.

Geographic Information systems (GIS): GIS are spatially-referenced data bases and they serve not only as repositories for information about, and a means of mapping, forest types, soil types, topography, and any other spatially referenced information, but as tools for analysis.

Most forest models are based on the assumption that the stand or ecosystem being modelled is spatially homogeneous. Even in the case of plantations this is (almost) never true. In a natural forest there is always considerable place-to-place variation in stand density and characteristics; the scale of the variation, in terms of the size of the units (polygons or cells) that can be assumed homogeneous, varies with forest type, and is also determined by the requirements of the user. In terms of remotely sensed measurements where the pixel (cell) size is, for example, 1 km^2, variation on the scale of a few metres cannot be analysed. In terms of an analysis of the distribution of forest types across a country or continent, the units of concern may be tens or hundreds of square kilometres.

The GIS packages available allow manipulation of data, so that, for example, it is possible to determine immediately, from data in the computer, the relative areas of different categories, their ratios, or similar information. More importantly, where the input data are held as layers for each polygon/cell, it is possible to apply models to evaluate the effects of change, or particular conditions, across heterogeneous landscapes. This is being done on a global scale for NPP, using satellite-derived estimates of LAI and PAR. It can be done for any variable for which values or estimates of the input data are available for regions. Other examples are water balance and mineralisation (from organic matter and climate data). Weather data, recorded at discrete points, can be interpolated across landscapes using digitised terrain data. The technology has great potential: the expenditure of considerable resources on accurate documentation (in GIS) of forest biomass, species composition and a range of other parameters, is justified; in fact it is arguable that this should have a higher priority for funding than a great deal of more "scientific" research, since without good information about forest resources, and their state, detailed information about processes is of limited value for policy and management purposes.

Given these data in GIS, in compatible formats, for many regions of the world, it will be possible to compare productivity and evaluate the consequences of global change at sites around the world. The use of GIS is essential in remote sensing studies, since these yield information about the variation in forest properties - as identified by their radiation signature - in pixels (cells). Hence GIS provide the means for scaling up from process-based models to the large-scale, simple models essential for wide area evaluation of forest growth and response to climate.

ACKNOWLEDGEMENTS

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Introductory Section from the GCTE Operational Plan Focus 3 Revision (May 1994)

Introduction

Global change presents a formidable and unique research challenge. The world's terrestrial ecosystems are being subjected to changing environmental conditions of an unprecedented scale, both in their rate and in their geographical extent. The ability of human societies to ameliorate, adapt to, and benefit from these rapid changes requires fundamental knowledge of the responses of terrestrial ecosystems to the forces of global change. To answer this major research challenge, the International Geosphere-Biosphere Programme (IGBP) has established a Core Project on Global Change and Terrestrial Ecosystems (GCTE).

The rationale for this Project, and the details of the strategic research plan, are laid out in Chapter 6 of IGBP Report No 12 "The International Geosphere-Biosphere Programme: A Study of Global Change. The Initial Core Projects" (IGBP, 1990), which followed two years of preliminary planning. The first edition of the GCTE Operational Plan (1992; IGBP Report No 21) took the strategic plan and developed it into a framework for the implementation of the research. It represented a synthesis of four international workshops held during 1991, the details of which are available as working papers of the GCTE Core Project.

This revision of the Focus 3 component of the Operational Plan updates the original document published in April 1992, to reflect the further evolution of GCTE Core Research.

The objectives of GCTE are:

- To predict the effects of changes in climate, atmospheric composition, and land use on terrestrial ecosystems, including (i) agriculture, forestry soils, and (ii) ecological complexity.
- To determine how these effects lead to feedbacks to the atmosphere and the physical climate system.

GCTE's operational definition of "global change" encompasses far more than just predicted climate change alone. It includes changes in atmospheric composition, such as the concentration of CO_2 and other greenhouse gases, which have increased and will continue to increase and which have direct impacts on vegetation with or without climate change. It also includes change in land use, as driven by demographic economic, technological, and social pressures. Over the next few decades this human dimension of global change will have a more profound influence on the fate of terrestrial ecosystems than will changes in climate and atmospheric composition; this aspect will particularly important in tropical regions.

The most challenging feature of global change, however, is that these driving forces are not independent but are strongly interactive. For example, population and economic pressures are leading to large-scale clearing of forests in the humid tropics, which is clearly an important contributor to change in atmospheric composition. This change, in turn, will likely lead to global warming, which could then allow the expansion of intensive agriculture toward higher latitudes. This, again, would likely cause further emissions of greenhouse gases to the atmosphere.

This interaction of driving forces, impacts, and feedbacks is the essence of global change. The response of humans to rapidly changing conditions in moving and adapting their agricultural and forestry production systems, and the response of more natural systems through migration, altered competition, and resilience to extreme events will lead to a changing mosaic of ecosystems across the earth's land surfaces. GCTE's goal is to develop a predictive understanding of these changes, robust enough to incorporate projections of direct, human-driven changes in land cover and soil conditions, interacting with rapidly changing atmospheric composition and climate.

The role of GCTE in the overall global change effort is, quite clearly, scientific research. However, given that the results of its research will have important implications for decisions about how to cope with global change, the project will be increasingly drawn into policy issues. GCTE's contribution to these complex policy debates will be in the role of honest broker. It will attempt to objectively prepare and interpret information for international and national bodies with policy responsibilities, in an attempt to clarify the potential effects of global change on all terrestrial ecosystems, be they managed to more natural.

Structure of the GCTE Core Project

The GCTE plan to meet the research challenge is based on a strategy that is global in scope and is comprised of a well integrated set of focused scientific questions. The structure of the programme is designed to ensure cohesiveness by facilitating the flow of people, ideas, expertise and information among its component parts.

The Operational Plan is organised into a hierarchy of *Foci*, *Activities*, and *Tasks*. The four Foci are:

Ecosystem Physiology

Change in Ecosystem Structure

Global Change Impact on Agriculture, Forestry and Soils

Global Change and Ecological Complexity

The first two Foci are designed to provide a fundamental understanding of the impacts of global change on ecosystem function, composition and structure, and their feedback effects. The third and fourth Foci are designed to examine the more specific impacts of global change on systems of great importance to humans, i.e. for the production of food and fibre, and for the maintenance of the Earth's diversity and ecosystem complexity.

The research programmes of the four Foci are closely interrelated, and the boundaries between the Foci, Activities, and Tasks are often blurred; there is much interaction among them. To ensure that the cohesive nature of the overall GCTE programme is maintained and enhanced, two Foci include integrating Activities which draw together the work of those Foci and link it to the rest of the GCTE research programme. In addition, groups of Activities/Tasks that contribute to a cross-cutting theme, such as terrestrial carbon pools and fluxes, are jointly "owned" and managed by two or more Foci as cross-Foci research.

In practice, joint management of Activities/Tasks will be carried out in a number of ways: (i) inclusion of representatives of all relevant Activities/Tasks in planning, implementation and synthesis workshops; (ii) inclusion of representatives of other relevant Activities/Tasks in the network or consortium of a particular Activity or Task; (iii) periodic synthesis reports on cross-cutting themes involving a number of Activities and Tasks. In addition to these more formal mechanisms, GCTE strongly supports and encourages scientist-to-scientist interaction and collaboration across Tasks, Activities, and Foci whenever and wherever appropriate.

GCTE Focus 3: Global Change Impact on Agriculture, Forestry and Soils
[Leader: P.B. Tinker]

The world's terrestrial ecosystems constitute a continuum from virtually pristine to intensively managed and highly modified systems devoted to production. Agroecosystems fall at the latter end of the spectrum and are essential to human well-being. They supply the bulk of humanity's food and fibre, and they cover a large portion of the Earth's land area.

Many of these agroecosystems are already threatened by damage to soil and water resources through inappropriate technology. Major land-use changes, which are part of global change, will greatly increase this stress, driven by increasing demands for agricultural and forest products from a growing population. Climatic and atmospheric changes - the other aspects of global change - will further impact upon these stressed and rapidly changing systems in ways we cannot yet predict with any accuracy. The ability to capitalise on the beneficial effects of global change, while avoiding or reducing adverse effects, will require a strong predictive capability.

While the lack of knowledge over the precise climate in the future makes exact predictions impossible, it is important to be able to predict the consequences of defined scenarios and to identify the most sensitive components of agricultural systems. To this end, GCTE aims to initiate strategic, interdisciplinary research to improve our general predictive ability for selected agronomic species and for forests, grasslands and rangelands. The research results will help national programmes to plan site-related management strategies and adaptive research, as and when climatic change becomes imminent.

There is now no doubt that atmospheric CO_2 and other greenhouse gases are steadily increasing, whereas the likelihood and extent of climate change is still being keenly debated. The most immediate manifestation of global change is nevertheless change in land-use, and is currently most prevalent in the tropics, where social, economic and population pressures drive the process; deforestation and desertification, which both lead to soil degradation, are the consequences of primary concern. In the temperate regions of the world it is less apparent, but predicted changes include, for example, major reallocation of surplus land in western Europe and changing land management in eastern Europe.

Agroecosystems around the world share a number of common characteristics so that an integrated research effort on global change is possible. Although some of the Tasks outlined below may have to be designed for specific agroecosystems, general applicability will be maintained as much as possible. As with other GCTE Foci, the main thrust will be on monitoring, experimentation and modelling; this Focus will however differ from other Foci by including a management component and emphasising the importance of harvestable products of economic importance.

Many nations and international research institutions (e.g. CGIAR, FAO, IUFRO, IUBS) are launching or developing their own programmes in global change issues. The work of this Focus will interact with, and strongly build on, the very large body of existing and ongoing agronomic and forestry related work throughout the world.

Within Focus 3, four major types of production system have been identified: monocrop agriculture, pasture and grazing systems, multi-species cropping (including agroforestry and rotational systems), and forestry. These have been grouped into three Activities.

Key agricultural systems. These include a representative selection of monoculture food crops, together with improved pastures and rangelands; the emphasis in this Activity is on harvestable product, i.e. the usable portion of the crop or animal.

Multi-species agroecosystems. These are the norm in much of the world, be they spatial or temporal complex mixtures. Modelling such complex agricultural systems is in its infancy, relative to modelling monocrop production or even rotation farming.

Managed forests. These encompass the spectrum from intensively-managed plantation crops through more natural forests which are either selectively logged or put to some other use with socio-economic implications.

Two further Activities crosscut these three major areas: one addresses the effect of global change on pests, diseases and weeds and the other addresses the effect of global change on soils. The full list of the Focus 3 Activities and their associated Tasks is given in Table 1, and their rationale and work plans are discussed below. (As GCTE planning has progressed, new Activities have been assigned the next sequential number. While this avoids the possibility of confusion brought about by re-numbering Activities and Tasks, it must be stressed that the number does not imply importance, or indicate any particular logical sequence.)

GCTE research will collaborate with, complement and coordinate national and international studies as appropriate. GCTE-initiated research will be general in nature; devoted to principles rather than local issues; devoted to major crops so that its impact is substantial; and integrative.

The collaborative aspect will be especially necessary for linking to the human dimension, particularly apposite when dealing with ecosystems from which a 'harvest' is taken; global change impact on agriculture and forestry is more than just impact on biology - it is impact on food, wealth, development and people.

Table 1 GCTE Focus 3 Structure: Global Change Impact on Agriculture, Forestry and Soils

A3.1: Effects of Global Change on Key Agricultural Systems

T3.1.1: Experiments on Key Crops with Changed Atmospheric Composition and Climate, on Different Soils

T3.1.2: Modelling Growth of Key Crops Under Changed Atmospheric Composition and Climate

T3.1.3: Global Change Impact on Pastures and Rangelands, and the Resulting Effects on Livestock Production

A3.2: Changes in Pests, Diseases and Weeds

T3.2.1: Global Monitoring Network and Data Sets for Pests, Diseases and Weeds

T3.2.2: Distributions, Dynamics and Abundance of Pests and Diseases Under Global Change

T3.2.3: Weed Distribution, Dynamics and Abundance Under Global Change

A3.3: Effects of Global Change on Soils

T3.3.1: Global Change Impact on Soil Organic Matter

T3.3.2: Soil Degradation Under Global Change

T3.3.3: Global Change and Soil Biology

A3.4: Effects of Global Change on Multi-species Agroecosystems

T3.4.1: Experimental Studies on the Relationship between Plant Species Number and Function in Agricultural Systems

T3.4.2: Long-term Agricultural Experiments Network

T3.4.3: Modelling Complex Agricultural Systems

A3.5: Effects of Global Change on Managed Forests

T3.5.1: Experimental and Observational Studies of Managed Forests

T3.5.2: Modelling Global Change Impact on Function, Structure and Productive Capacity of Managed Forests

Activity 3.5: Effects of Global Change on Managed Forests
[Leader: S. Linder]

From an economic point of view it is an obvious imperative to secure long-term wood supply to timber and pulp industries. Biomass production in less intensively managed forest ecosystems may, however, be equally important since they provide fuel, fodder and other utilities for a large proportion of the world's population. Hence, the term "managed forests" is here used in a broad sense to include forest ecosystems managed and used for purposes other than industrial production. Forest ecosystem is here defined as a system where the trees are a dominant component. Intensively managed urban forests and parklands are here not defined as forest ecosystems. Agroforestry systems are not included since they are studied within Activity 3.4, but links will be established regarding the tree component in such systems.

The primary aim of Activity 3.5 is to understand and evaluate potential effects of global change on future structure, biomass production, and yield of managed forests and to identify resource management strategies for sustainable forestry under changed climatic conditions. This will require the prediction of both short-term forest responses to altered climate, disturbance and silvicultural practices, and effects on long-term sustainable site productivity. The long-term emphasis will require conceptual advances in capacity to characterise ecosystem sustainability and resilience in response to altered rates of input, loss and cycling of carbon, water and mineral nutrients.

The role of managed forests as carbon sinks or sources will be evaluated in close collaboration with Activities 1.1 and 1.4, as well as Activity 3.3. The possibility of increasing carbon sequestering in forest ecosystems by means of silvicultural practices will be assessed. Effects of changes in land-use will, however, mainly be studied within Activities 1.2 and 3.3, with close links to the Human Dimensions Programme (HDP) of ISSC.

The mechanisms which cause productivity to decline and carbon allocation to shift as stands age are poorly understood and need attention for successful long-term predictions. Other major gaps in understanding concern mechanisms for dynamic allocation of carbon and nutrients and how biogeochemical feedbacks constrain growth responses to perturbations such as CO_2 enhancement and nitrogen deposition. Links with Task 2.1.3 will be developed to deal with population dynamic processes associated with regeneration and death of individual trees since these processes are likely to be sensitive to changing climate and may override direct effects of climatic change on forest productivity. Given the need to develop a predictive capability, the overall objectives of this Activity are to develop and validate generic, modular forest growth simulators as tools to predict growth and harvestable yield of managed forests, and to quantify impacts of global change on biomass production and carbon storage at the patch and regional scale. The research will be divided between two closely integrated Tasks.

Task 3.5.1: Experimental and Observational Studies of Managed Forests
[Leaders: S. Linder (boreal and temperate) and J.J. Landsberg (semi-arid and tropical)]

Experimentation and modelling is required to develop quantitative indices characterising sustainability of forest ecosystem processes on specific sites subjected to treatments manipulating

CO_2, climate or supply of water and nutrients. Indices should characterise the rate and extent of post-disturbance recovery of plant and soil pools of carbon and nutrients and may be either based on mechanistic models incorporating the closure of carbon, water and nutrient budgets, or empirically-based. The experiments will monitor both short- and long-term responses to disturbances such as soil warming, altered rainfall, CO_2 enhancement, forest logging, fertilisation, and conversion of land-use from agriculture or grassland to forestry. At the regional scale, as opposed to at the patch scale, sustainability and resilience depend also upon biodiversity which influences the system's capacity to recover after major perturbation.

Predicting the consequences of climate change, including effects on nutrient supply, for leaf area production and retention is particularly important because of feed back on both water balance and carbon accumulation. Factors controlling assimilate allocation and litterfall in relation to nutrition and water status are poorly understood for forests, largely because of difficulties in acquiring long-term quality biomass data necessary for sub-model development and validation. Experimentation is required specifically tailored to develop and test mechanistic models of these processes.

Objectives:

- To determine, through inter-disciplinary field experiments, how components of global change affect forest productivity through alteration of the biogeochemical cycling of carbon, nutrients and water.

- To assess the long-term sustainability of forest production, and disturbance-response of particular sites under specified management regimes.

Implementation

Inter-disciplinary field forest experiments will be undertaken, both as transect studies along gradients of the major environmental variables, and as controlled experiments manipulating the supply of carbon, nutrients and water. The primary goal of the transect experiments is to quantify ecophysiological responses to current environmental variability, and the selection of sites along transects and design of experiments will, whenever possible, be closely coordinated with other GCTE efforts.

Experiments will focus on effects on sustainable productivity. Long-term experiments (greater than 15 years) are required to follow aging effects and feedbacks associated with slowly varying plant and soil pools and in some systems with successional changes in species composition. (Links with Activity 3.3 are required in dealing with impacts of global change on soil carbon and litter decomposition.) A modelling approach, essential because of the diverse nature of forests and their long natural lifespans, will be integral to all experimentation, with models used to guide collection and interpretation of data and to focus attention on process-based explanations of responses.

The following criteria will be stressed in selecting field sites for controlled experiments:

(i) magnitude of anticipated environmental change;

(ii) susceptibility of forest system to change, including likely timescale of ecosystem response;

(iii) scientific and environmental significance of proposed project;

(iv) economic importance of forest production;

(v) existing knowledge of tree physiology and site characteristics; and

(vi) feasibility of the experiment in terms of access to facilities and relevant expertise.

Based on the above criteria, the following systems have initial priority:

(i) boreal forests, which contain much of the world's available softwood and where considerable warming has been predicted, though physiological responses to CO_2 enhancement may be limited by low temperature and infertile soils;

(ii) northern hemisphere temperate coniferous and mixed coniferous-deciduous forests which form the basis for most of the present timber and pulp industry;

(iii) softwood and eucalypt plantations in semi-arid and sub-tropical regions where changes in precipitation may have considerable effects; and

(iv) tropical forests, where warm conditions may lead to a large CO_2 fertilisation effect.

A series of experimental sites should be established along transects representing gradients in temperature and precipitation. If possible, a minimum of one transect per continent (except the Antarctic) will be established. Along each transect sites representing different forest types should be included, e.g. boreal, temperate, semi-arid. One of the most useful applications of transect experiments would be to forest systems which are similar, but occur in different environments. Each main site should include treatments with manipulation of availability of water and mineral nutrients. Where possible experiments will incorporate high CO_2 and soil warming treatments and will follow the same protocols. Two forest experiments along those lines have been established in conifer plantations in Sweden and southeastern USA, respectively, and will be extended to a network of sites representing major managed forest ecosystems of the world.

Links will be strengthened with Activity 1.2 to estimate the effects of altered land-use, and with Activity 2.2 for extrapolation of results to spatially heterogeneous landscapes.

Field research on CO_2 effects will focus on the scales of leaf, branch and single trees using leaf chambers, branch bags and trees enclosed in chambers. A European network of high CO_2 experiments along these lines on a number of tree species has been established, and could play a useful model for future similar research. The programme will draw heavily on links with Task 1.1.1, where whole-ecosystem FACE experiments are planned. Links with Focus 1 modelling activity are also essential in extrapolating from leaf, branch and whole tree measurements to the stand, and in representing biochemical feedbacks. Validation of canopy CO_2 and water exchange submodels should be achieved through linkages with eddy-covariance experimentation conducted under Activity 1.3.

Task 3.5.2: Modelling Global Change Impact on Function, Structure and Productive Capacity of Managed Forests
[Leader: R.E. McMurtrie]

Task 3.5.2 will be closely linked to Task 3.5.1 in that the experiments will be designed to provide data and understanding to aid the development of generic forest growth models. The models developed will be modular and allow options between process-based and empirical sub-models; to some extent, this generic model development will be guided by experience in crop modelling (Task 3.1.2). Relationships employed in generic models will often be simplified from extant forest models such as those developed within the SCOPE project. Model simplification will be achieved by developing a series of nested models of widely differing levels of resolution, ranging from detailed models treating specific processes to comprehensive stand level models with simple formulations.

Detailed models, high in the hierarchy, aid understanding and the development of simpler models that can be applied to forest management and to estimation of regional productivity. The models will be set up to provide clear frameworks and standardised data bases for experimental work at a number of levels and on various aspects of the system.

The simple models must encompass the appropriate mechanisms and processes, so they can be used to predict the response of trees and soils to different and changing climatic conditions and management practices. Models will be used to simulate impacts of regional climate change scenarios provided by climate modellers and to identify management strategies appropriate to maintain production in the short- and long-term under current and altered climates. Process-based generic models encapsulating fundamental physical and biological relationships are intended to supplement and eventually replace traditional, regression-based mensurational models as tools for forest yield estimation. The process-based models will be extended through decision support and geographic information systems (DSS and GIS) to the patch and regional scale.

Objective:

- To develop and test relatively simple, process-based forest growth and regeneration models able to predict yield of a range of forest products for a variety of tree species growing under widely different environmental conditions.

Implementation

A wide range of forestry models currently exists, and this Task will build on this foundation. Rigorous model testing will be achieved by applying several alternative models to a number of existing and proposed experiments, including those established under Task 3.5.1. This activity, building initially on comparative modelling studies initiated by SCOPE, will aim to identify strengths and weaknesses in various modelling approaches and to hasten progress towards robust, flexible and reliable models.

APPENDIX 2

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Pack Forest, Seattle, 12 - 15 April, 1993

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