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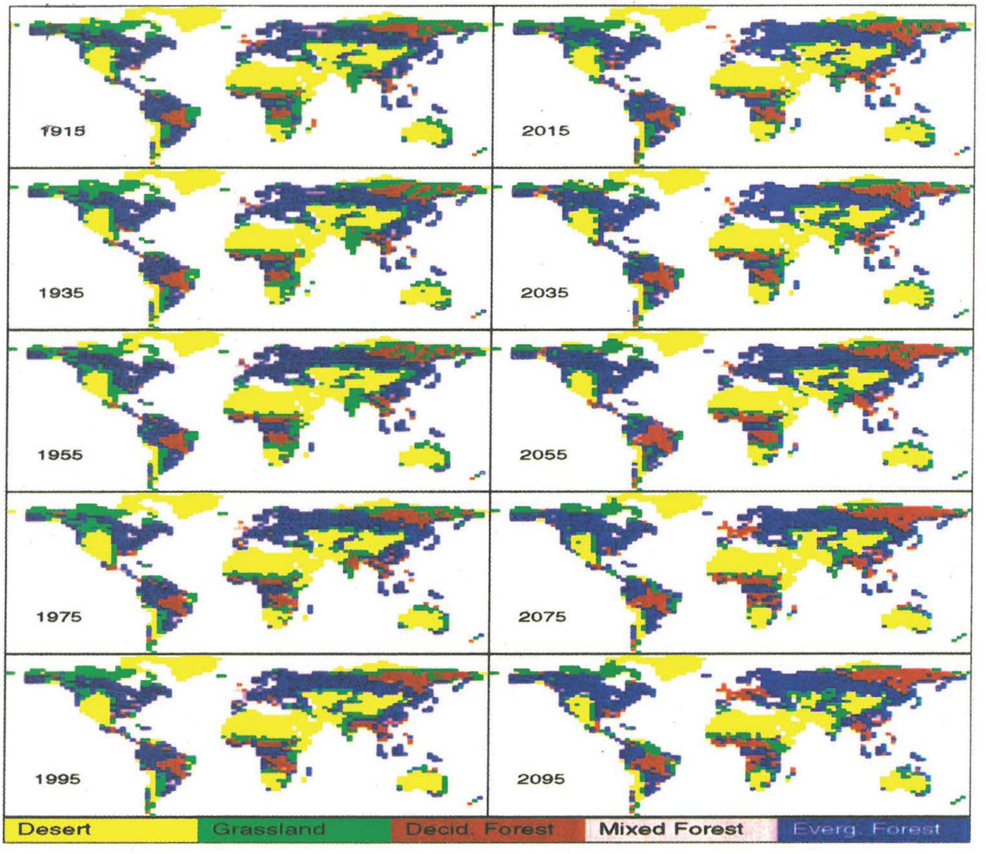
REPORT No. 38



Natural Disturbances and Human Land Use in Dynamic Global Vegetation Models

The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP)
of the International Council of Scientific Unions (ICSU)
Stockholm, 1996

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Natural Disturbances and Human Land Use in Dynamic Global Vegetation Models

A Report of a workshop co-convened by the GAIM, GCTE, LUCC* and IGBP-DIS Programme Elements of the IGBP
Manchester, UK, 1-3 May 1995

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Workshop Report

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Cover illustration: "Vegetation dynamics as simulated by a recent Dynamic Global Vegetation Model (DGVM) for 20 year long time steps during the 20th and 21st century, driven by increasing ambient CO_2 and sulphate aerosol concentration and the associated climate change. The climate simulation is derived from a UKMO GCM simulation, and the DGVM output comes from the IBIS model (preliminary results, kindly provided by Jon Foley, University of Wisconsin)."

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Executive Summary

A current limitation in the projection of vegetation distribution and functioning into future environments is the poor understanding of processes which occur at the landscape scale (a few km^2 to thousands of km^2). Many of these processes are associated with disturbances - both natural and anthropogenic - which modify vegetation from its equilibrium state. This report summarises the findings and recommendations of an International Geosphere-Biosphere Programme (IGBP) workshop which aimed to develop an approach to modelling landscape-scale disturbances in the context of global vegetation change.

The starting point for such modelling is the existing suite of Dynamic Global Vegetation Models (DGVMs), all of which simulate potential vegetation as a function of climatic and edaphic (soil) constraints. Most DGVMs "grow" vegetation by simulation of basic physiological processes such as photosynthesis and respiration, and include diurnal dynamics and seasonal variations in climate. However, none include disturbance and the associated long-term successional dynamics of vegetation.

There are several important considerations in designing general disturbance models: (i) whether the state of the vegetation itself affects the occurrence and intensity of disturbance (*e.g.*, fire); (ii) the frequency and spatial extent of the disturbance; and (iii) interactions between disturbances. A further requirement is that, if at all possible, the model be based on a process-level understanding of the disturbance rather than on a parameterisation of data alone. An example is fire, where experience has shown that a model that relates frequency and extent of fire to the quantity and quality of the fuel load (vegetation) and the weather is a more effective prognostic tool than an algorithm based solely on fire data.

In the global context, all major forms of disturbance - drought, grazing, storms, in addition to fire - will need to be considered. This brings an inevitable requirement for environmental drivers. The most critical variables for disturbances in most ecosystems are likely to be variability measures (*e.g.*, extremes) of temperature (both frost and extreme heat events), moisture, winds (storms), and combinations of these.

Important as natural disturbances are in determining vegetation structure, it is likely that they will be overshadowed by direct human-driven disturbance in the next few decades. Thus, the coupling of human land-use and land-cover change models with current generation DGVMs is necessary to project *actual* vegetation distribution into future environments. The development of human land-use models at the global scale is a major objective of Land Use Land Cover Change (LUCC). These models will include both social and biophysical driving agents and will operate over a range of spatial and temporal scales.

In the context of global biogeochemistry, the impact of human land use on the global carbon cycle, through changes in terrestrial vegetation, is a major research issue. One approach to simulating this impact is based on bookkeeping models, in which rates of carbon change are calculated from the rates of land-use change and the associated per hectare changes in carbon stocks. Such an approach could be combined with DGVMs to give a geographically explicit simulation of the terrestrial carbon cycle via a three stage process: i) the DGVM determines potential, equilibrium biomass as a function of climate and coil properties; ii) the biomass is adjusted for the effects of natural disturbance regimes; and iii) the biomass is further adjusted to account for current and past human-driven disturbances.

A phased approach towards a more mechanistic model of land-use/cover change is suggested. This consists of: (i) a mask for current DGVMs based on satellite data of current land cover; (ii) historical reconstructions of land-use/cover change over the past 200-300 years; and (iii) process models based on a three-dimensional framework of land-use classes, social conditions and biophysical properties, coupled with a matrix of conversions between forest, grassland, wetland and agricultural cover types.

Data will be critical for developing and validating DGVMs that include natural and human disturbances. The most important immediate requirement is the IGBP-DIS 1 km land cover data set, derived from satellite measurements. The current focus in the project is on a global land cover classification at 1 km resolution and validation of the data set. Validation of the DGVMs will be facilitated if they are developed independently of any remotely sensed data, freeing these data for validation. Also, comparisons and validations may prove more effective at the regional rather than global scales, especially for sites where intensive global change process studies will be carried out (*e.g.*, the IGBP Terrestrial Transects).

The workshop made a number of recommendations that will facilitate the early inclusion of disturbances in DGVMs: (i) production of a global database of the nature, extent and frequency of natural disturbances of the world's major biomes; (ii) development of a generic fire and fire/grazing module for inclusion in DGVMs; (iii) production of additional new datasets, such as the 1 km land cover database, digital terrain models, climatic datasets which include extremes and storms, and historical land cover databases; (iv) development of methodologies for disaggregation of land use and land cover data and for the classification of farming systems; and (v) coordination of major global change process and observational studies, such as the IGBP Terrestrial Transects and the LUCC Case Studies.

Preface

This report is the outcome of a workshop co-convened by the GAIM, GCTE, LUCC and IGBP-DIS programme elements of the IGBP * and funded through the IGBP inter-element programme scheme. The workshop, held in Manchester, UK, from 1-3 May 1995, aimed to develop strategies for the incorporation of realistic long-term (decadal) land cover dynamics, both natural and human-driven, in Dynamic Global Vegetation Models (DGVMs).

The specific objectives of the meeting were:

- to review the global-scale modelling developments involving land cover within GCTE, LUCC, and GAIM
- to explore strategies for ensuring the effective coupling of models and model components simulating the dynamics of change in the Earth's land cover
- to assess the suitability of current and planned land cover and land use databases for global vegetation models
- to devise a workplan for the future development of integrated terrestrial models arising from GAIM, GCTE, LUCC, and IGBP-DIS.

This report is the primary product of the workshop, and is a significant step forward in devising and implementing strategies for the construction of integrated, dynamic land cover models.

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(* The LUCC Core Project is co-sponsored by IHDP)

Background

Terrestrial vegetation is sensitive to changes in climate and atmospheric composition. Any future climatic changes, as a consequence of increasing atmospheric concentrations of greenhouse gases, are expected to influence both the functioning and the geographical distribution of vegetation. The nature and rate of these changes are current objectives of many international, (*e.g.*, Global Analysis, Interpretation and Modelling (GAIM); Global Change and Terrestrial Ecosystems (GCTE)) and national research efforts. A current limitation to projecting vegetation into future environments - through a generic research objective described as developing Dynamic Global Vegetation Models (DGVMs) - is the poor current understanding of processes which occur at the landscape scale.

These landscape-scale processes are primarily concerned with natural and human-induced removal, partial removal or modification of natural vegetation to derive vegetation which is different from equilibrium-state vegetation determined entirely as a result of climatic and edaphic (soil) constraints.

The removal or modification of "equilibrium vegetation" at the landscape scale very often occurs through a process called "disturbance". Disturbances, which can be either natural or anthropogenic, affect all terrestrial ecosystems. Events such as wildfire, drought, high winds, flooding, frost, and ice can be as important as other environmental and edaphic conditions in determining the structure and function of terrestrial ecosystems. In some cases, disturbance can dominate the distributions of biomes. For example, fire is responsible for maintaining extensive tropical savannas as is flooding in maintaining hydromorphic grasslands. Human-driven disturbances are often seen as the conversion of natural vegetation into systems managed for the production of food or fibre, for example, arable crops or plantation forests. In many cases, it is a sequence of disturbances or an interaction of different types of disturbance that determines the structure and composition of ecosystems.

A common feature of disturbances is the initial removal of existing vegetation, which allows the potential for new species to invade and change the nature of the vegetation. The new species may migrate naturally from different areas or they may be planted as agricultural or sylvicultural species. The arrival and establishment of new species has a number of concerns. In the most extreme case of replacement of natural vegetation by agriculture, species diversity may be rapidly reduced. Slower changes occur in biogeochemical and hydrological properties of the soil, often at small spatial scales. At the global scale the conversion of large areas of natural vegetation to agriculture may already be exerting a marked effect on climate. This follows from current experiences which show that vegetation plays an important part in the global climate, through influences on energy transfer on the monthly to yearly time scale and over decades through influences on global biogeochemical cycles, in particular water, carbon, and nitrogen.

Workshop Aim

The aim of the workshop was to bring together groups of researchers all of whom had a major research focus in understanding and modelling how disturbance - both natural and human-controlled - influences the responses of terrestrial ecosystems to changing climate and atmospheric composition. Inclusion of this understanding in DGVMs will bring their projections closer to reality, with the specific aims of improving the linkage of the terrestrial biosphere to the atmosphere in general circulation models and for regional assessments of vegetation change in its own right.

Two kinds of terrestrial disturbance need to be considered (Figure 1). Changes in atmospheric conditions, as evidenced by increasing atmospheric CO_2 and changing climate, are important determinants of land use. In some instances natural vegetation remains the dominant land cover, in other cases, particularly when the climate is appropriate for agriculture or sylviculture, the original natural vegetation is modified by human use. Less extreme human modifications include the use of grasslands for pasture and selective harvesting of forests. In general, natural disturbance is seen (Figure 1) as maintaining the current status of natural vegetation, while human-driven disturbance leads to the conversion of modification of natural vegetation.

Both natural and human-induced disturbances exert a feedback - currently incompletely known - on the atmosphere and climate system. Although it is difficult to determine the impact of such changes in the land cover on the physical climate, there are some early indications that the conversion of forests to agriculture in the mid-latitudes has led to a significant cooling of the climate through an increase in the winter albedo.

Within the context of this inter-Core Project workshop, it was recognised that all Programme Elements have overlapping interests in the development of a research programme to quantify current and future geographical distributions and processes of natural and human-induced disturbances. In terms of the general description of this research (Figure 1), GAIM is concerned with melding all aspects of the atmospheric, oceanic and terrestrial interactions, *en route* to a general earth system model, with current-day data provision by Data and Information Systems (IGBP-DIS). LUCC, aims to investigate the interacting influences of changing climate, atmospheric composition and human activities on the land cover, and the use of this land cover at different scales. GCTE has a major aim in developing a DGVM, which will project a representation of actual vegetation into future climates, simulating dynamic ecological and agricultural responses to transient changes in climate and CO_2. Other IGBP Core Projects which are likely to benefit from DGVM and disturbance developments are Biospheric Aspects of the Hydrologic Cycle (BAHC) and International Global Atmospheric Chemistry (IGAC).

This report first describes dynamic global vegetation models as a tool for investigating future changes to the earth's land surface. It then examines several aspects of natural disturbances - the importance of landscape phenomena for global vegetation change, approaches for modelling disturbances and their application to DGVMs, and the driving variables and data requirements for simulating natural disturbances. The report then focuses on human-driven changes to land cover and land use, with sections describing the dynamics of land use and techniques for projecting changes in land cover and land use. Validation issues are also discussed, and the report concludes with a series of recommendations for future research directions.

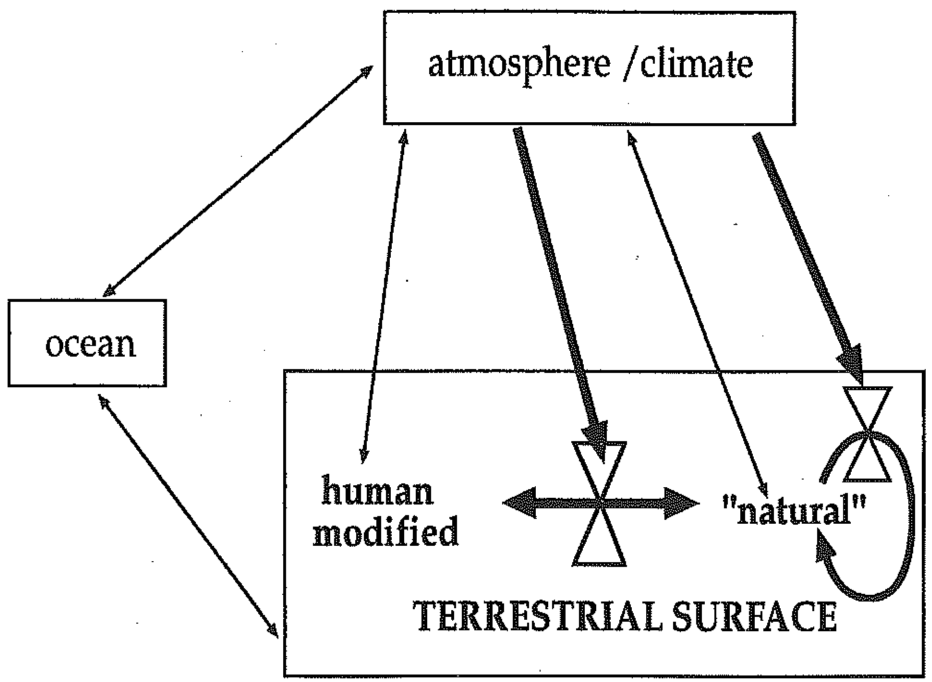

Figure 1 Simplified diagram of the Earth system, focussing on the disturbance processes (triangular symbols) which connect "natural" (potential) to actual vegetation. The circular heavy line indicates that natural disturbances are an intrinsic part of vegetation dynamics. The straight heavy lines represent the influences of: i) atmosphere/climate on natural disturbances (*e.g.*, storms, fires); ii) human disturbances (*e.g.*, land over conversion) on natural vegetation; and iii) atmosphere/climate on the relationship between human and natural disturbances.

Dynamic Global Vegetation Models (DGVMs)

Introduction

A number of research teams around the world are working towards the completion of a DGVM. No DGVM is yet completed; however, general approaches to the product are similar. DGVMs divide the surface of the earth into a series of grid cells of a particular size - currently and usually a uniform 0.5° grid. Vegetation is represented in each of the grids in a variety of ways. In some cases (*e.g.*, Potter *et al.* 1993) vegetation is initialised using data from satellite remote sensing. This approach can, in principle, be used in a DGVM as the science to be added would be concerned with ways of changing the initial vegetation in an ecologically realistic fashion. In other approaches (*e.g.*, Woodward *et al.* 1995) a global-scale climatic and soils data base is used to drive vegetation process models for each grid cell. The process models can be growth models which construct plants, or models which can define the productivity and structural limits to the growth of plants. The process models need to be able to respond to at least seasonal variations in climate, and if linked to a General Circulation Model (GCM) will most likely operate at a one-half to one hour time resolution. In order to predict the yearly and decadal effects of changing climate on vegetation structure, there needs to be some form of memory component to the modelling, which simulates realistic temporal dynamics of vegetation response to climatic changes. This memory component could be achieved by plant growth or patch models, but they need to be operable at the global scale. In addition, the rates of growth need to be sensitive to the shorter-term changes in climate simulated by the process models. The final component is disturbance, which needs to be introduced into each grid cell, at an appropriate frequency, with the effect of allowing new species or functional types of plants to migrate into and establish within the grid cell.

The proposal of a DGVM is clearly very ambitious and some of the inherent problems of the approach are only just becoming realised. A major issue which has been a concern in GCMs is the relatively coarse 0.5° scale of the typical DGVM grid. This scale is approximately 50 km by 50 km, and many vegetation processes and disturbances can occur within this scale. These sub-grid scale phenomena could be described by a simple distribution function (Emanuel 1996). However, operation at a 1 km by 1 km scale might allow all of the processes to be modelled explicitly rather than parameterised. The greater resolution would greatly increase the computing requirements, but this could probably be resolved. A major advantage of the smaller scale would be the capacity to model some (but not all) of the disturbance events at the scale at which they occur. This would diminish the problem of averaging non-linear processes and would allow a validation or comparison potential with the 1 km remote sensing data base soon to be available from IGBP-DIS. A finer scale of operation would have the potential to blur the boundaries between adjacent cells and allow the vegetation boundaries to be tailored more exactly with topographic boundaries - a feature which may improve the capacity to predict processes of species migration. The finer scale of resolution may also ease the description of soil properties which are not easily aggregated.

A problem yet to be resolved is the implied change in both spatial and temporal scaling within a DGVM. For example, DGVMs may explicitly model processes at the scales of leaves, canopies, whole stands and biomes. Each step may entail new limiting processes which need to be either explicitly modelled in the DGVM, or which need to be emerging properties at each scale change. For example, at the leaf level, a doubled CO_2 concentration can lead to a 40% increase in the rate of photosynthesis, but at the biome scale the major effect of CO_2 enrichment is seen in semi-arid regions, as a consequence of increased vegetation water use efficiency (Woodward, personal communication). Some of these scaling problems will be incorporated when DGVMs are incorporated in GCMs, as this will provide a fully interactive environment, *i.e.*, from climate to vegetation and vegetation to climate. However, planetary boundary layer models may need to be incorporated in DGVMs to aggregate spatially heterogeneous processes of energy exchange.

The importance of landscape scale (km) phenomena

DGVMs represent the surface of the earth as a series of grid cells of a particular size. At any time the vegetation in each of these cells is described in most models by a single state vector - *i.e.* , it is of a particular type and successional stage. This vector can be elaborated to represent a series of different stages but this will carry additional computational load and parameterisation effort. Thus, the tendency has been to represent the vegetation in each cell as a single point model. An important question in developing a DGVM is how phenomena at a landscape scale affect the dynamics of the vegetation.

A landscape is an interacting set of contiguous patches covering an area of a few km^2 to thousands of km^2. Many critical processes that dominate the interactions between the biotic, abiotic and human processes emerge only at this scale (*e.g.*, fire spread, nutrient redistribution, meta-populations, human settlements). It is at this level that most decisions about environmental management are made (*e.g.*, farming, crop selection, urban planning).

Currently a gap exists in the modelling of important processes at the landscape scale. The reductionist tendency in the natural sciences has led to most models being designed to deal with much smaller scales, *e.g.*, hypothetical points or small patches of vegetation. A "patch" is an idealised location in which it can be assumed that many individual plants exist and a wide range of interactions such as shading, competition for water and nutrients *etc.*, occur but which is small enough that every plant fully interacts with every other plant. Thus, detailed spatial relationships between the individual plants can be ignored.

Some modellers have tackled larger spatial units by linking together a series of patch models with a selected set of inter-patch interactions. The heavy computational loads of this approach mean that the processes and interactions that emerge at landscape scales via such models have been little explored. Another approach is to define simple rules about the interactions between the elements of the landscape and to explore the impact of changing the intensity or frequencies of some of the interactions. This approach is limited by our ability to define the rules. Experimental studies at the landscape scale are difficult and observational studies are usually confounded by numerous uncontrolled variables.

Another approach has been to accept the need to synthesise landscape models from models derived from smaller scales. This approach requires a suite of models of vegetation change of different resolution. The models are linked in the sense that the output from a more complex (high resolution) model can be used to parameterise a simpler model. For example, the biological effects of different fire regimes in a detailed patch model can be explored and used to estimate the probabilities of mortality of different species. These life-history data can be used to parameterise a simpler model that can be applied to a gridded landscape. Moore and Noble (1990) have also explored transforming moderately complex models into more mathematically tractable semi-Markov processes. The semi-Markov representation of the model reduces running of the model to accessing a look-up-table. This means that they may be incorporated into a geographical information system (GIS) as another data layer.

Noble (personal communication) has developed a version of the vital attributes model of Noble and Slatyer (1980) operating on a grid. A simple fire spread model is incorporated which allows fires to spread from cell to cell depending on the vegetation composition of the cells. The vital attributes model itself provides a simple but comprehensive description of changes in community composition of a representative stand in response to disturbances. The gridded version provides the opportunity to explore the differences in predicted vegetation dynamics between point and landscape versions of the same model. Preliminary results show that for many vegetation types (*i.e.*, combinations of functional types that are available at a site) the dynamics predicted by the point and landscape models differ significantly. Essentially, the landscape version develops a pattern of community types with patches of fire-prone communities maintained by frequent fires alongside patches of communities that resist fire spread. The average site composition can vary significantly between the point and landscape versions even where overall fire frequency is adjusted to be the same. The amount by which they differ is very sensitive to both the vegetation type and the fire regime and as yet no simple rules have been found to describe this sensitivity.

General disturbance models and their application to DGVMs

Most of the models described above can be used to simulate the effects of natural disturbances on ecosystem dynamics at the landscape scale. Although modelling such effects at the global scale is in its infancy, a number of techniques are being developed to simulate them. An important consideration is whether the state of the vegetation itself affects the occurrence and intensity of disturbance. For example, disturbances by climatic extremes such as wind or frost are essentially independent of biotic influences, and DGVMs treat such events as external processes. On the other hand, the state of vegetation has substantial influence on disturbances such as drought, fire, and insect outbreaks.

Frequency and spatial extent also affect the perceived influence of disturbance on vegetation. Commonly occurring events are often viewed as intrinsic to the ecosystems they affect, and models represent these as aspects of climate or the environment. At the other extreme, rare events are perceived as extrinsic and disastrous. In models, such infrequent but catastrophic events tend to alter states instantaneously. Between these common and rare events are sporadic or intermittent disturbances. Models often represent these randomly occurring events as stochastic forcing functions, perhaps derived from disturbance models that treat, among other factors, the dependence of disturbance on the state of the vegetation.

Interactions between disturbances are important. Interacting disturbances can substantially alter ecosystems, when the same events occurring independently do not. For example, fire following drought can cause almost complete mortality in a plant community when fire alone does little long-term harm to plants. Similarly, repeated disturbance events can be significant where a single event is not. The first fire in a region may cause little damage, but a subsequent fire may eliminate virtually all vegetation. In many instances, regeneration is more sensitive to disturbance than are other aspects of vegetation dynamics. For example, fire or flooding may kill tree seedlings but not harm established, large trees of the same species.

It appears feasible to incorporate fire, drought, temperature extremes, and wind into DGVMs. With improved topographic data, surface hydrologic models can probably be adapted to treat flooding as well. However, at this stage, insects, herbivory, and disease are significantly less tenable.

Perhaps the most important natural disturbance, in a global change context, is fire. Experience indicates that models are a more practical means of treating fire than is an algorithm based solely on fire data. Generic fire models can simulate the occurrence, intensity, and extent of natural fire within DGVMs. These fire models can be derived from numerous models that are now working well for specific regions and ecosystem types. In a general fire model, the probability of fire occurrence is a function of fuel and weather as well as the number of days that fires have occurred in the region and the rates of daily spread of those fires. Fire intensity depends on fuel and the weather at ignition. Fire temperature largely determines the effects of fire on vegetation.

Derivation and calibration of fire models require data on seasonal fire frequency at any point and on average fire area for each ecosystem type. Data on fuel accumulation and fire weather are also required. In addition to fire frequency, data are needed on the number of fires on large land units each year. At continental to global scales, remote sensing data appear to accurately characterise fire occurrence but not intensity, duration, spread, or the number of fires. Within a DGVM, fuel can be derived from vegetation and dead organic matter state variables. Fire frequency can be characterised for each biome from data and will also depend on the state of vegetation. Rates of fire spread are more difficult to treat.

The incorporation of flooding and drought into DGVMs is based on climatic data, but requires higher spatial and temporal resolution data than are required to characterise climate as it affects other vegetation processes. Biology strongly mediates drought. Thus, DGVMs must inherently treat components of the water balance that determine drought conditions. Topography must be specified with sufficient resolution to characterize run-on and run-off from each land unit represented within global models. Currently available topographic data lack the spatial resolution required to simulate inundation on flat, low-lying areas where hydromorphically-maintained ecosystems occur. Similarly, data on soil characteristics are in many instances too coarse to simulate drought patterns and their influence on vegetation. Progress on continental-scale runoff and river basin models is encouraging; however, again these models are spatially too coarse to simulate detailed influences of drought and flooding.

Several initiatives can expedite a broader understanding of natural disturbance to terrestrial ecosystems and its inclusion in DGVMs. First, an assessment is needed to identify significant types of disturbance within each biome and their effects on the extent of the biome and its major plant functional types. This review activity can be coordinated by a post-doctoral researcher interacting with specialists for each biome. The assessment can draw heavily on organised field study areas, including the IGBP Terrestrial Transects (Koch *et al.* 1995 (IGBP Report No. 36)), and in addition to qualitative summaries of disturbances, should assemble available data on the occurrence and intensity of disturbances and their impacts on vegetation and patterns of recovery.

A general fire model that can be incorporated into a DGVM can be assembled over the next 18 months to two years by adapting existing regional fire models. The task requires a review of existing models, focussing on groups that are developing wildfire models, and then the formulation of a general model drawing on the approaches and implementations identified by the review. The work must also involve interaction with those groups developing DGVMs to ensure the compatibility of the wildfire model.

It is important to test the modules incorporated in DGVMs at a representative selection of sites. The IGBP Terrestrial Transects are ideal for such tests. As part of the recommended review of disturbance that will include these transects, data should be assembled to allow simulation of disturbance responses. It is particularly timely to analyse the importance of treating surface hydrology in DGVMs. To facilitate such tests, high-resolution digital elevation models should be developed for each IGBP transect.

Natural disturbances: Driving variables and data requirements

As noted above, there is a strongly perceived need for the development of a generic fire model which could be readily applied to any area of the terrestrial surface. In addition, this generalised fire model would need to have the capacity to project human-modified fire regimes. An important underpinning for this effort is the collection and dissemination of appropriate data sets, such as the currently developing IGBP-DIS global fire frequency data base.

A global emphasis on natural disturbance indicates a need to consider all major forms of disturbance, which include other forms such as wind-blow, drought and grazing in addition to fire. This brings an inevitable requirement for environmental drivers. Not all required driving variables for disturbance models are climatic, but indeed many of them are. Also, the models of interest in the IGBP context should be sensitive to climate change, and hence there is a particular interest in those disturbances that indeed are driven by climate. In addition to well-known climatic parameters such as temperature and precipitation, global-scale fields of humidity, or preferably dew point temperature or water vapour pressure deficit are also important requirements for most DGVMs which are currently being developed.

Useful climatic drivers need to be found by identifying the optimal compromise between *data needs* and *data availability*. No new monitoring programs are likely to be set up for climatic variables in the near future, although satellite-based systems may allow better spatial coverage for some variables. Data availability is therefore constrained by what is frequently observed by the standard meteorological networks, combined with the limits of techniques for gridding (interpolation) that are available. Data needs are a function of: (i) the type of disturbance being considered; and (ii) the nature of the functions and processes being built into the particular model component. To a large extent, however, the development of the disturbance model is going to be data-driven, and the availability of the climatic data is therefore necessary to be clarified at an early stage of model development.

Climatic data will have to be used either for calibration/validation of the model or for analysis of future scenarios. This implies that we need independent but consistent data sets for the past (observations) and the future (models) - in other words, the model-derived data should be of a kind that is comparable to the observations.

The most critical variables for disturbances in most ecosystems are likely to be variability measures (*e.g.*, extremes) of:

- *Temperature:* frost and extreme heat events,
- *Moisture:* floods,
- *Winds:* storms,
- *Combinations* of these: weather conditions with high risk of droughts (high temperature, low rainfall), fires (dry conditions + available fuel) or insect outbreaks (various particular weather conditions).

Extremes can be identified generally on the basis of the likelihood of recurrence for the particular event. More pragmatically, they can be identified as average annual minima/ maxima, or extremes observed over defined longer periods (*e.g.*, 30 years, perhaps also defined as a particular period such as 1961-1990). Each of these variables has its own particular confines of availability.

- Extremes of *temperature* are found in temperature records and can be gridded to relatively high resolution on a global scale. It is important to distinguish weather generators (which require data being provided in the form of statistical measures of variability) from gridded observed time series (which, within certain limits, can be used as replacements for weather stations). This gridding of time series data is a new development - we currently assume that this is feasible to a resolution of 5-10 km, but only with time steps between 7 and 10 days (ongoing project, currently not resolved). Time series data of this kind will be needed for identification of the temperature extremes, but also for the combined effects such as drought or fire condition assessments. Gridding will provide different levels of plausibility for different regions, depending on station density and regional weather variability.
- Extremes of *moisture availability* are not appropriately described by rainfall measurements alone. Instead, they require hydrological models to be applied to both rainfall and other weather variables, in a Digital Elevation Model (DEM) context, to generate risk assessments for either floods or drought conditions. Precipitation, however, can be derived from weather stations in a similar way to temperature

(gridding or weather generator) - it must be noted that the spatial variability is higher for precipitation than for temperature and hence more stations are used for plausible grid estimates.

- *Wind* data are highly sensitive to local conditions around the observation station, and many of those are biased because of the location of these stations near large surfaces of grass and concrete (international airports). Wind is also a variable with highly skewed frequency distributions, and gridding techniques that can acount for this skewness are probably not available. The only exception is perhaps wind data from agrometeorological or forest meteorological research stations which could be used for assessments of disturbances at those sites.
- Data for the *fire* module can be derived from the other sources mentioned above (details obviously depend on the method being used to simulate fires).

Scenarios of future changing climatic variables as input for the DGVM can be developed using several methods. It is important to note that currently no GCM is known to be capable of directly reproducing the present pattern of extreme weather events at the Earth's surface - there is hence little to be expected for future climate scenarios from these models. However, it is possible to derive scenarios by investigating more fundamental trends from climate simulations (or from other considerations), and to apply these to one of the several weather generators now available. This could be done, for example, by prescribing changed or unchanged ranges between mean and maximum temperatures, *etc.* This theme shall not be explored in greater depth here, but it must be mentioned that an important requirement for any weather generator is physical consistency, such as algorithms that produce rainfall not only at the rates and intensity being prescribed in the parameterizations, but also at times when humidity and temperature are in ranges that are consistent with the occurrence of rainfall.

Human Land Use

As described in the previous sections, DGVM development is dependent on incorporating models of natural disturbances into the current process-based models of plant and vegetation function and structure. In addition to the time needed to develop generic models of disturbance, and to accumulate the data needed to drive these models in current-day validations or tests, there is a need to define and incorporate the rules and complexities of landscape-scale processes. After these significant developments have been achieved, DGVMs will be capable of projecting *potential* vegetation into future climates. However the necessity for projecting *actual* vegetation into the future will require the incorporation of human land use and land cover models into the DGVMs.

The impact of humans on natural vegetation is clear to see following deforestation. However, many more effects occur with long term consequences and impacts on secondary vegetation. For example, soil carbon levels in the central USA decreased by 50 % during the first 50 years of cultivation and started to increase during the last 40 years (Figure 2). The increases during the last 40 years were primarily due to increased C inputs into the soil that results from extensive fertilizer inputs, improved tillage practices and improved plant varieties. Model projections into the future and model simulations of the past, using *CENTURY* (Parton *et al.* 1994), are sensitive to assumed land use patterns, which need to be reconstructed from a variety of historical land data from the last 100 years. The type of information needed to run the model included plant yield data, and information on the crop varieties and rotations, tillage practices and crop harvest practices (Figure 3). This type of information is necessary to simulate properly the carbon input levels and soil temperature and water, which control the turnover rate of soil organic matter. Soil trace gas flux models also require this type of information since CH_4 and N_2O fluxes are influenced by fertilizer application, soil N mineralisation rates and soil tillage practices.

Different ecosystem models have been developed for simulating the long term dynamics of carbon and nutrients in natural and managed ecosystem. These models could be used to simulate the fate of C, N and P in plant-soil systems during the last 300 years for global managed and unmanaged ecosystems. The major limitation in using these models is the lack of historical land use data. These data need to include a thorough description of the agricultural farming systems and forestry management systems used during that time period and a spatially explicit time series description of the land use patterns. We also need to know the frequency of major disturbances for unmanaged ecosystems (*e.g.*, hurricanes, large wind storms and fire frequency).

This regional consideration of the impacts of land use change on ecosystem processes indicates both the necessity for including human land use effects for appropriate projections of ecosystem behaviour and the complexity of information required to project future or past land use effects on ecosystem activity. The requirement for completing a DGVM with actual vegetation, and at the global scale, can only be satisfied by a global-scale treatment based on models of past, current and future understanding of changes in human land use activities. One ultimate goal of these models will be to discriminate the effects of natural disturbances from human-caused disturbances. To do this, it will be

necessary to develop geographically-referenced, multi-temporal models of land use and land cover change which interact with DGVMs.

The development of human land use models at the global scale is a major objective of LUCC. The primary emphasis of LUCC is to gain a better understanding of the driving agents of land use and land cover change. These driving agents include both socially- and biophysically-derived and mediated factors which operate over a range of temporal and spatial scales (Figure 4). Large-scale social and biophysical driving forces which operate at global scales influence land use changes, which actually operate at much finer scales. In practice, land-use/cover change occurs at the scale of the unit of production, but may be manifested regionally, or globally. This scale-dependency inherent in the analysis of land-use/cover change is a key issue for building quantitative and accurate LUCC models. To do this it will be necessary to match the scaling of social driving forces with biophysical driving forces. In other words, hierarchical LUCC models will need to be explicitly integrated with hierarchical DGVMs if we are to get the LUCC models right. LUCC models need the feedback from the physical and biological environment, which is a major point of cooperation and collaboration with GCTE and GAIM.

A likely approach is shown diagramatically in Figure 5. Land use and cover change in multiple ways. They can change as a result of: (i) independent changes in biophysical drivers; (ii) human activity, either directly or indirectly; (iii) be mediated through the biophysical realm; or (iv) through a more complex chain of human activity and feedbacks from the natural environment. Thus, LUCC operates in tandem with changes in the natural environment, and in fact the interactions between land-use/cover change and vegetation mutually influence each other and must be accounted for in building LUCC models. A limited example of such a LUCC model is incorporated in the *IMAGE* 2 model (Alcamo 1994). This model aims to address climate change and evaluate relevant policies; changes in land use and cover are important aspects.

The problem of scaling is clearly demonstrated in examples from tropical deforestation, a major agent of vegetation change globally (see Skole *et al.* 1994). In the Brazilian Amazon for instance, the problem of land cover change is complex and cuts across many scales of analysis. In the case of deforestation, regional trends are influenced by large-scale external forces but mediated by local-scale conditions. A three-level, interdisciplinary approach to the study of deforestation in Brazilian Amazonia seems appropriate.

The overall approach to developing a generalised global model of land-use change would start with direct measurements of the rate, location, spatial pattern, and temporal characteristics of deforestation. Satellite remote sensing is a promising tool for objectively making these measurements at different spatial and temporal scales, from large-scale assessments of regional trends to local-scale analysis of complex dynamics. Although regional-scale satellite data alone might form the basis for empirical models with limited predictive capability (*e.g.*, spatial trend or diffusion modelling), mapping of deforestation at scales of 1:100,000 to 1:500,000 with remotely sensed data would establish the regional context for integration with socio-demographic data from agricultural and demographic census documents. Such integration would provide useful information on land use, tenure, and management.

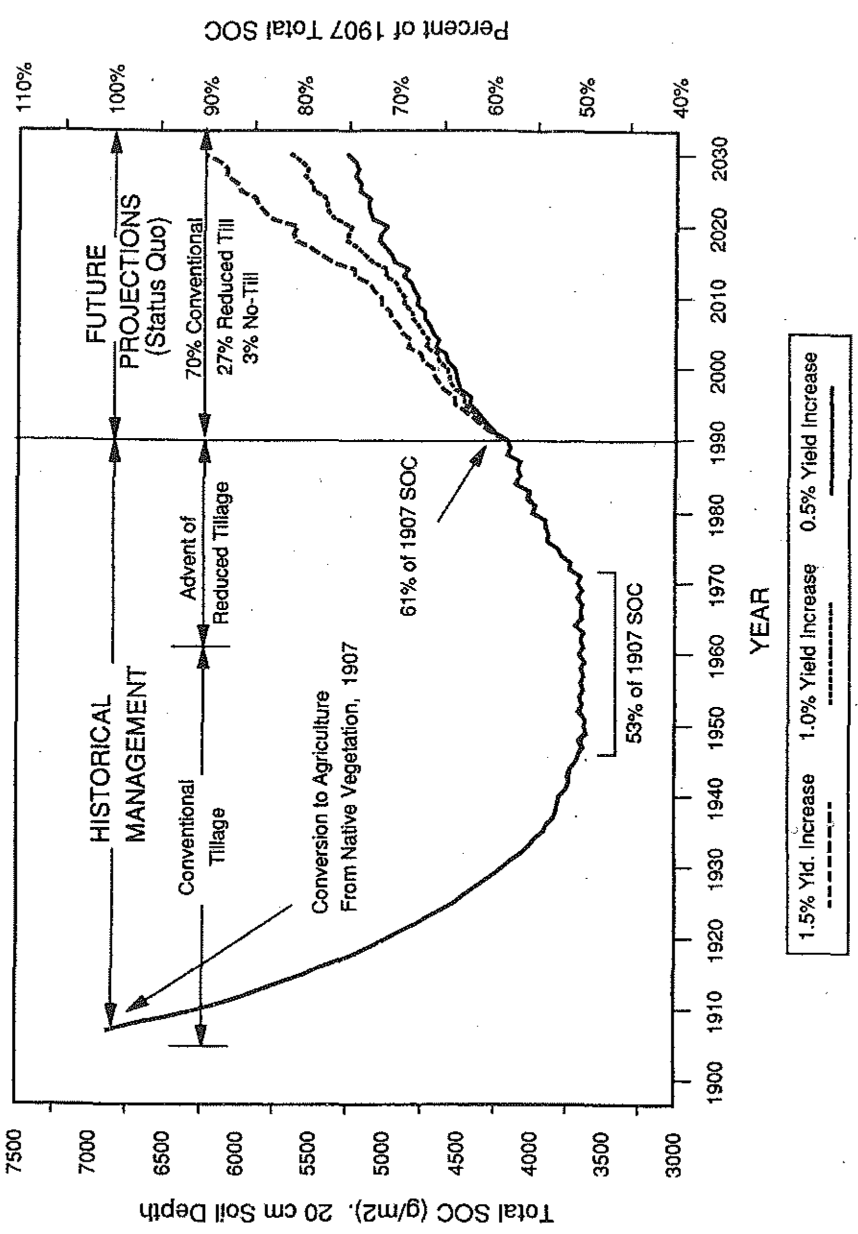

Figure 2 The effects of land use (cultivation) on soil organic carbon in the Central Great Plains of North America (modified from Donigian *et al.* 1995)

At a second level of analysis, case studies and field investigations could be carried out in conjunction with multi-temporal, high-resolution satellite data at 1:50,000 to 1:100,000 scale to gain insight into local-scale dynamics of deforestation, abandonment, and secondary growth turnover. These case-study analyses would use survey research and statistical data from census documents to define the parameters that control local land-use strategies, which would in turn illustrate how changes in land use affects changes in land cover. Complementary to this view is the work of Moran *et al.* (1994) and of Hecht (1993), which describes the important role that local conditions play in determining land use and individual economic strategies.

The causes of deforestation may also significantly relate to external institutional and economic factors; thus, an elucidation of driving forces cannot be made with satellite data and field studies alone. In Brazil, the factors responsible for deforestation in the Amazon originated far outside the region. They involved land-tenure changes in the south of Brazil and changes in the rapidly developing national economy, to some extent catalysed by excess petro-dollars and international lending. The substitution of machinery for labour, which was an important component of national agricultural modernisation efforts, affected the forests of the Amazon. Migration to the Amazon was partly a response to conditions and processes far removed from Rondonia and not solely the product of Brazilian population growth. Thus, deforestation is a more complex problem than simply there being too many people.

Political, institutional, and economic forces establish and modulate long-term conditions. Thus, it would be necessary at a third level of analysis to define the large-scale external factors and conditions that influence deforestation in the Amazon. The causes of Amazonian deforestation could then be considered in an international context.

Dynamics of land-use change

Both GAIM and LUCC have significant research activities into global-scale changes in human activities over historical periods. These studies extend backwards in time for 200 to 300 years, encompassing changes since the onset of the industrial revolution, but with more extensive studies over the contemporary period of the last two decades, with the developing potential for extending into two to three decades of the future. A number of needs will be satisfied by the historical perspective. The approach will indicate the past sensitivities of natural vegetation to human influences. The current actual terrestrial vegetation is partly the result of historical influences, including changes in human land use, and these historical influences have strong effects on biogeochemical cycles, such as for carbon, nitrogen and water. These biogeochemical cycles interact with vegetation and climate. The historical changes in human land use are dynamic and a knowledge of the control of these dynamics is central to the development of DGVMs.

The impact of human land use on the global carbon cycle, through changes in terrestrial vegetation, is a major research concern in understanding the control of the global carbon cycle, and therefore future climatic changes, by land and ocean (Houghton *et al.* 1983; Siegenthaler and Oeschger, 1987). The historical measurements of atmospheric CO_2 from ice cores (*e.g.*, Friedli *et al.* 1986) provide a constraint within which historical accounting of ecosystem modification and change must fit. The constraint provided by the ice cores

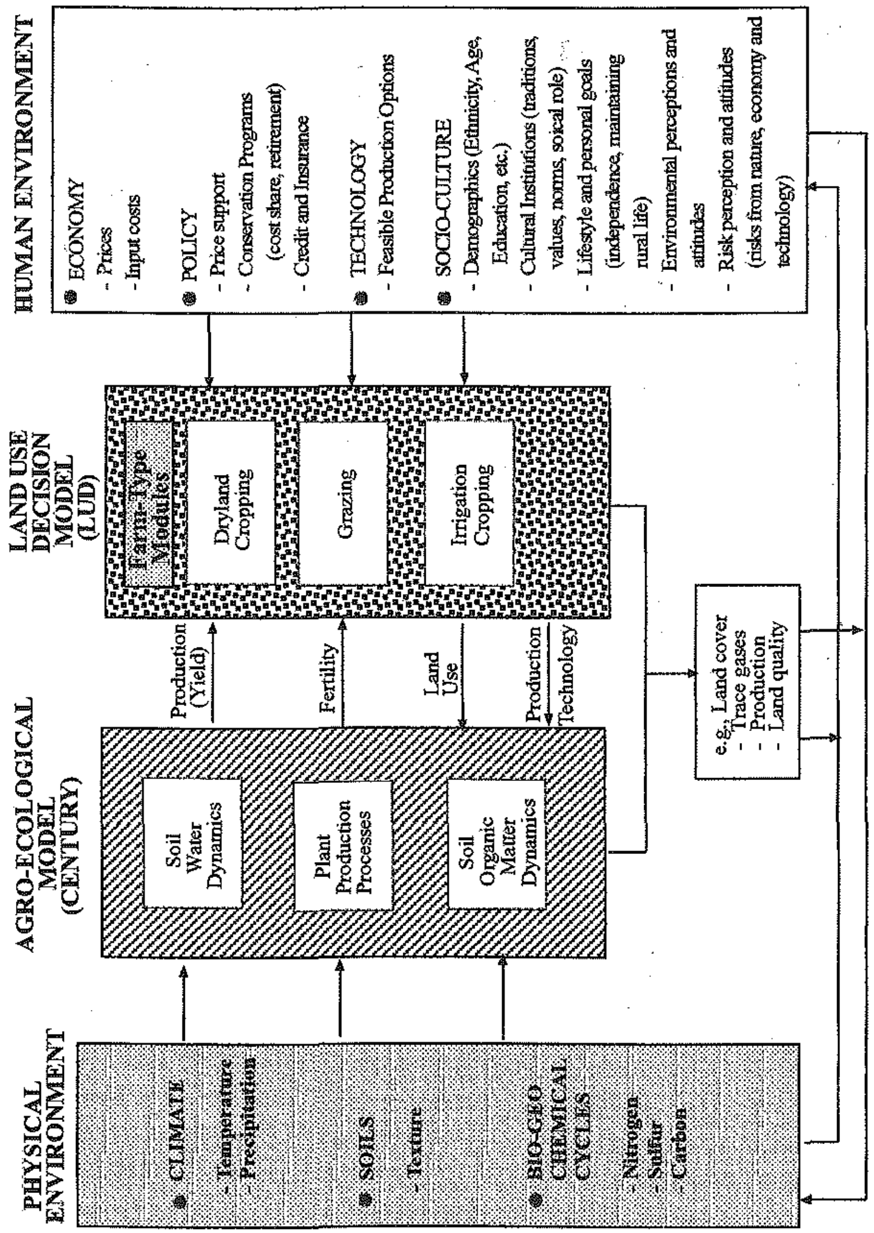

Figure 3 Conceptual model of land use in the Central Great Plains of North America (Riebsame et al. 1994).

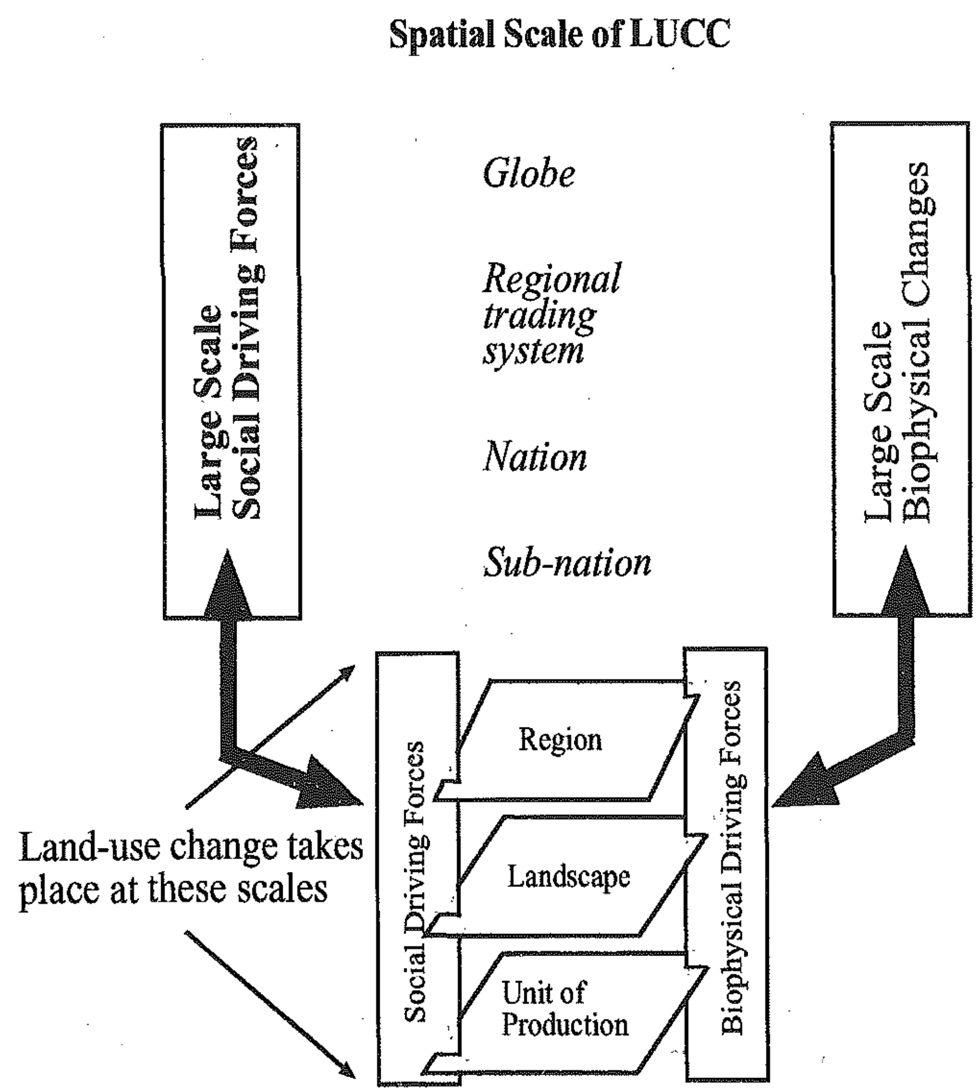

Figure 4 The spatial scales over which the social and biophysical driving forces of land-use change operate.

has been a major stimulant in the development of earth system modelling and in the development of compilations of terrestrial land use change since the onset of the industrial revolution. Since the early 1980s data have been compiled to document global changes in land use that affect the storage of carbon in terrestrial ecosystems. The approach requires two types of data: rates of land-use change and per hectare changes in carbon that follow a human-induced disturbance.

The types of land use considered by Houghton (1995) include conversion of natural ecosystems to cropland, pastures, and shifting cultivation, abandonment of these agricultural areas, logging (and regrowth), and afforestation. The approach ignores ecosystems not deliberately affected by human activity, and so natural disturbance cycles (*e.g.*, fire and insects) are ignored, as are possible changes in carbon storage associated with CO_2 fertilisation, N deposition, or variations in climate.

Land-use data are aggregated. The world is divided into 9-10 geopolitical regions, each with 3-8 natural biomes or ecosystem types in addition to the several types of land use. Data cover the period 1850 to 1980 or 1990. Although the bookkeeping model computes the annual flux of carbon, the rates of land-use change are generally average rates that apply over ~ 25-year intervals for the early part of the 140-year record and over ~ 10-year intervals for the more recent decades. The approach accounts for all of the carbon initially held in the disturbed ecosystems: live vegetation, soil carbon (to a depth of 1 m), detritus, and harvested products. The annual flux includes the lags in carbon release and accumulation associated with decay and growth of ecosystems disturbed in years prior to the year for which the flux is calculated. Model calculations show a release of about 120 Pg C from global changes in land use over the period 1850 to 1990 (Houghton 1995). The global annual flux generally increased over this period from about 0.35 Pg C/yr in 1850 to 1.65 Pg C/yr by 1990. Forests accounted for more than 80% of the flux, temperate zone grasslands for most of the rest. The early part of the interval was dominated by emissions from temperate zone ecosystems; since 1950 the emissions have increasingly originated from tropical countries.

In addition to the globally integrated historical land-use data set of Houghton *et al.* (1983) and Houghton (1995), there is other work (Leemans and van den Born 1994, Esser and Lautenschlager 1994, Klein Goldewijk and Battjes 1995) which provides a geographically resolved indication of land use. The workshop recommended an immediate interest and requirement for geographically referencing the Houghton global data. These global totals are strongly constrained by global carbon models and so there is some accuracy in these reconstructions. The interest will be in geographically locating the changes and making comparisons and evaluating differences with the Esser and Leemans products.

It was estimated during the 1980s that the flux of carbon from temperate and boreal zone countries was close to zero, in contrast to recent estimates that carbon has accumulated in the forests of these countries. The difference may be the result of different data used in analyses. Recent studies, based on data from forest inventories, include the accumulation of carbon in growth following fire and insect outbreaks as well as in growth following harvest. Whether they consistently account for mortality in addition to harvest is unclear.

The long-term flux of ~ 120 Pg C is considerably less than the net release calculated from inversions of ocean models with historic CO_2 concentrations. The inversion by

Sarmiento and Sundquist (1992) determined a net release of 25 Pg C over the period 1850-1990. The difference between this net release and the release from land-use change (120 Pg C) suggests that about 95 Pg C has accumulated in the vegetation and soils of ecosystems undisturbed by changes in land use (or in ecosystems deliberately disturbed and responding to changes in the global environment ignored in the land-use change analysis).

As data on land-use change become available from satellite data of high spatial resolution, there is an opportunity to increase the accuracy of flux estimates by linking geographic variation in deforestation rates with geographic variation in biomass and soil carbon. The challenge is to determine biomass at the time and place of disturbance. As biomass is constantly changing in response to both natural and human-induced disturbances, one approach for estimating initial biomass is to measure it directly. Global coverage would require satellite data, but satellite microwave data are currently of wavelengths that saturate at ~ 15 t dry wt/ha. Airborne radars may distinguish above ground biomass to 100-150 t dry wt/ha, but aerial coverage would be restricted.

Alternatively, one might determine geographically-specific biomass in several steps:

Step 1 Determine maximum biomass with a DGVM as a function of climate (and soil fertility)

Step 2 Adjust the biomass to account for natural disturbance and time since last disturbance

Step 3 Adjust biomass to account for current and past human-induced disturbance.

Data requirements might be satisfied with the same high resolution satellite data used to measure rates of land-use change.

Human land use and land cover projections

The development of DGVMs which project the distribution of actual vegetation into the future is currently most limited by methods of incorporating human land-use effects. At present the most likely method for incorporating this land use is by applying a mask on the natural vegetation. A mask based on satellite data is available at a 1° resolution (de Vries and Townshend, 1994). This will be an important initial product for estimating the nature of the climatic feedback due to the presence of converted vegetation.

The satellite mask will be a useful first step. However, the history and nature of land use changes over at least the previous century will be a critical requirement for running DGVMs in a transient mode. Here there is an expectation that the DGVMs should run from the onset of the industrial revolution, integrating the human-induced and natural disturbances so that an actual current-day vegetation is projected, with appropriate underlying soil properties (*e.g.* Figure 2) which can only result from these long term runs. Therefore the second product for DGVMs, and other biogeochemical models, will be the gridded Houghton land use map, tested against the Esser and Leemans global maps. This second product could become available on a one year time-scale.

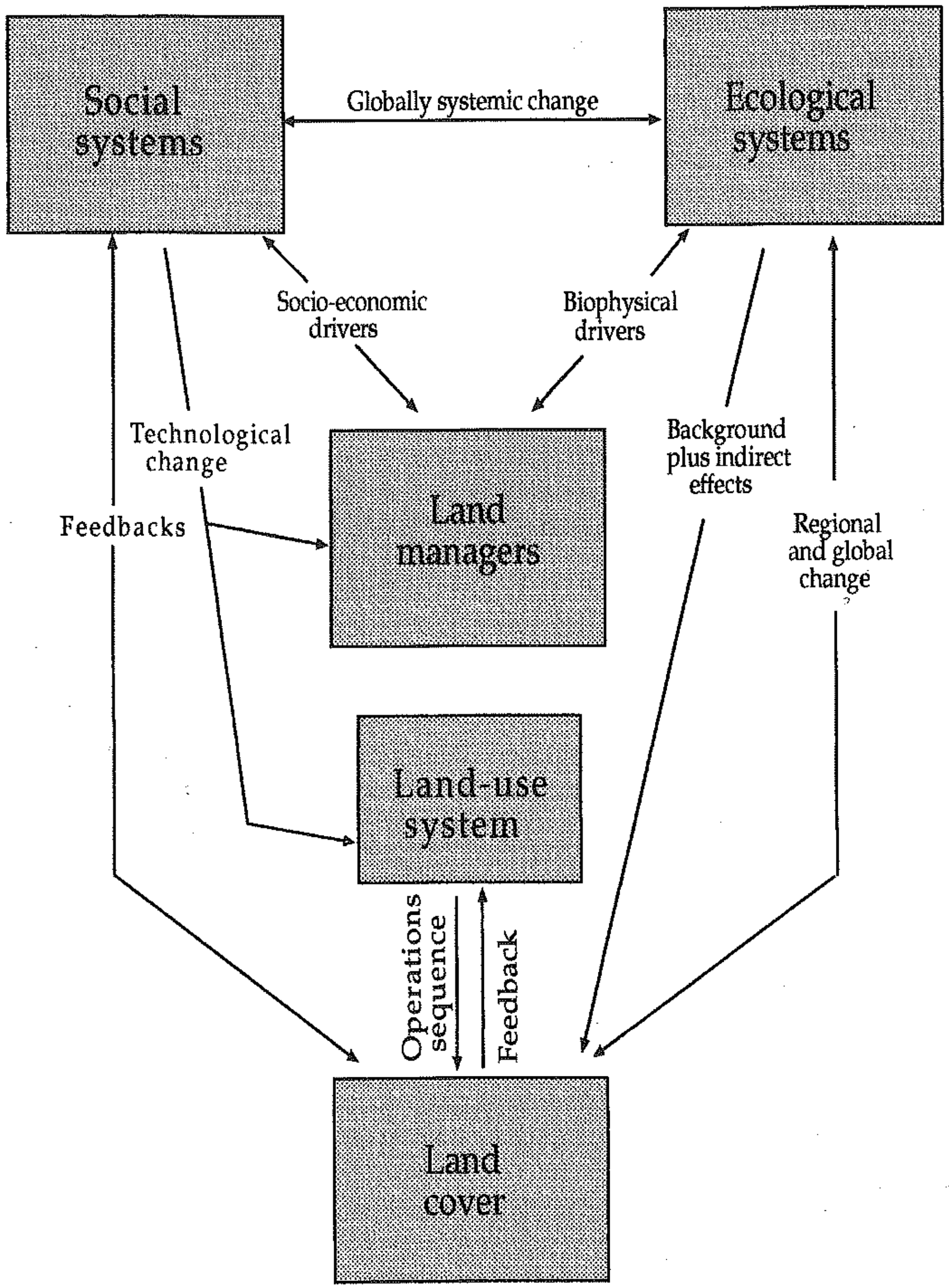

Figure 5 A potential framework for understanding and modelling land-use/cover change.

The third step in the historical reconstructions of the previous two or three centuries will be a LUCC and IGBP-DIS product, perhaps within three to four years. The plan is that both land cover and land use change should be documented, although areas having undergone relatively complete conversion to agriculture should be the main thrust of the reconstruction effort, while modification of natural cover types will be more difficult to document — realistically, a "best effort" product is anticipated in the latter case. The time intervals over which changes are to be averaged may become longer as the analysis is pushed back in time. Annual increments in the recent (20 year) past may be expanded to 25 year increments over prior periods.

The goal is to construct a matrix of conversions between forest, grassland, wetland, and agricultural cover types for most areas of the globe during different historical eras. The data will be collected as inventories of these various cover types, so net conversion rate estimates (rather than gross changes) are anticipated. High resolution case studies should be possible in data-rich areas.

A three-dimensional model framework should be developed for data-rich areas, with axes for land use classes (*e.g.*, after FAO system, in preparation), social conditions, and biophysical properties. For the land use classes, a minimum set of defining attributes would include stocking densities for grazed lands, crop types and rotations, irrigation versus rain-fed areas, system inputs (fertilizers and mechanization), and outputs (manure, yields, and residue management). Points within the 3-D model space should serve as historical "indicator" types for land use management systems that could be considered characteristic of larger regions. A "logging" analogue (similar to this "cropped" system framework) should be developed also.

More research is required in rule-based methods for redistribution of land cover and land use attributes from extensive "polygon" representations into smaller grid cells. Likewise, research is needed on the methodology for determination of the appropriate grid cell resolution (starting from the nominal 0.5° size) for detecting changes in land cover and land use. It is also possible that pollen and sediment profiles could serve as proxy validation data for the historical reconstructions.

It is proposed to evaluate the accuracy of the 300 year reconstruction by two methods: (i) start with an "initial" pre-disturbance (1700 A.D.) DGVM map and march forward to eventually match 1 km Advanced Very High Resolution Radiometer (AVHRR) (IGBP-DIS) map for all land cover types; and (ii) start with a 1 km land cover map and project backwards to 1700 using historical checks at variable temporal intervals. Some areas in the 1700 DGVM map will be affected by concomitant climate variations, which will be incorporated in the land cover characterisation (*e.g.*, ecosystems in the southwestern USA). No solution was proposed, which means that the 1700 world would be (wrongly) assumed pristine with regard to human impacts, except in areas of well-documented anthropogenic disturbance.

Data requirements for land-cover change

LUCC also plans to assess regional and global changes in land use and land cover for the last 20 years and forwards for the next 10 years. This is viewed as a diagnostic product which involves development of the integrated DGVM with the human-driven land cover and land use component. Data sources for immediate use include TREES, 1 km Landsat Pathfinder, MARS, FIRES, Africover, FAO Agrostat (1991) and urban population data sets. The importance of case studies was emphasised. The need for coordination of several existing efforts (IGBP Terrestrial Transects, LUCC case studies, 1 km map confidence sites, high resolution sites) was raised.

An important data set for the model developments in the current period is the satellite-derived DIS 1 km data set. DIS began the 1 km land cover project in 1992. This has the goal of collecting, archiving and processing daily data from the AVHRR for all terrestrial surfaces and then deriving land cover data sets from this archive for the IGBP Core Projects. The work has been co-ordinated by the IGBP-DIS Land Cover Working Group (LCWG). There are now over 70, 000 satellite scenes available in the 1 km project's archive. Most of these data have been assembled into a coherent global archive and radiometric, geometric and atmospheric corrections and compositing are carried out to give 10 channel data sets (including visible, near-infrared, thermal and vegetation index data) mapped to the Interrupted Goode Homosoline Projection (Eidenshink and Faundeen 1994). Global composites are available for the period 1 April 1992 to 30 September 1993, both on a media tape from the Eros Data Center (Sioux Falls, USA,) and through the World Wide Web at: http://edcwww.cr.usgs.gov/landdaac/1KM/1kmhomepage.html.

Recognising that the IGBP Core Projects have diverse information requirements and that, subsequently, there is no single land cover product that will meet all requirements, the LCWG is undertaking a sequential programme. The project focuses on four main actions:

Action 1 A global land cover classification at 1 km resolution

Action 2 Direct parameterisation of key land cover variables (*e.g.*, albedo and NPP)

Action 3 Functional classifications of vegetation / land cover (*e.g.*, seasonality)

Action 4 Data set validation.

The LCWG is currently concentrating on Actions 1 and 4. A 'fast track' 1 km global land cover data set is planned for 1997. The initial fast track land cover classification scheme retains key elements of the Running *et al.* (1994) scheme, including removal of climate from class definitions, and reliance on ancillary remotely-sensed measures, such as vegetation greenness indices, to provide relative indicators of temporal dynamics of biophysical properties. The scheme is based on definitions of three canopy components: above ground biomass, leaf longevity, and leaf type. Above ground biomass defines whether the vegetation retains perennial or annual above ground biomass, a critical question for seasonal climate and carbon-balance modelling. It is also a major vegetation determinant of the surface roughness length parameter that climate models require for energy and momentum transfer equations. Leaf longevity (evergreen versus deciduous canopy) is a critical variable in carbon cycle dynamics of vegetation, and affects seasonal albedo and energy transfer characteristics of the land surface. Leaf longevity indicates whether a plant annually must completely regrow its canopy, or a portion of it, with inferred consequences to carbon partitioning, leaf litter fall dynamics, and soil carbon. Leaf type (needle leaf, broadleaf, and grass) affects gas exchange characteristics.

The global 1 km land cover data set will be created on a continent by continent basis. Whilst different sets of image classification rules may be needed for different areas, the methodologies will be fully documented, objective, reproducible and with globally consistent output classes. Current proposals include the classification approach used in North American 1-km AVHRR land cover studies, based on unsupervised classification of Normalised Difference Vegetation Index (NDVI) time series, (Loveland *et al.* 1991, Brown *et al.* 1993) and multispectral classifications using AVHRR channels in addition to the NDVI used in the Tropics (Malingreau and Belward 1994).

The validation exercise, proposed by the land cover Validation Working Group (VWG), will provide information on the accuracies for each cover type included in the data set so that users will be aware of the level of confidence that should be placed on the data set. The validation exercise will also support the development of methodologies for future land cover product generation. A two tier validation strategy has been proposed. Firstly, a core sampling strategy is applied to systematically assess the accuracy of each cover type included in the global land cover product. Recognising that there is no current 'state of the art' for validation of global land cover data sets, the VWG has proposed a stratified unaligned random sample as being the current 'state of the practice' (*e.g.*, Moody and Woodcock 1994). Secondly, confidence sites, where fine-resolution land cover information is available for a substantial region, are used. The core sampling strategy will be based on visual interpretation of high resolution data (*e.g.*, Landsat or SPOT) co-registered with the AVHRR data. The VWG will define a sampling design taking into account the spatial variance of all the cover types. Decision rules and interpretation keys also will be developed to aid visual interpretation of the high resolution data. A prototyping phase of the validation exercise will resolve a number of issues including the implications of mixtures of cover types on the sampling procedure, the effects of misregistration on accuracy assessment, and implications of sampling single *vs.* blocks of pixels.

Confidence sites will be selected to test protocols for the validation methodology, aid in developing interpretation keys for visual interpretation of high resolution data, and provide more detailed information on the variability of cover types within a 1 km cell. Wherever possible local land cover information will be provided by local experts with detailed knowledge of the site. Development of confidence sites will be carried out in co-ordination with other IGBP initiatives such as the terrestrial transects, the LUCC case study sites and the IGBP-DIS high resolution data test sites. It is expected that the operational phase of the classification and validation will begin in 1996 and be completed in 1997.

The IGBP-DIS Land Cover Classification (LCC) of natural vegetation has been designed after much consultation and is likely to be the scheme to be adopted generally in areas of IGBP concerned with terrestrial vegetation. The scheme, presented below, therefore has much relevance for the DGVM developments.

The land classification scheme adopted by IGBP-DIS is therefore expected have a large impact on the user community and on vegetation modellers. The approach is likely to be central to the approach taken by LUCC when defining a methodology for conducting contemporary assessments (next 10 to 100 years) of regional land cover and land use change and extrapolation from local situations to areas up to 1000 km^2 in size.

A likely approach may be to use the IGBP-DIS classification of the current dominant land cover type (LCT) at a spatial resolution of 1 km over the entire region of interest (up to about 1 x 10^6 km^2 area). Greater resolution of classification than the DIS set may be required for smaller scale studies and an alternative approach may be to derive classes of LCT for several forest, grassland, wetland, and cropped ecosystems from 1 km AVHRR data sets over the period of 1992-1993. Monthly data sets of NDVI from the same data sets will then serve as inputs (or validation) to ecosystem production algorithms, such as is the case in some terrestrial ecosystem models (Potter *et al.* 1993).

The dynamics of land cover change through the last few decades will be determined at relatively high spatial resolution (70 m). This will be conducted by a comparison of selected sets of Landsat images of the same area over years from the 1970's, 1980's and 1990's. Each image will be classified into cover categories for natural (forest or grassland) and cleared land cover pixels. Location(s) of selected Landsat scenes within the larger region will then be chosen to coincide with the location(s) of other spatial data layers in a geographic information system (GIS) of social, demographic, economic, and biophysical attributes.

Changes at the local scale (Figure 5) will be determined by an analysis of the sequence of land use changes over several years, starting at the basic economic unit-of-use level of organisation, followed by a documentation of the progression of land cover changes and characteristics of land use intensification on converted field plots. The land use(s) will then be classified according to a system developed by the FAO. Individual and community level surveys will then be required to determine those social and economic factors associated with land use decisions. Finally, there will also be a need to measure ecological features (biomass, soils, *etc.*) and biogeochemical fluxes in the various land cover and land use types of the area.

There will then be sufficient data to construct generalised flow model(s) of net annual changes in area coverage among LCT and land use categories. This model can then be applied over the region of interest, with the aim for global coverage and a final integration into a DGVM.

Modelling human-modified vegetation

Initially, global models of change in the distribution of potential vegetation and in human-driven change in land cover have been developed independently. Thus, an urgent priority, in addition to improving each type of model, is to develop viable strategies for linking them to create realistic models of the earth's changing land surface. In the first instance, linkage can be achieved through a simple overlay of a land-cover change map with potential vegetation distribution as determined by a DGVM. The second generation of linked models, however, will have to include intricate coupling within the DGVM of land-use and land-cover change with change in disturbance regimes (*e.g.*, fire).

Of particular importance is the treatment of systems that are modified by human action, but where natural successional processes and disturbances also play a significant role in determining the structure of the vegetation. Much of the world's ecosystems fall into this

category, and they are the most difficult to model as they are driven by both human and natural variables, often interacting. Examples include selective logging, which can potentially be important for the global carbon balance, and the Miombo woodlands of Africa, where changes in fire frequency through human action can cause woody invasions, which change the N cycle, *etc.*

There are several potential strategies for simulating the dynamics of human-modified systems. These include: (i) modifying the important process terms, such as production and respiration, in physiologically-based models; (ii) prescribing a pattern of carbon allocation to simulate the dynamics along a successional pathway following disturbance or land-cover change; (iii) using a transition matrix/look-up table based on a functional type approach; and (iv) using modified plant or crop growth models directly.

As discussed earlier, a fire model specifically for use in DGVMs should be produced as an urgent priority. To be most useful, however, it will need to handle human-modified fire regimes as well as naturally occurring ones. In addition, since the combination of fire and grazing is common around the world, it is suggested that a fire/grazing model should be developed as an initial example of an intricately linked human/natural disturbance module.

Table 1. The IGBP-DIS Land Cover classification

1	Evergreen Needleleaf Forests: Lands dominated by trees with a percent canopy cover >60% and height exceeding 2 meters. Almost all trees remain green all year. Canopy is never without green foliage.
2	Evergreen Broadleaf Forests: Lands dominated by trees with a percent canopy cover >60% and height exceeding 2 meters. Almost all trees remain green year all year. Canopy is never without green foliage.
3	Deciduous Needleleaf Forest: Lands dominated by trees with a percent canopy cover >60% and height exceeding 2 meters. Consists of seasonal needleleaf tree communities with an annual cycle of leaf-on and leaf- off periods.
4	Deciduous Broadleaf Forests: Lands dominated by trees with a percent canopy cover >60% and height exceeding 2 meters. Consists of seasonal broadleaf tree communities with an annual cycle of leaf-on and leaf- off periods.
5	Mixed Forests: Lands dominated by trees with a percent canopy cover >60% and height exceeding 2 meters. Consists of tree communities with interspersed mixtures or mosaics of the other four forest cover types. None of the forest types exceeds 60% of landscape.
6	Closed Shrublands: Lands with woody vegetation less than 2 meters tall and with shrub canopy cover is >60%. The shrub foliage can be either evergreen or deciduous.
7	Open Shrublands: Lands with woody vegetation less than 2 meters tall and with shrub canopy cover is between 10-60%. The shrub foliage can be either evergreen or deciduous.
8	Woody Savannahs: Lands with herbaceous and other understory systems, and with forest canopy cover between 30-60%. The forest cover height exceeds 2 meters.
9	Savannahs: Lands with herbaceous and other understory systems, and with forest canopy cover between 10-30%. The forest cover height exceeds 2 meters.
10	Grasslands: Lands with herbaceous types of cover. Tree and shrub cover is less than 10%.
11	Permanent Wetlands: Lands with a permanent mixture of water and herbaceous or woody vegetation that cover extensive areas. The vegetation can be present in either salt, brackish, or fresh water.
12	Croplands: Lands covered with temporary crops followed by harvest and a bare soil period (*e.g.*, single and multiple cropping systems). Note that perennial woody crops will be classified as the appropriate forest or shrub land cover type.
13	Urban and Built-up: Land covered by buildings and other man-made structures. Note that this class will not be mapped from the AVHRR imagery but will be developed from the populated places layer that is part of the Digital Chart of the World (Danko, 1992)
14	Cropland/Natural Vegetation Mosaics: Lands with a mosaic of croplands, forests, shrublands, and grasslands in which no one component comprises more than 60% of the landscape.
15	Snow and Ice: Lands under snow and/or ice cover throughout the year.
16	Barren: Lands exposed soil, sand, rocks, or snow and never has more than 10% vegetated cover during any time of the year.
17	Water Bodies: Oceans, seas, lakes, reservoirs, and rivers. Can be either fresh or salt water bodies.

Validation

The descriptions of the very varied ranges of model developments indicate a large and ambitious programme. Central to all of these developments is model validation or comparison with independent data sets. In terms of DGVM development, an obvious approach is to develop DGVMs independently of any remote sensing data, freeing these data for comparisons. The various historical transients of terrestrial vegetation processes, including human land use changes, will need to be compared with other data sets. The aggregated land use data set of Houghton *et al.* (1983) can be compared with model inversions of the global carbon cycle; however, these indicate uncertainties which cannot easily be identified and are not clarified in comparisons with ice core CO_2 data (Enting and Mansbridge, 1987). The annual oxygen cycle may prove to be an important independent test, although the data set is short.

A disaggregated global map and model of changes in human land use and cover change over the last one to two hundred years will be an important addition to a DGVM when running in transient mode from the 18th century to the present day, at which time the model should provide a representation of what is seen in the one-year IGBP-DIS land cover map, based on remote sensing.

Validations and comparisons may prove more effective at regional rather than global scales, especially for sites which have and will have extensive scientific investigations, such as the IGBP Terrestrial Transects and the LUCC case study sites. Comparison with smaller scale ecosystem dynamics models may also give some indication of the realism of the DGVMs. Of course, no degree of comparison or testing against current or past data can serve as a validation of projections of the future.

Conclusions and Recommendations

There is a clear need for the development of a DGVM, both as an important component in climate feedbacks and also as a method of simulating ecological change. No DGVM is yet completed, although a number of research groups are working to this end. A major limitation to projecting the dynamic changes in vegetation in response to transient changes in climate and CO_2 is the lack of a global-scale coverage of the nature, extent and frequency of natural disturbances which can open vegetation to change.

A first requirement is the production of this global-scale data base of current-day disturbances. This data base should be accompanied by generic models of disturbance, suitable for inclusion in DGVMs and the first such product should be a fire model.

DGVMs are aimed for application within GCMs but should also operate in stand-alone mode. Therefore there is a need for new climate data sets. These include dew point temperature or water vapour pressure deficit, extremes of temperature, occurrences of extremes of water supply (droughts and floods), return frequencies and intensities of storms and information about weather conditions with high risks of combined effects such as high temperature, drought and conditions conducive for fires.

Further developments of DGVMs depend on the inclusion of data bases and models of human land use effects on natural vegetation. The first approach and requirement is for a human land use mask over a global map of natural terrestrial vegetation. This mask, to be derived from satellite data, will be used in coupled GCM experiments to determine the feedback of human-managed landscapes to climate.

The importance of landscape-scale phenomena in DGVMs is well recognised and requires more extensive testing to determine those features of landscape-scale processes which are essential for realistic projections of vegetation change. At the same time there will be a need to discuss explicitly the nature of cross-scale processes and the size of the basic grid-cell units of operation for DGVMs. Of major concern is the likely nature and extent of sub-grid scale phenomena, the capacity to aggregate these processes and the methods of allowing grid-cell interactions.

DGVMs should be able to run from the onset of the industrial revolution to the present, with an expectation of predicting the current day vegetation, as seen and classified from the IGBP-DIS land use product, based on satellite remote sensing. The capacity to fulfil this objective will be strongly determined by a knowledge of the global extent and nature of human modifications of natural vegetation. The aims of producing a historical map of geographically referenced human land use for the last two to three hundred years and projecting some decades into the future is the major aim of LUCC. One first product along this development will be to disaggregate geographically the Houghton data set of human land use over the last 150 years. This series of maps may then be compared with those of Esser and from the IMAGE group to test for inconsistencies. This will be the first important product to be used as a changing data base as DGVMs run from the 18th century to the present. There will also be a need for an actual pre-industrial vegetation for initialising the DGVM runs.

Further developments in producing a model for projecting human-land use at the global scale will be split into historical and contemporary plus future projections. These are programmes central to LUCC, but with obvious collaborations with IGBP-DIS, GCTE, GAIM and other core projects of IGBP such as BAHC and IGAC. It is difficult to provide realistic estimates of the rates at which these developments will progress; however, some usable developments should be available within the next three to five years.

The following specific actions were recommended by the group. The ordering of the list does not imply any priorities.

1. *Biome-by-biome assessment of disturbance regimes, on a FT basis.* What disturbances in which biomes are responsible for significant change in ecosystem structure? The main disturbances to consider are wind (storms), water (droughts and floods), temperature extremes and fire. Much of the data can be gathered from "local experts" working on the set of IGBP Terrestrial Transects. This assessment and resulting database should be carried out by the LEMA Data and Information Centre at the Potsdam Institute for Climate Impact Research, Germany. **Action: GCTE/LEMA**

2. *Development of a fire and fire/grazing model for inclusion in DGVMs.* This project requires a post-doctoral researcher working for 18 months with a modelling group(s). **Action: GCTE/LEMA**

3. *Development of a high resolution Digital Terrain Model (DTM)*, and the testing of the DTM via sensitivity studies using ecological models at study sites on the IGBP Terrestrial Transects. The DTM sensitivity tests will be carried out as a LEMA activity. **Action: IGBP-DIS; GCTE/LEMA**

4. *Development of methodologies for the disaggregation of land-use and land-cover change data collected by large administrative units* (*e.g.*, countries or provinces). The first step is a LUCC workshop to initiate and coordinate work in this area. **Action: LUCC**

5. *Provision of 1 km land cover database.* This project is well advanced through coordination by IGBP-DIS. The global product, created on a continent by continent basis, will be available in June 1997 (see http:www.meteo.fr/cnrm/igbp, IGBP-DIS Activities, Global 1km Land Cover Projects). As an interim measure, the 1 degree land cover database of de Vries and Townshend is available (see http://geog13.umd.edu/landcover/1d-map.html). **Action: IGBP-DIS**

6. *Development of historical (beginning in 1700) land cover database with associated database on land use (farming systems, etc.).* This was identified as a joint LUCC-GAIM-DIS activity, with LUCC taking a lead role. **Action: LUCC**

7. *Development of a methodology for classifying farming systems*, including information on the biogeochemical implications of various farming systems. This should be carried out jointly by LUCC and GCTE Focus 3, in close collaboration with the FAO, with LUCC taking a lead role. **Action: LUCC/GCTE**

8. *Coordination of four major, related activities involving process and case studies, model development and validation, and data gathering*: IGBP Terrestrial Transects, LUCC Case Studies, 1 km database map confidence sites, high resolution data pilot project sites. The group strongly recommended that work in these four activities be co-located and done in close collaboration whenever feasible and scientifically justified. The group suggested that an overall coordinator is required to coordinate the suite of activities, with scientists/officers with responsibility for individual components located within the core projects and framework activities: IGBP Terrestrial Transects (BAHC, IGAC, GCTE - ideally one scientist for each core project); LUCC Case Studies (LUCC); 1 km confidence sites and high resolution sites (DIS). GCTE was asked to prepare a proposal for the establishment of a coordinating team for this suite of activities. **Action: GCTE**

9. *Provision of additional databases to support DGVM development.* The following databases were suggested, along with IGBP groups responsible for their provision:

- *Grazing/livestock numbers* - **LUCC/IGBP-DIS**
- *Vapour pressure deficit (dew point)* - **BAHC**
- *Actual pre-industrial vegetation (ca 1700)* - **GCTE/LUCC**
- *Storm frequency and intensity* - **BAHC**

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Acronyms and Abbreviations

AVHRR	Advanced Very High Resolution Radiometer
Africover	Land Cover Classification over Africa (FAO)
BAHC	Biospheric Aspects of the Hydrological Cycle
CENTURY	*Name of long-term model*
DEM	Digital Elevation Model
DGVM	Development of a Dynamic Global Vegetation Model (GCTE)
DIS (IGBP-DIS)	Data and Information System (IGBP)
FAO	Food and Agriculture Organisation (UN)
GAIM	Global Analysis, Interpretation and Modelling (IGBP)
GCM	GeneralCirculation Model
GCTE	Global Change and Terrestrial Ecosystems (IGBP)
GIS	Geographical Information System
IGAC	International Global Atmospheric Chemistry Project
IGBP	International Geosphere-Biosphere Programme
IHDP	International Human Dimensions Programme on Global Environmental Change
IMAGE	Integrated Model to Assess the Greenhouse Effect
Landsat	Land Remote-Sensing Satellite (USA)
LCT	Land Cover Type
LCWG	Land Cover Working Group
LUCC	Land Use Land Cover Change (IGBP/IHDP)
NDVI	Normalised Difference Vegetation Index
SPOT	Satellite pour l'Observation de la Terre (France)
TREES	Tropical Ecosystem Environment observation by Satellite
VWG	Validation Working Group

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No. 12 The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP). The Initial Core Projects (1990). Stockholm: IGBP, 330 pp.
The IGBP science plan is composed of research projects aimed at answering a number of key questions related to global change, through the establishment of Core Projects on the distinct sub-components of the Earth system, and related activities on data systems and research centres. An implementation strategy provides for its fulfilment.

No. 13 Terrestrial Biosphere Exchange with Global Atmospheric Chemistry. Terrestrial Biosphere Perspective of the IGAC Project: Companion to the Dookie Report. Report on the Recommendations from the SCOPE/IGBP Workshop on Trace-Gas Exchange in a Global Perspective. Sigtuna, Sweden, 19-23 February, 1990. Edited by P. A. Matson and D. S. Ojima (1990). Stockholm: IGBP, 103 pp.
The Sigtuna workshop contributed to the development of a scientific action plan on terrestrial ecosystem gas exchange, complementing the International Global Atmospheric Chemistry Project (an IGBP Core Project) in areas of natural variability, boreal regions, global integration and modelling of fluxes, and trace gas fluxes in mid-latitude ecosystems.

No. 14 Coastal Ocean Fluxes and Resources. Report of a CP2 *Ad Hoc* Workshop, Tokyo, Japan, 19-22 September 1989. Edited by P. Holligan (1990). Stockholm: IGBP, 53 pp.
The focus of IGBP Co-ordinating Panel 2 on Marine Biosphere-Atmosphere Interactions is the elucidation and prediction of the feed-back loops between climate and ocean biogeochemistry under conditions of significant anthropogenic changes to the trace gas composition of the atmosphere. The workshop concentrated on global change and the coastal oceans.

No. 15 Global Change System for Analysis, Research and Training (START). Report of a Meeting at Bellagio, December 3-7, 1990. Edited by J. A. Eddy, T. F. Malone, J. J. McCarthy and T. Rosswall (1991). Stockholm: IGBP, 40 pp. Also available in Spanish and French.
START is a plan for the development of an international network of regional research centres and sites to gather data and study global change problems in their regional contexts. These regions are identified. Issues to be addressed are: How changes in land use and industrial practices alter the water cycles, atmospheric chemistry and ecosystems dynamics; how regional changes affect global biogeochemical cycles and climate; and how global change leads to further regional change in the biospheric life support system.

No. 16 Report from the IGBP Regional Meeting for South America, São José dos Campos, SP, Brazil, 5-9 March 1990 (1991). Stockholm: IGBP, 58 pp.
The workshop discussed, in a South American context, past global changes, the effects of climate change on terrestrial ecosystems, the role of ocean processes in global change, land transformation and global change processes, the importance of the Andes for general circulation models, and regional research centres. Recommendations promote the role of South American science in global change research.

No. 17 Plant-Water Interactions in Large-Scale Hydrological Modelling. Report of a Workshop, Vadstena, Sweden, 5-8 June 1990 (1991). Stockholm: IGBP, 44 pp.
The workshop addressed plant-water interrelationships at landscape to continental scales: the spatial pattern at landscape level of the dynamics of water flows and waterborne fluxes of dissolved and suspended mater; plant/vegetation characteristics and properties affecting return flow to the atmosphere; methodological issues of large-scale modelling; research in humid tropical, semi-arid and temperate zones.

No. 18:1 The Recommendations of the Asian Workshop, New Delhi, India, February 11-15, 1991. Edited by R. R. Daniel (1991). Stockholm: IGBP, 36 pp.
Recommendations of the Workshop address issues of prime concern to Asian countries, with reports and recommendations from Working Groups on IGBP Core Projects and key activities.

No. 18:2 Proceedings of the Asian Workshop, New Delhi, India, 11-15 February 1991, ed. by R. R. Daniel & B. Babuji. Madras, Committee on Science and Technology in Developing Countries (COSTED) and the Indian National Committee for the IGBP (1992). Madras, COSTED, Asia Regional Office, 152 pp
The Proceedings include 19 papers on Earth system research and global environmental change in Asia, and national reports on global change programmes.

No. 19* The PAGES Project: Proposed Implementation Plans for Research Activities, ed. by John A. Eddy (1992). Stockholm: IGBP, 112 pp.
The Past Global Changes (PAGES) project will secure better understanding of the natural and human-induced variations of the Earth system in the past, through studies of both natural and written records. Focus is on changes within two temporal streams: global changes for the period 2000 BP, and changes through a full glacial cycle. Implementation plans address: solar and orbital forcing and response, Earth system processes, rapid and abrupt global changes, multi-proxy mapping, palaeoclimatic and palaeoenvironmental modelling, advances in technology, management of palaeodata, and improved chronologies for palaeoenvironmental research.

No. 20* Improved Global Data for Land Applications: A Proposal for a New High Resolution Data Set, Report of the Land Cover Working Group of IGBP-DIS, Edited by John R. Townshend (1992). Stockholm: IGBP, 75 pp.
This report outlines a proposal to produce a global data set at a spatial resolution of 1 km derived from the Advanced Very High Resolution Radiometer primarily for land applications. It defines the characteristics of the data set to meet a number of requirements of IGBP's science plan and outlines how it could be created. It presents the scientific requirements for a 1 km data set, the types and uses of AVHRR data, characteristics of a global 1 km data set, procedures, availability of current AVHRR 1 km data, and the management needs.

No. 21* Global Change and Terrestrial Ecosystems: The Operational Plan, edited by W. L. Steffen, B. H. Walker, J. I. Ingram and G. W. Koch (1992). Stockholm: IGBP, 97 pp.
The objectives of GCTE are: to predict the effects of changes in climate, atmospheric composition, and land use on terrestrial ecosystems, including agricultural and production forest systems, and to determine how these effects lead to feedbacks to the atmosphere and the physical climate system. The research plan is divided into four foci: ecosystem physiology, change in ecosystem structure, global change impact on agriculture and forestry, and global change and ecological complexity. Research strategies are presented.

No. 22 Report from the START Regional Meeting for Southeast Asia, Arranged by The International Geosphere-Biosphere Programme: A Study of Global Change (IGBP), in collaboration with Human Dimensions of Global Environmental Change (HDGEC) Programme (1992). Stockholm: IGBP, 114 pp.
The report presents general recommendations on global change research in the region, thematic studies relating to IGBP Core Project science programmes, global change research in studies of eight countries in the area, and conclusions from working groups on the participation of the region in research under the five established IGBP Core Projects and the related HDGEC programme.

No. 23 Joint Global Ocean Flux Study: Implementation Plan. Jointly published with the Scientific Committee on Oceanic Research (SCOR) (1992). Stockholm: IGBP, 78 pp. (JGOFS Report No. 9)
The Report describes how the aims of JGOFS are being, and will be, achieved through global synthesis, large scale surveys, process studies, time series studies, investigations of the sedimentary record and continental margin boundary fluxes, and the JGOFS data management system.

No. 24 Relating Land use and Global Land-Cover Change: A Proposal for an IGBP-HDP Core Project. A report from the IGBP/HDP Working Group on Land-Use/Land-Cover Change, edited by B. L. Turner, R. H. Moss, and D. L. Skole (1993). Stockholm: IGBP, 65 pp. (Human Dimensions of Global Environmental Change Programme, HDP Report No. 5)
The report presents the main findings of the joint Working Group of the IGBP and the International Social Science Council on Land-Use/Land-Cover Change; it describes the research questions defined by the group and identifies the next steps needed to address the human causes of global land-cover change and to understand its overall importance. It calls for the development of a system to classify land-cover changes according to the socio-economic driving forces. The knowledge gained will be used to develop a global land-use and land-cover change model that can be linked to other global environmental models.

No. 25 Land-Ocean Interactions in the Coastal Zone (LOICZ) Science Plan. Edited by P.M. Holligan and H. de Boois, with the assistance of members of the LOICZ Core Project Planning Committee (1993). Stockholm: IGBP, 50 pp.
The report describes the new IGBP Core Project, giving the scientific background and objectives, and the four research foci. These are: the effects of global change (land and freshwater use, climate) on fluxes of materials in the coastal zone; coastal biogeomorphology and sea-level rise; carbon fluxes and trace gas emissions on the coastal zone; economic and social impacts of global change on coastal systems. The LOICZ project framework includes data synthesis and modelling, and implementation plans cover research priorities and the establishment of a Core Project office in the Netherlands.

No. 26 Towards a Global Terrestrial Observing System (GTOS): detecting and monitoring change in terrestrial ecosystems. Report of the Fontainebleau Workshop. Edited by O. W. Heal, J.-C. Menaut and W. L. Steffen (1993). Paris: MAB, 71 pp. (UNESCO Man and the Biosphere Digest 14)
The Fontainebleau Workshop, July 1992, defined a strategy to initiate a global terrestrial monitoring system for the IGBP project on Global Change and Terrestrial Ecosystems, the French Observatory for the Sahara and the Sahel, and the UNESCO Man and the Biosphere programme, in combination with other existing and planned monitoring programmes. The report reviews existing organisations and networks, and drafts an operational plan.

No. 27 Biospheric Aspects of the Hydrological Cycle. The Operational Plan (1993). Edited by BAHC Core Project Office, Berlin (1993). Stockholm: IGBP, 103 p.
A presentation of the mandate, scope, principal subjects and structure of the BAHC research plan is followed by a full description of the four BAHC Foci: 1) Development, testing and validation of 1-dimensional soil-vegetation-atmosphere transfer (SVAT) models; 2) Regional-scale studies of land-surface properties and fluxes; 3) Diversity of biosphere-hydrosphere interactions; 4) The Weather Generator Project.

No. 28 The IGBP in Action: The Work Plan 1994-1998 (1994). Stockholm: IGBP, 151 pp.
This Report provides an overview of the global change research to be carried out under the aegis of the International Geosphere-Biosphere Programme over the next five years. It represents a follow-up to IGBP Report No. 12 (1990) that described the basic structure of the global change research programme, the scientific rationale for its component Core Projects and proposals for their development. The IGBP Core Projects and Framework Activities present their aims and work programme in an up-to-date synthesis of their science, operational and implementation plans.

No. 29 Africa and Global Change, A Report from a Meeting at Niamey, Niger, 23-27 November, 1992. (1994). Stockholm: IGBP, in both English and French under the same cover; 55 pp. each language.
A summary is given of the conference arranged by the Global Change System for Analysis, Research and Training (START) on behalf of the IGBP, the Human Dimensions of Global Environmental Change Programme (HDP), and the Joint Research Centre of the Commission of the European Communities (CEC) that describe the global change scientific research situation in Africa today.

No. 30 IGBP Global Modelling and Data Activities, 1994-1998. (1994). Strategy and Implementation Plans for Global Analysis, Interpretation and Modelling (GAIM) and the IGBP Data and Information System (IGBP-DIS). Stockholm: IGBP, 86 pp.
This report sets out the goals and directions for GAIM and IGBP-DIS over the next five years, expanding on the recent overview of their activities within IGBP Report 28 (1994). It describes the work within IGBP-DIS directed at the assembly of global databases of land surface characteristics, and within GAIM, directed at modelling the global carbon cycle and climate-vegetation interaction

No. 31 African Savannas and the Global Atmosphere. Research Agenda. 1994. Report of a joint IGBP/START/IGAC/GCTE/GAIM/DIS Workshop on African Savannas, Land use and Global Change: Interactions of Climate, Productivity and Emissions, 1-5 June 1993, Victoria Falls, Zimbabwe. Edited by Chris Justice, Bob Scholes & Peter Frost. Stockholm: IGBP, 53 pp.
The workshop focused on interactions between African savannas and the global atmosphere, specifically addressing land-atmosphere interactions, with emphasis on sources and sinks of trace gases and aerosol particles. The report discusses the ecology of African savannas, the research issues related to carbon sequestration, ongoing and proposed activities, and gives a research agenda.

No. 32 International Global Atmospheric Chemistry (IGAC) Project. The Operational Plan (1994). Stockholm: IGBP, 134 pp.
The goals of IGAC are to: develop a fundamental understanding of the processes that determine atmospheric composition; understand the interactions between atmospheric chemical composition and biospheric and climatic processes, and predict the impact of natural and anthropogenic forcings on the chemical composition of the atmosphere. The Operational Plan outlines the organisation of the project. The plan describes the seven Foci, their related Activities and Tasks, including for each the scientific rationale, the goals, strategies.

No. 33 Land-Ocean Interactions in the Coastal Zone. Implementation Plan (1995). Edited by J. C. Pernetta and J. D. Milliman. Stockholm: IGBP, 215 pp.
LOICZ is that component of the IGBP which focuses on the area of the Earth's surface where land, ocean and atmosphere meet and interact. The implementation plan describes the research, its activities and tasks, and the management and implementation requirements to achieve LOICZ 's science goals. These are, to determine at regional and global scales: the nature of these dynamic interactions, how changes in various compartments of the Earth system are affecting coastal zones and altering their role in global cycles, to assess how future changes in these areas will affect their use by people, and to provide a sound scientific basis for future integrated management of coastal areas on a sustainable basis.

No. 34 BAHC-IGAC-GCTE Science Task Team. Report of First Meeting, Massachusetts Institute of Technology, Cambridge, Massachusetts, USA, 10-12 January, 1994 (1995). Stockholm: IGBP, 45 pp.
The Science Task Team discussed and developed recommendations for multi-Core Project collaboration within the IGBP under three headings: process studies in terrestrial environments, integrated modelling efforts, and partnership with developing country scientists. Three interrelated themes considered under process studies are: transects and large-scale land surface experiments, fire, and wetlands. Methods for implementation and projects are identified.

No. 35 Land-Use and Land-Cover Change. Science/Research Plan (1995). Edited by B. L. Turner II, David Skole, Steven Sanderson, Günther Fischer, Louise Fresco and Rik Leemans. Stockholm/Geneva, IGBP/HDP. 132 pp. (IGBP Report 35/HDP Report 7).
The Science/Research Plan presents land-use and land-cover change and ties it to the overarching themes of global change. It briefly outlines what is currently known and what knowledge will be necessary to address the problem in the context of the broad agendas of IGBP and HDP. The three foci address by the plan are: (i) land-use dynamics, land-cover dynamics - comparative case study analysis, (ii) land-cover dynamics - direct observation and diagnostic models, and (iii) regional and global models - framework for integrative assessments.

No. 36 The IGBP Terrestrial Transects: Science Plan (1995). Edited by G. W. Koch, R. J. Scholes, W. L. Steffen, P. M. Vitousek and B. H. Walker. 53. pp.
The IGBP Terrestrial Transects are a set of integrated global change studies consisting of distributed observational studies and manipulative experiments coupled with modelling and synthesis activities. The transects are organised geographically, along existing gradients of underlying global change parameters, such as temperature, precipitation, and land use. The initial transects are located in four key regions, where the proposed transects contribute to the global change studies planned in each region.

No. 37 IGBP Northern Eurasia Study: Prospectus for an Integrated Global Change Research Project (1996). Edited by W.L. Steffen and A.Z. Shvidenko. 95 pp. Also available in Russian
This report was prepared by scientists representing BAHC, IGAC, and GCTE. It is a prospectus for an integrated hydrological, atmospheric chemical, biogeochemical and ecological global change study in the tundra/boreal region of Northern Eurasia. The unifying theme of the IGBP Northern Eurasia Study is the terrestrial carbon cycle and its controlling factors. Its most important overall objective is to determine how these will alter under the rapidly changing environmental conditions.

IGBP Booklet

Global Change: Reducing Uncertainties.
Prepared by Philip Williamson, with editorial assistance from the Scientific Committee for the IGBP (June, 1992; reprint August 1993) 40 pp.

IGBP NewsLetter
Global Change NewsLetter. Quarterly, 1989 (latest December 1996)

IGBP Directory
Directory 1994
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