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The Institute's research on global change embraces:
- ***the greenhouse gas budgets and cycles***
- ***land-atmosphere interactions***
- ***the terrestrial impacts of climate change.***

Global change

Photo: Met Office

During the last decade, the prospect of global warming has ceased to be just a hypothesis. It has become a likely scenario, which governments addressed seriously at Kyoto in 1997. Global Change is a priority research area for the Natural Environment Research Council (NERC) and is a part of the UK government's strategy for sustainable development. The Institute has played a central role in developing science. Staff have been fully involved in International Geosphere Biosphere Programme (IGBP) committees, in the work of the Intergovernmental Panel on Climate Change (IPCC), on committees within the European Union and Review Groups of the Department of the Environment, Transport and the Regions (DETR) and in the development, management and execution of NERC thematic programmes – notably the Terrestrial Initiative on Global Environmental Research (TIGER).

Greenhouse gas budgets and cycles

It is certain that atmospheric greenhouse gas concentrations are increasing: concentrations of CO_2 (358 ppmv), CH_4 (1725 ppbv) and N_2O (311 ppbv) are now about 28, 45 and 20% greater than in pre-industrial times and are increasing by about 1.8 ppmv/yr, 8 ppbv/yr and 0.6 ppbv/yr, respectively. However, both the global and UK budgets of CO_2, CH_4 and N_2O have unacceptable source-sink uncertainties. This makes it impossible to predict the effect of natural processes on future emissions, or to convert emissions into atmospheric concentrations and hence to changes in radiative forcing. Over the last decade, ITE's global vegetation models have enabled the terrestrial part of the carbon cycle to be better quantified. Measurements of gas fluxes in various parts of the world have lessened uncertainty about the natural sources of CH_4 and N_2O. ITE has made a significant contribution to determining the inventory of CH_4 and N_2O emissions in the UK, which are reported by the UK government under the Framework Convention on Climate Change.

Land-atmosphere interactions

Climate change model 'experiments' were initially carried out by comparing runs in the current climate with runs representing the earth in a changed state. New experiments are now being implemented where both of these factors change interactively. The future requirement is for the land surface and atmospheric composition to change dynamically as well as interactively with climate change. ITE's ecosystem models have been central in this development, both in the UK and USA The long-term challenge (no less than the 'grand challenges' in UK physics research) is to develop a comprehensive, predictive numerical model of the total earth system This model incorporates current climate models with the best terrestrial and ocean biogeochemical models This will provide the complete carbon cycle, and fully represent land-atmosphere and land-ocean, as well as ocean-atmosphere, interactions

Impacts of climate change

The time-scale of expected global change is such that significant climate anomalies and trends are likely to be detected within the next two decades Current emission scenarios will mean that further climate changes will be unavoidable There is, therefore, a need to predict the impacts and identify sensitivities and adaptive strategies, at local, national and regional scales The main 'drivers' will be changes in temperature, CO_2, rainfall (affecting soil moisture) and UV-B These key drivers will interact with other changes such as associated changes in vapour pressure deficit, and solar radiation, pollution climate (especially N and acid deposition) and land use, to modify changes on species and ecosystems Within the TIGER thematic programme, ITE has made significant advances in understanding the likely responses of UK species and habitat types to increasing temperature and in identifying the flora and fauna which may be at greatest risk ITE has also been a major player in the research community investigating the direct role of increasing CO_2 concentrations on photosynthesis and whole ecosystem performance The Institute's research has now focussed on

- likely gains and losses of plant and animal species
- changes in phenology, physiology and composition which may disrupt trophic interactions
- effects of elevated CO_2 on photosynthesis and belowground processes
- the identification of indicators of climate change in the UK.

There is a long way to go before we can confidently predict the threats and opportunities that may be presented by climate change and what actions should be taken

The time-scale of expected global change is such that significant climate anomalies and trends are likely to be detected within the next two decades.

M G R Cannell

Plate 1. An evergreen rainforest in South America. Future climate changes may transform such regions into savanna or grassland

It is accepted that the greenhouse effect can be enhanced by increasing concentrations of radiatively active gases in the atmosphere.

Development of global terrestrial ecosystem models to predict changes in vegetation and the carbon sink on land

The 1980s saw the development of global change research, following the acceptance that the natural greenhouse effect could be enhanced by increasing concentrations of carbon dioxide, methane and other radiatively active gases in the atmosphere (Houghton *et al.* 1996). The Natural Environment Research Council (NERC) started the Terrestrial Initiative on Global Environmental Research (TIGER) in 1990, the largest thematic research programme it had ever mounted in the terrestrial sciences. ITE managed over half of this programme and made a major contribution to the research itself. In 1992, the UK government took a lead at the Earth Summit in Rio, and subsequently signed the Climate Change Convention. The UK also established offices of the Intergovernmental Panel on Climate Change (IPCC) and formed the Hadley Centre for Climate Prediction.

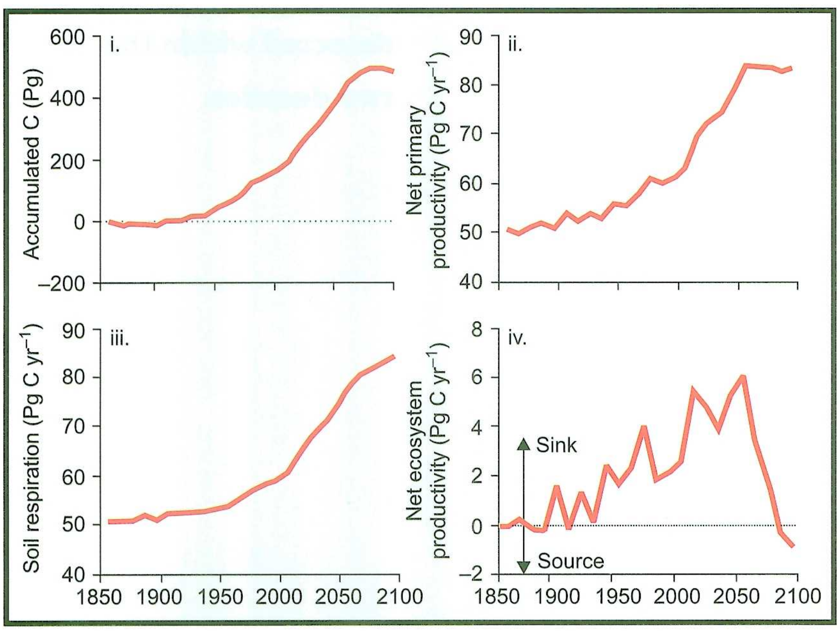

Figure 1. Changes in the amount and fluxes of terrestrial carbon (in soils and vegetation) in the world from 1850 to 2100 predicted by the ITE ecosystem model Hybrid. *i.* Total amount of carbon in soil and vegetation, showing an increase over time. *ii.* Net Primary Productivity of global vegetation (photosynthetic production minus plant respiration). *iii.* Soil respiration (which equals NPP when the system is at equilibrium). *iv.* Net Ecosystem Productivity, the difference between NPP and soil respiration; when this is positive the system is a net sink of carbon and when it is negative it is a net source

The issues for the terrestrial sciences were:

- to better quantify the global cycles of the greenhouse gases, so that future emissions could be converted to atmospheric concentrations
- to determine how climate change, as predicted by global circulation models (GCMs), might affect the distribution and functioning of global biomes – and, in particular, to indicate when irreversible or 'dangerous' change might occur (as stated in the Climate Change Convention)
- to determine whether changes in vegetation distribution and functioning might affect the climate (and hence modify GCM predictions) primarily by changing the earth's energy and water balance
- to estimate the size of the terrestrial carbon sink and how it might respond to climate change (including increasing atmospheric CO_2 concentrations).

To meet some of these challenges, ITE built a Dynamic Global Vegetation Model (DGVM) called Hybrid, capable of predicting future year-by-year transient changes in vegetation and terrestrial carbon pools and fluxes (Friend *et al.* 1997, Friend & White in press). In the ITE Annual Report 1996–97 (White & Friend 1997) an account was given of predictions of vegetation distribution. Here, we focus on the terrestrial carbon cycle.

Hybrid is a mechanistically-based DGVM and has three essential properties.

- It couples the physiological and physico-chemical processes regulating the carbon, water and N cycles, describing all the major interactions, feedbacks and exchanges between vegetation, soils and the atmosphere on a sub-daily timestep. Central to the model is an integrated biochemical description of photosynthesis and stomatal conductance.

- It contains no constraints, such as statistical relationships derived from observed vegetation properties and functions in the current climate.
- It describes vegetation regeneration, growth and death, and all major physiological processes for eight generalised plant types integrated over time and is consequently able to predict transient responses to climate, atmospheric CO_2 and N deposition.

Each plant type is described by fundamental parameter values that influence its growth in a given climate. Dominant types emerge as a result of competition for light, water and N, among individual trees and between trees and an herbaceous understorey.

Averaged over the 1980s, it is likely that about 28% of the carbon emitted as CO_2 by human activities was absorbed by the global land surface – increasing the store of carbon in organic matter in vegetation and soils. This terrestrial sink has acted as a substantial 'brake' on the rate at which the CO_2 concentrations have increased in the atmosphere and thereby slowed the rate of enhanced greenhouse warming. Hybrid has been used to determine whether global terrestrial ecosystems will continue to provide a negative feedback on radiative forcing in a future, warmer world.

The Hybrid model was driven by transient climate output from the UK Hadley Centre coupled with the atmosphere-ocean GCM (HadCM2). Atmospheric CO_2 concentrations (including other greenhouse gas CO_2 equivalents) were increased from 280 ppm in 1860 to nearly 800 ppm in 2100, following the best-guess scenario of future greenhouse gas emissions (IPCC scenario 1992a, see Houghton *et al.* 1996). Also, the present and future global distribution of atmospheric N deposition was derived from NH_x and NO_y deposition estimates for pre-industrial, current, and 2050 conditions, assuming an exponential increase with time.

Plate 2. The forest-tundra boundary may shift northwards as a result of climate change, increasing the coverage of forest vegetation

Predicted changes in accumulated carbon, net primary productivity (NPP), soil respiration, and net ecosystem productivity (NEP, the difference between NPP and soil respiration) are shown in Figure 1. The model predicts a net accumulation of carbon by the land surface of about 500 Pg (≈30% of total carbon in the 1860s) during the 240 year simulation. From the 2050s onwards the model predicts a reduced rate of carbon sequestration, with a net loss of carbon from the land surface predicted for the last two decades.

The Hybrid model has been used to determine whether global terrestrial ecosystems will continue to provide a negative feedback on radiative forcing in a future, warmer world.

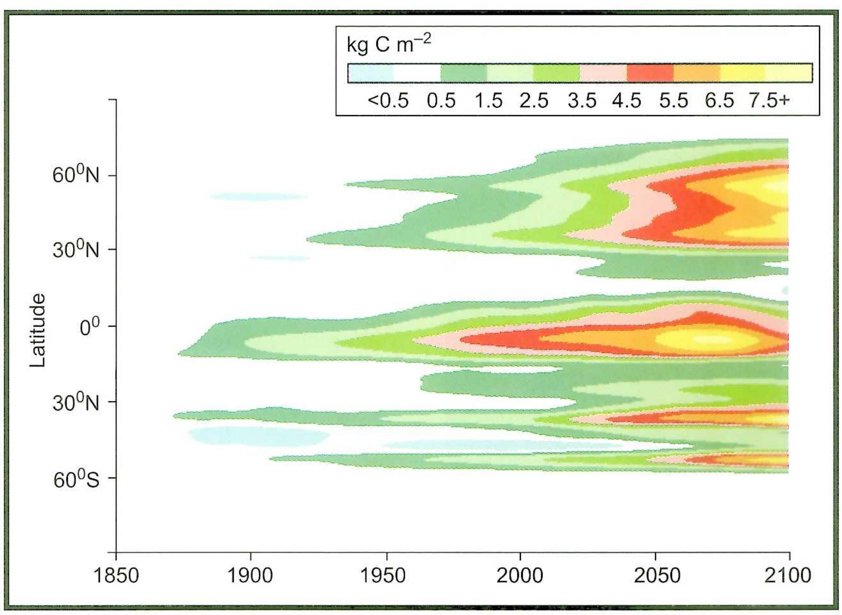

Figure 2. The development of the terrestrial carbon sink at different latitudes from 1850 to 2100, as predicted by the Hybrid model. The units are decadal means of additional carbon accumulated in each latitudinal zone over time

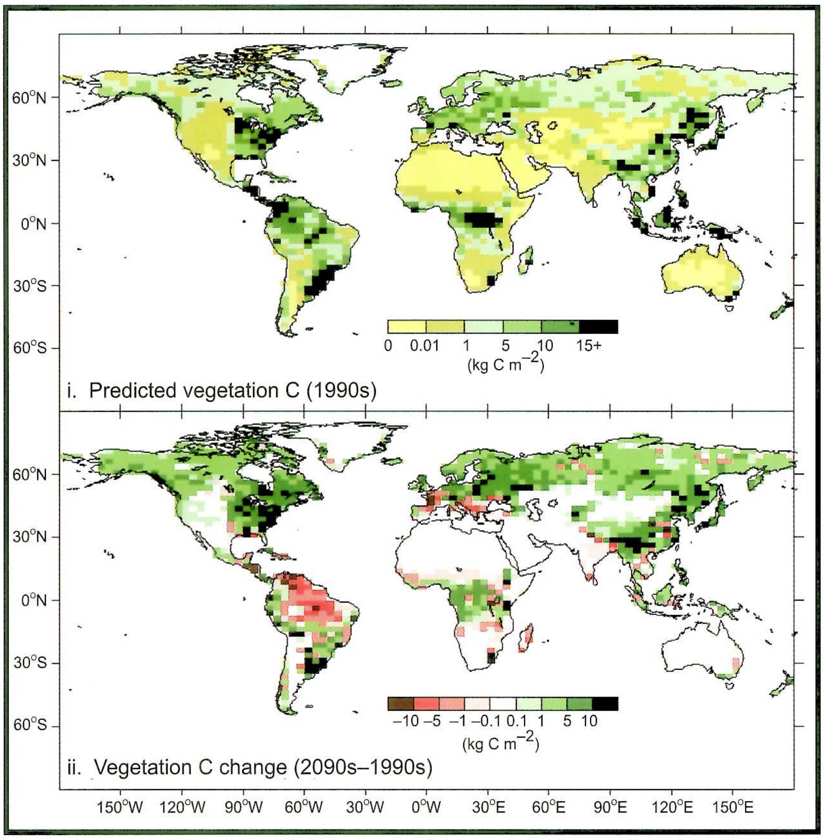

Figure 3i. The predicted distribution of vegetation carbon for the 1990s, *ii.* and the change in the this distribution between the 1990s and 2090s. Note the decrease in carbon in northern South America, the Sahel, India and parts of western and continental Europe

In summary, the model predicts that the "brake" on global warming currently provided by the terrestrial carbon sink will be released within the next century.

Plate 3. The impacts of human disturbance, such as burning, will accelerate the rate release of carbon from terrestrial ecosystems

This loss is due to a fall in NPP from a peak of 84 Pg C yr^{-1} (reached during the 2050s) and a continued increase in soil respiration. These patterns are reflected in changes in NEP – the net flux of carbon between the atmosphere and the terrestrial biosphere. The model predicts that there is currently a terrestrial carbon sink of 1–2 Pg per year (which is similar to the estimates using CO_2 concentrations and isotopes), increasing to about 4 Pg per year by 2050. After 2050 the terrestrial sink decreases dramatically and disappears entirely by about 2080 (Figure 1iv). In summary, the model predicts that the 'brake' on global warming currently provided by the terrestrial carbon sink will be released within the next century. Increasing the fraction of anthropogenic CO_2 which remains in the atmosphere will result in faster warming – a dangerous positive feedback.

The distribution of accumulated carbon across latitudes during the 1860–2100 period is shown in Figure 2. Tropical regions became a sink early in the simulation, with temperate and boreal regions following a few decades later. The tropical sink peaked in about 2075, followed by a net loss of carbon (although there was still more carbon at the end of the simulation than at the beginning). Temperate and boreal regions continued to be a strengthening sink through to 2100. Tropical carbon losses towards the end of the simulation were associated with mean-monthly temperature increases of 5–8 °C by 2100, coupled with a reduction in precipitation in regions such as northern South America, the Sahel, and India. These climate changes cause increased evapotranspiration, and lower soil moisture potentials, hence reducing stomatal conductances and increasing cavitation in tree stems. Some regions which were previously evergreen rainforest became savanna, grassland, or even desert (Plate 1). Many tropical C_4 grasslands were transformed to C_3 grasslands or desert. These changes result in a reduction of vegetation carbon stocks (Figure 3) and the release of large amounts of carbon into the atmosphere. The vegetation in boreal and temperate regions continued to sequester carbon in response to warming (Figure 3), due to:

- increased productivity as a result of CO_2 fertilisation
- increased mineralisation of N
- an extended growing season.

There is also an increase in the area of forest in North America and Central Asia, although for forest systems vegetation changes are not as significant as changes in productivity and carbon store within each vegetation type. For some northern ecosystems, particularly tundra, vegetation change to forest is important, since it enables vegetation productivity increases to counter carbon losses from increased soil respiration (Plate 2).

It is important to note that, so far, we have not fully coupled the GCM with the ecosystem model. At present, the scenario of increase in atmospheric CO_2 used to drive the GCM does not take account of changes in the terrestrial carbon sink. However, if we accept the IPCC 1992a scenario of CO_2 emissions, then the land surface is predicted to take up around 40% of projected industrial emissions between 1980 and 2060, after which this fraction will decline and eventually become negative (Figure 4). Thus, these simulations indicate that the land surface may play a major role in determining future atmospheric CO_2 levels.

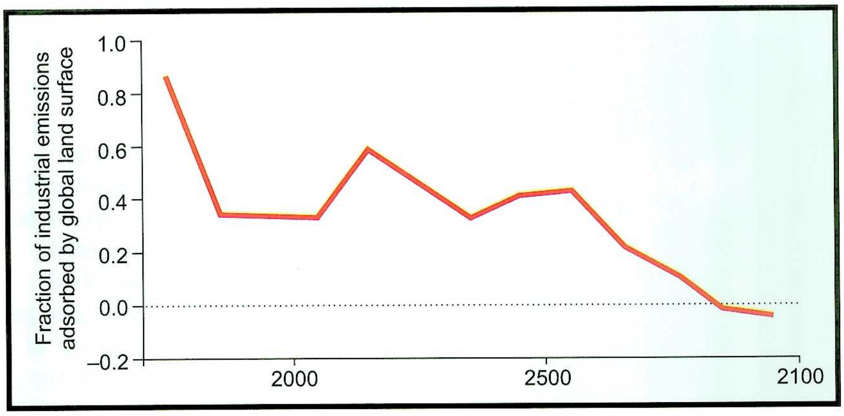

Figure 4. One likely prognosis is that global emissions of carbon from burning fossil fuels will increase over the next century. This graph shows the fraction of those emissions that may be taken up by the global land surface and stored in vegetation and soils (as a result of the growth of the terrestrial carbon sink) as predicted by the ITE Hybrid model. After 2050, when the land takes up a smaller fraction of the carbon, a correspondingly larger fraction will remain in the atmosphere as CO_2

The simulations presented here demonstrate the sensitivity and potential importance of the land surface for the behaviour of the global carbon cycle over the next century (they should not be viewed as definitive predictions). The ecosystem model is under continuous development and future work will focus on coupling this DGVM to models of the global carbon, climate, and ocean systems (through links between ITE, the Hadley Centre and NASA's Goddard Institute for Space Studies in the USA). A future challenge will be to add influences of land use change (Plate 3) in order to make consistent and comprehensive predictions of the future behaviour of the global climate system.

In 1997, the Kyoto Protocol gave renewed impetus for work on the effects of land use practices on the carbon cycle. It introduced the possibility that terrestrial sources and sinks might be included in future international negotiations on limiting greenhouse gas emissions. Particular attention is likely to be paid to the role of forests, which has been another focus of ITE's work, aimed at quantifying the carbon storage potential of different land management options (eg Cannell & Milne 1995, Cannell 1996).

A White and A D Friend

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The 1997 Kyoto Conference introduced the possibility that terrestrial sources and sinks might be included in future international negotiations on limiting greenhouse gas emissions.

Future research will aim to produce interactive coupled models of global carbon, climate and ocean systems.

Plate 1. Validation of remotely sensed observations: collecting ground reference data, in Uganda, using a global positioning system to relate site location to geo-referenced land cover data

The application of remote sensing to the study of global processes

It has been argued convincingly (Graetz 1989) that many aspects of earth system science are impossible without access to data from Earth Observation (EO). Studies of the causes and effects of climate change, in particular, depend on the use of general circulation models (GCMs) to define the drivers of change, and of large-scale ecosystem models to predict impacts. The variables needed to drive these models cannot be measured globally. Instead, observations made *in situ* must be extrapolated across the region of interest. This requires a consistent geo-spatial framework at national to global scales that only remote sensing can provide. However, it is rarely possible to utilize EO data directly for this purpose. Instead, variables required by the models must be computed or inferred from remotely-sensed measurements of spectral radiance or microwave backscatter. These remotely-sensed variables can then be used to define the initial model states, to constrain outputs within the bounds of reality and to validate the model predictions.

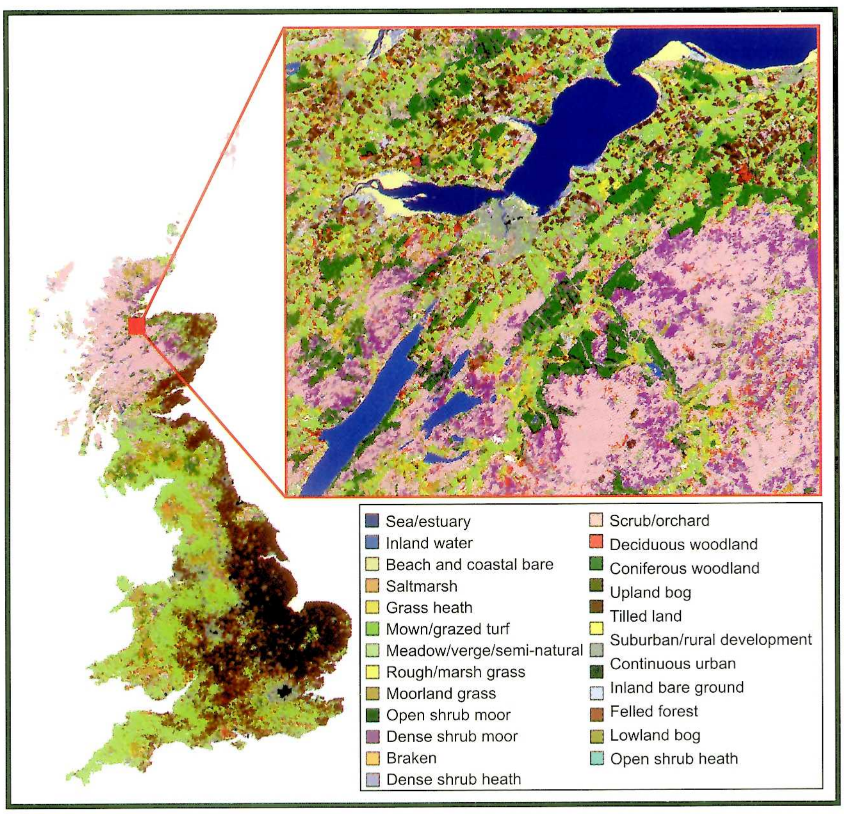


Figure 1. An overview of the Land Cover Map of Great Britain showing dominant land cover per 1 km square. The full resolution map records 25 cover classes, on a 25 m grid, for all GB in 1990: the detailed subsection shows a 20 km square area around Inverness in Scotland

The origins of remote sensing applications in ITE lie in the early 1980s (Fuller 1981), when the Natural Environment Research Council (NERC) was among the first in the UK to exploit computerised image processing for environmental science applications. In 1989, separate research groups concerned primarily with upland (ITE Bangor) and lowland (ITE Monks Wood) applications, were integrated within the newly-constituted Environmental Information Centre (EIC). The capacity was further enhanced in 1998 by amalgamation with the terrestrial sciences component of the NERC Remote Sensing Applications Development Unit (RSADU). Much of the work described in the following sections was carried out prior to 1998, when RSADU was an independent unit within the NERC Earth Observation programme. In many instances, the research described was undertaken in collaboration with various teams in universities and industry.

From the outset, remote sensing research in ITE has followed a consistent pattern, addressing:

- conversion of remotely-sensed data into physical measurements, (eg digital numbers to reflectance).
- derivation of spatially-explicit estimates of biophysical variables that can be used (*inter alia*) as model inputs, (eg albedo, proportional vegetation cover, land cover type).
- deployment of these datasets to inform ecological understanding. This often involves collaboration with groups outside the specialist remote sensing community.

Although the primary motivation for the Institute's interest in EO has always been the contributions that the technology can make to terrestrial ecology, the realisation of this aim has frequently required innovative

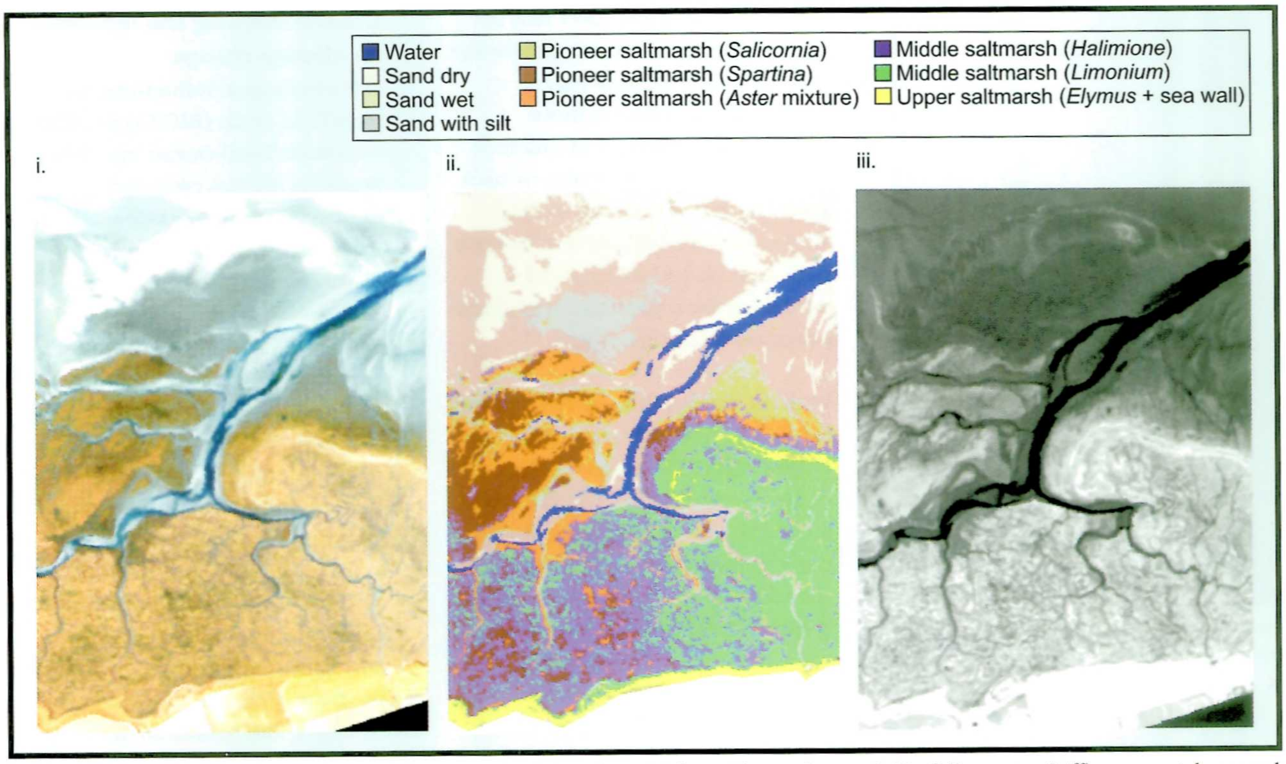


Figure 2i. An airborne image covering a 1.6 km stretch of shoreline, 2.2 km wide, on the north Norfolk coast at Stiffkey, remotely sensed using a ***casi*** sensor. *ii.* A map of saltmarsh cover and sediment types, produced by a statistical maximum likelihood classification of the ***casi*** image. *iii.* The normalised difference vegetation index (NDVI) map calculated from the ***casi*** image – the NDVI is closely related to biomass where the absence of vegetation shows black and dense cover shows white on the image. These three procedures are being used to model the coastal processes of erosion and accretion to examine the potential consequences of global climate change and sea level rise

developments in the science of EO itself. This paper reviews the application of EO to ITE's global change research programme.

From the late 1980s, ITE began to examine the potential of remote sensing for the study of continental and global ecological issues, such as desertification (Stewart *et al.* 1987) and forest degradation (Cannell *et al.* 1992). However, the catalyst for more widespread use of EO data in NERC's terrestrial sciences was the Terrestrial Initiative in Global Environmental Research (TIGER) Thematic Programme (Briggs & Wyatt 1993). Within TIGER, remote sensing contributed to a number of modelling activities, covering:

- the terrestrial carbon cycle
- the hydrological cycle and
- large-scale impacts of global change.

In addition, land cover information from remote sensing provided a spatial reference frame for many large-scale studies within TIGER and in subsequent programmes.

Large-scale mapping of land cover

Information on land cover from remote sensing has been used to investigate many aspects of global change. Land cover, on the one hand, contributes to environmental change and, on the other hand, is itself affected by changes in climate and land use. Changes in land cover may modify the surface energy budget, for example through changes in albedo. Land cover change is thus a potentially important driving force within GCMs. Conversely, changes in land cover induced by climate may impact upon ecosystem function and biodiversity. Changes in the use of land may reinforce or moderate these effects. In all cases, land cover information is utilised directly by the various models that have been developed to explain and predict these climate-land interactions. Physically-based models of energy and material cycles often require estimates of land surface variables that cannot be achieved at the scales required for global predictions. In these

Earth Observation provides vital datasets, at local to global scales, in support of earth system science.

Plate 2. Auto-tracking Land and Atmosphere Sensor (ATLAS)

ITE staff are developing novel instrumentation for the retrieval of the optical and physical properties of radiatively significant atmospheric constituents.

circumstances, land cover may be used indirectly as a surrogate for the variables needed, drawing on experimental evidence about relevant characteristics of different land cover types. Examples of such applications for remotely-sensed land cover data include land surface parameterisation within SVAT models or the computation of global or regional carbon budgets.

With the publication, in 1992, of the Land Cover Map of Great Britain, (Fuller *et al.* 1994), and with its planned revision in 2000, ITE has taken the lead in large-area land cover mapping by automated classification of remotely-sensed data (Figure 1). The Land Cover Map supports a range of national environmental change studies. As a result of ITE's membership of the European Topic Centre on Land Cover, within the European Environment Agency, the same map forms the primary source of British data within the European Co-ORdination of INformation on the Environment in Europe (CORINE) data base. Institute staff are also members of an international Steering Group of the International Geosphere-Biosphere Programme (IGBP), set up to plan and implement a global 1 km land cover dataset. (http://edcwww.cr.usgs.gov/landdaac/1KM/1kmhomepage.html).

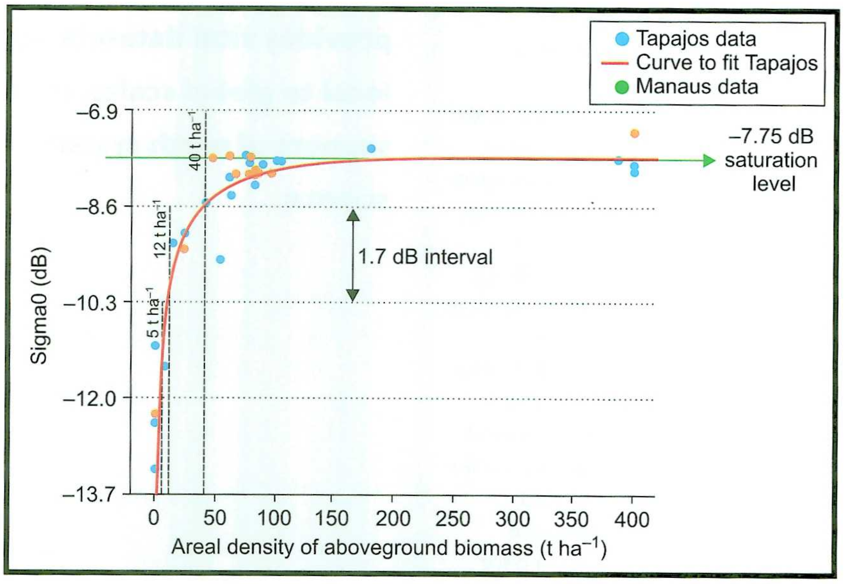


Figure 3. Regression of forest biomass against SAR backscatter

Coastal mapping and modelling for climate change

ITE's Biological Influences On interTidal Areas (BIOTA) programme within the Land-Ocean Interaction Study (LOIS) has provided opportunities to develop techniques for modelling coastal processes (Thomson *et al.* 1998, in press a, b). Airborne remote sensing with the Compact Airborne Spectrographic Imager (***casi***) has been used to derive classifications of vegetated cover and inter-tidal sediments (Figure 2) and, by using vegetation indices, to make quantitative estimate of vegetation density in saltmarshes (Eastwood *et al.* 1997). The methods allow field-based observations to be extrapolated to the North Sea coast of England, from the Humber Estuary to north Norfolk. The results are then used as inputs to models which predict the processes of coastal erosion and accretion. These techniques are now being utilised to simulate the impacts of rises in sea levels, induced by global warming, on coastal ecosystems, within a model system in the Netherlands that has come about as a result of dredging activities in the West Schelde (Cappenburg 1998).

The terrestrial carbon cycle

Tropical forests provided the initial focus for the application of EO data to studies of the terrestrial carbon cycle. ITE undertook pioneering work in the use of imaging radar to study the current state and temporal evolution of the Amazonian rainforest. Synthetic Aperture Radar (SAR) was used to provide information on forest extent and structure, including estimates of tree density, biomass and height. The research established relationships between radar backscatter and above-ground biomass (Luckman *et al.* 1997). By applying these relationships to spaceborne SAR imagery (Figure 3), it was possible to estimate aboveground biomass at regional scales (Figure 4) and to extrapolate groundbased measurements of CO_2 fluxes to quantify and map carbon pools.

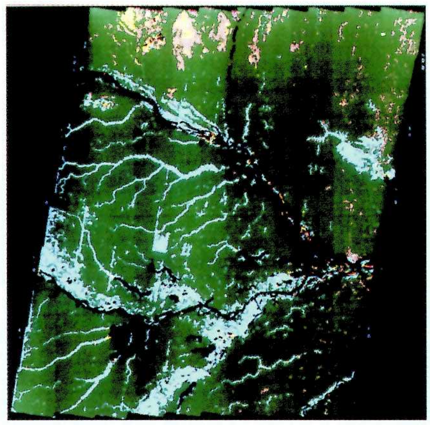
This work has provided new insights into the importance of mature tropical forests as a carbon sink (Grace *et al.* 1995).

Remote sensing at visible and near-infrared wavelengths complements the structural information from SAR, because the optical data are sensitive to canopy roughness, biochemistry and phenology. ITE successfully participated in a NERC funded programme to evaluate the potential of the Along-Track Scanning Radiometer (ATSR-2) for tropical forest mapping (Gerard *et al.* 1997). Fundamental research was also undertaken on methods for the atmospheric correction of ATSR-2 (North *et al.* in press) and for derivation of land surface temperature, vegetation fractional cover and fraction of absorbed photosynthetically active radiation (f_{APAR}) at regional scales (Briggs *et al.* 1997). ITE's work on the remote sensing of forests is now being applied to the international programme, Boreal Ecosystem-Atmosphere Study (BOREAS), to address similar interests in the boreal forest region, which also makes a significant contribution to the terrestrial carbon budget.

ITE is a partner in two other major international programmes on aspects of the terrestrial carbon cycle. SAR Imaging for Boreal Ecology and Radar Interferometry Applications (SIBERIA), is a European collaboration, funded by the European Union, in which ITE's principal contribution is the use of SAR for forest inventory. The project will generate a large-scale forest map of Central Siberia from a combination of:

- ground survey
- detailed aircraft polarimetric measurements
- wider satellite radiometric surveys
- multi-temporal SAR radiometry and interferometry from ERS and JERS-1 data.

The VEGETATION project is dedicated to testing the predictions of a global ecosystem model by combining it with reflectance model predictions over the BOREAS and First ISLSCP Field Experiment (FIFE) study sites. ITE's contribution to the project has been on the interface between the ecosystem and reflectance models and comparison with data from the ATSR-2 sensor, as a simulator for the recently launched (March 1998) VEGETATION instrument.



Backscatter values (dB)		Cover type	Biomass density (t h^{-1})
noise floor to –13.7	■	Water	
–13.7 to –12.0	□	Pasture and crops	0–5
–12.0 to –10.3	□	Young regrowth	5–12
–10.3 to –8.6	□	Established regeneration	12–40
–8.6 to –6.9	■	Old regen./virgin forest	>40
–6.9 to maximum	□	Flooded forest/urban	

Figure 4. Estimation of above-ground biomass and land cover type, in the Tapajos-Manaus region of Amazonia, from a mosaic of JERS-1 SAR data

Land surface water and energy balance

The TIGER programme made important contributions to the World Climate Research Programme, notably through participation in the Hydrological Atmospheric Pilot Experiment in the Sahel region of west Africa between 1990 and 1992. ITE staff designed and built an auto-tracking ground-based radiometer (ATLAS, Plate 2) to characterise the bi-directional reflectance distribution function (BRDF) of vegetation, and deployed the instrument as part of the HAPEX-Sahel experiment.

TIGER also addressed hydrological responses to climate change at the scale of large catchments. In this research, remote sensing contributed to models of river flow by the provision of information on land cover, needed to derive spatially explicit information on catchment permeability.

Ecological impacts of environmental change

TIGER considered the impacts of climate change at a variety of scales. The principal contribution from EO was at the global level, where the capacity for synoptic observation is uniquely relevant. ITE partnered the Sheffield Centre for Earth Observation Science, the Hadley Centre, the Institute of Hydrology and Cranfield University in the development of a global dynamic model to predict the responses of large-scale vegetation systems (biomes) to climate change (Woodward *et al.* 1995). Specific contributions from remote sensing were:

- to validate model predictions of biome distributions, using global coverage from the NOAA AVHRR sensor
- to provide information on the spatial and temporal frequency of disturbance from fires and other causes in different biomes, to parameterise model predictions of rates of succession and change.

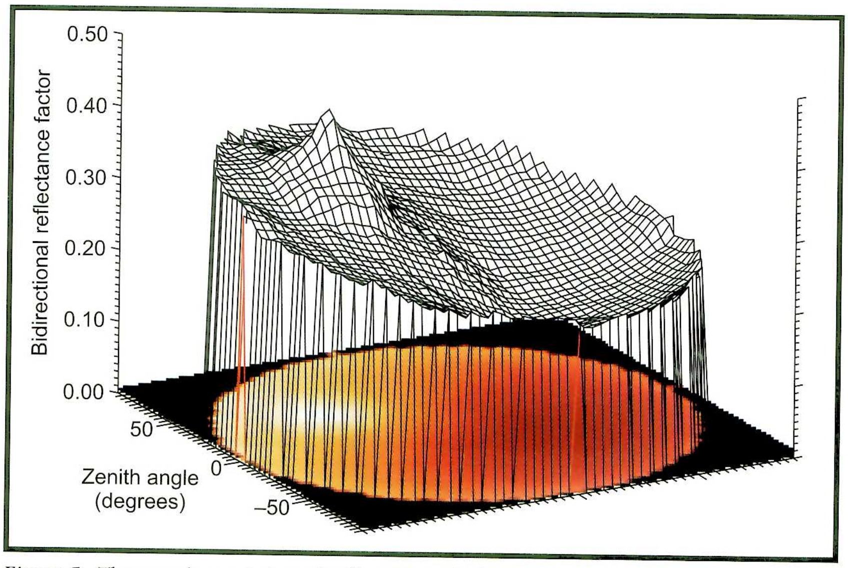


Figure 5. The angular variation of reflectance of a forest canpoy, predicted by a model of photon transport developed at ITE. The model allows relation of satellite measurements to vegetation biophysical characteristics such as foliar chemistry and structure

Remote sensing has been formative in its contribution to global environmental research.

Aspects of the work are continuing, through studies of the use of data from the VEGETATION instrument for modelling forest dynamics.

Underpinning research in Earth Observation

Accurate models of radiation interactions with the land surface are required to derive the variables needed for climate and vegetation studies from remote sensing. Observed reflectance varies not only with wavelength, but with view direction, solar zenith angle and atmospheric conditions. ITE staff have developed a new model of light interaction with vegetation canopies, based on Monte Carlo simulation of photon transport (North 1996). BRDF modelling involves simulation of the chain of scattering events incurred by a photon in its path from the source until it leaves the canopy or is absorbed within it. The model allows treatment of multiple scattering within and between crowns, trunk and the ground surface (Figure 5).

The atmosphere modifies the signal measured by optical and thermal satellite sensors, the effects being typically of the same order of magnitude as the surface flux. This problem is generic to all satellite and airborne instruments, so that there is a need for accurate radiometric calibration and atmospheric correction of EO data, and for the validation of derived geophysical data products that spans all applications. Recognising this requirement, ITE staff are developing novel instrumentation for the retrieval of the optical and physical properties of radiatively significant atmospheric constituents. ITE manages a sun photometer as a UK node within the AERONET network of more than 60 world-wide instruments. Membership of the network gives the whole UK science community access to the global dataset of atmospheric aerosol characteristics for validation of satellite retrievals and for local, regional, and global climate studies.

ITE is also involved in development of calibration and validation strategies for current and proposed sensors, in collaboration with the European Space Agency and UK industry, to enable global and long-term datasets of environmentally important parameters to be produced. Further research will exploit a new generation of instruments that sample top-of-atmosphere radiance at an increased number of view directions and spectral bands. The research programme includes the development and testing of atmospheric correction procedures for the ATSR sensor series, and examination of methods that will deploy the resulting data to determine aerosol characteristics.

Conclusions

Remote sensing has been formative in its contribution to global environmental research. ITE has made substantial contributions to these developments, generating research results, data and algorithms that are utilised by the wider user community in Britain and Europe, and that contribute significantly to major international programmes. The Millennium will see the launch of three major multi-sensor satellites, the American Earth Observing System (EOS), the second Japanese ADvanced Earth Observing Satellite (ADEOS-II) and the European ENVISAT system. In addition, major international research programmes will be initiated, for example, the Large-Scale Atmosphere Biosphere (LBA) experiment in the Amazon. With its experience from TIGER, BOREAS, HAPEX-Sahel and the

VEGETATION programmes, ITE is well placed to continue its contribution to the study of remote sensing of global processes

B K Wyatt, R M Fuller, S E Plummer, J R Baker, A K Wilson and A G Thomson

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Future work will refine methods for estimating biophysical parameters required for modelling global processes and, especially, for predicting and measuring the impacts of climate change.

The Institute's applications development programme in Earth Observation will enhance the UK contribution to the understanding of global processes and will help to assess and predict impacts of change at local, national, continental and global scales.

Plate 1. Heathland burnt during the great drought of 1976 took several years to regenerate. Climate change could increase the frequency of such events, which profoundly affect vegetation dynamics

Past climatic change has had a large effect in shaping Britain's fauna and flora. Predicting the time-scale of future change is proving elusive.

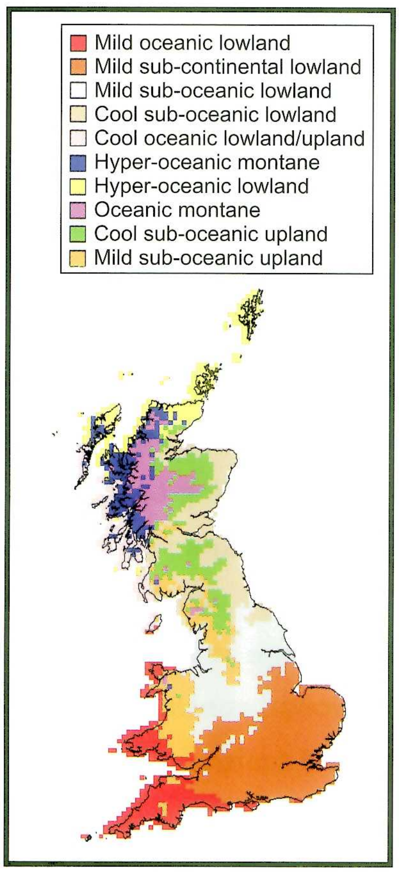

Figure 1. Bioclimatic zones of Britain, based on twelve physical variables and seven groups of organisms. High bioclimatic diversity in the north and west is not matched by high species richness

Impacts of global change on UK species and communities

Introduction

Global change, now a major topic of environmental debate in politics and the media, was not part of ITE's research programme in 1973. Past climatic change was known to have had a large effect in shaping Britain's fauna and flora, but was perceived as having little relevance for the modern ecologist. It was something given, a starting point, rather than a continuing process.

The weather, on the other hand, was always a topic of interest. In ITE's early years, following the International Biological Programme, the focus of interest was on ecosystem function (eg nitrate release following storm events). The exceptionally hot summer of 1976 (Plate 1) stimulated more general interest in the subject. Jeffers (1977), at that time ITE's Director, coordinated a report on the effects of that extreme event, speculating on the need for a programme of work on climate change and noting that this should take account of hydrology, agriculture and forestry.

During the 1980s the prospect of global warming attracted increasing attention from scientists. Researchers at ITE Edinburgh were studying the factors predisposing trees to damage by spring frost. They extended their models to include the prospect of climate warming and found that in a 2°C warmer climate, apples in Kent would blossom about three weeks earlier whereas spruce trees in Scotland would burst their buds only five days earlier (Cannell & Smith 1986).

Shortly afterwards, the Department of the Environment (DOE) commissioned a review of global change impacts, concentrating on the effects of CO_2, temperature, rainfall and sea level (DOE 1988). ITE's contribution figured prominently. In collaboration with scientists from Sheffield and Edinburgh universities, ITE reviewed the probable effects on trees, forests, ecosystems of conservation and amenity interest, and on soft coasts. Predictions were made against a base scenario of climate change for the UK (Table 1), adopted in order to make the individual papers comparable. Early predictions were made on the basis of general ecological knowledge with only a small amount of extra research.

From 1990, ITE has been actively engaged in studies of the potential effects of climate change on ecosystems and species. This started with the DOE Core Model Programme (Parr & Eatherall 1994) and continued with several projects under the Natural Environment Research Council (NERC) thematic programme Terrestrial Initiative in Global Environmental Research (TIGER). On the basis of this research more quantitative advice on the ecological consequences of climate change has been given to the UK conservation agencies and the European Topic Centre for Nature Conservation. ITE has also made major contributions to a range of further reviews (Cannell *et al.* 1990, Cannell & Hooper 1990, United Kingdom Climate Change Impacts Review Group 1991, 1996).

Past climate change

Past climate change can throw light on potential responses to future change and can explain several of the

Table 1. Scenarios of climate change for the UK in 2050. Later scenarios have tended to be less extreme. Examples given here have been used in ITE's advisory work for the Department of the Environment (DOE), Climate Change Impacts Review Group (CCIRG) and Scottish Natural Heritage (SNH)

Variable	DOE (1988)	CCIRG (1991)	CCIRG (1996)	SNH (1998)
CO_2 (ppmv)	540	525	525	511
Temperature	+3°C	+2.3°C	+1.6°C	+1.0°C
Precipitation	± 20%	± 16%	+10%	+8%
Sea level	+80 cm	+30 cm	+37 cm	+31 cm

characteristics of the present biota. Britain is remarkable for its large gradients of temperature and rainfall over relatively short distances (Figure 1), but in spite of this the UK does not support a particularly large or diverse fauna and flora. Because the land was either ice-covered or open tundra at the time of the last glacial maximum (20 000 years ago), most species had to invade after the ice melted. Consequently, the present biota consists mainly of widespread European species, with exceedingly few endemics.

About 7 000 years ago the land bridge between Britain and Europe was severed. Summer temperatures then were about 2°C higher than at present and summer insolation was about 7% higher. These conditions were favourable for species requiring summer warmth, such as butterflies (Figure 2). ITE scientists have studied the thermal requirements of butterflies. They have found that several ground-dwelling species that inhabit tall swards or shaded woodland in the warmer regions of central-southern Europe, depend on warm microclimates associated with short turf or early-successional patches in felled woodland under current British climates. If Britain had been covered in high forest or mature heaths and grasslands 5 000 years ago, when temperatures started to fall again, these butterflies would have become extinct. Thomas (1993) proposed a solution to the paradox of butterfly survival, namely that the activities of prehistoric man maintained enough early successional habitat for thermophilous insects to survive (Figure 3). In contrast, arboreal species requiring high temperatures are presumed to have died out 5 000 years ago.

Interpreting scenarios of change

For the last few thousand years the climate was relatively stable, but it is now changing as a result of human activities. Since the early 1960s atmospheric CO_2 levels have continued to increase by about 1 ppmv per year and the UK climate has become warmer. So far, the 1990s have been about 0.5°C warmer than the 1961–1990 average and four of the five warmest years in central England in the 340-year record have occurred since 1988. The succession of warm winters and dry summers in the 1990s provide an indication of the potential future climate.

Ecologists making impact studies require either a single scenario of change or a range of scenarios among which to compare differences. Scenarios of future changes in atmospheric CO_2 and climate used by ITE, have been progressively refined at the global level by the Intergovernmental Panel on Climate Change, and at the UK level by the Climate Change Impacts Review Group. Currently, scenarios are provided by the University of East Anglia through the UK Climate Impacts Programme. Future landscapes will be shaped by economic and social factors as well as by climate change. These are notoriously hard to predict, especially beyond the next decade or two. Yet, if they are the major factors driving change, they cannot be ignored.

Given scenarios of climate and landscape, ecological impacts can be predicted by analogy and models, building on experience and theory. Ideally, predictions should be tested against reality by experiment and observation. Such tests present formidable difficulties because of the long time-scales and large spatial-scales that have to be considered. However, if we wait for a sure test, it will probably be too late to mitigate the effects of climate change. Fortunately, short-term experiments are often informative, especially with elevated CO_2 and temperature changes.

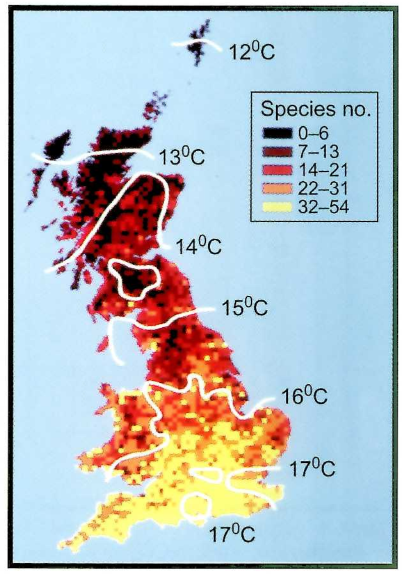

Figure 2. Species richness of butterflies in Britain. Isotherms show July temperatures for comparison

Effects of elevated CO_2 and raised temperatures on plants

Analogue systems with high CO_2 are effectively unavailable, because at no time in the recent geological past has the CO_2 concentration in the atmosphere been as high as at present. ITE has adopted an experimental approach using the Solardome Climate Change Facility,

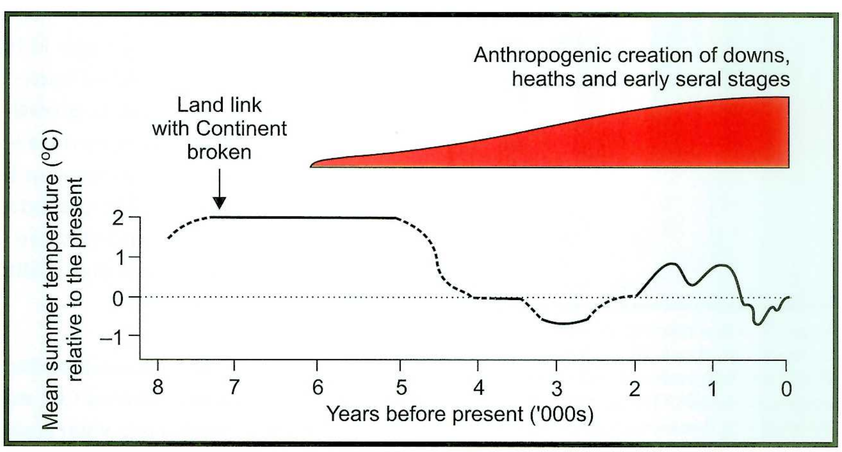

Figure 3. Reconstruction of how insects depending on warm early-successional habitats survived past climatic cooling in Britain as a result of human activity

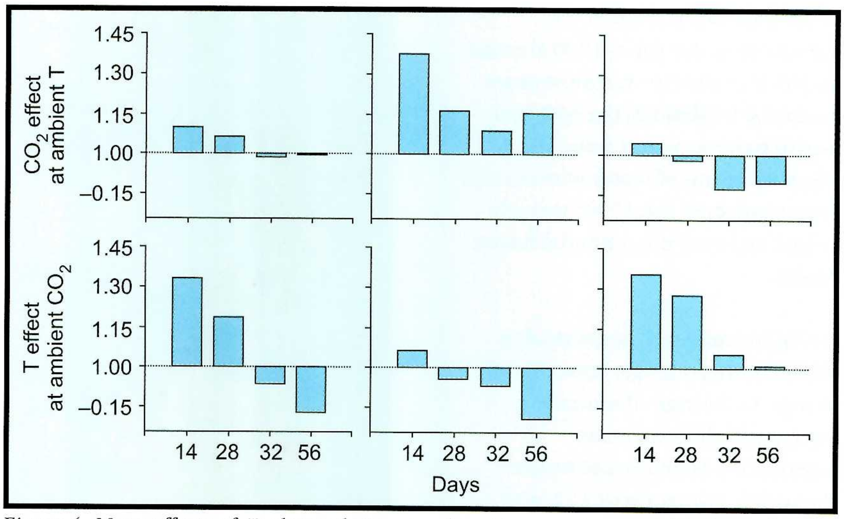

Figure 4. Mean effects of (i) elevated CO_2 at ambient temperature and (ii) elevated temperature at ambient CO_2 on Relative Growth Rate (RGR), Net Assimilation Rate (NAR) and Leaf Area Ratio (LAR) of five fast growing native plant species

Initially, plant growth will increase in response to elevated temperatures and CO_2, but this will reduce over time due to acclimation.

given to ITE by National Power plc in 1992. This has provided a unique large-scale system for experimental studies to help evaluate the likely impacts of future climates on vegetation. The facility comprises eight hemispherical glasshouses which provide a factorial combination of two levels of CO_2 (ambient and ambient +340 ppm), two levels of temperature (ambient and ambient +3°C) and two replicates of each CO_2 x temperature combination (Rafarel *et al.* 1995).

Generally, studies on individual plants have shown that, at least in the short-term, most species have the capacity for increased biomass production in response to both elevated CO_2 and elevated temperature. The growth response to elevated CO_2 is primarily because of an increase in photosynthetic efficiency per unit of leaf area (ie net assimilation rate; NAR) rather than because of a change in leaf area (ie leaf area ratio; LAR) (Figure 4). In contrast, increased relative growth rate (RGR) at elevated temperature is primarily because of an increase in LAR and NAR is unaffected. The combined effects of elevated CO_2 and elevated temperature are often less than additive (Ashenden *et al.* in press).

In the long term, the initial stimulation of photosynthesis at elevated CO_2 may be attenuated, resulting in what is often termed 'acclimation' of photosynthesis. This loss of photosynthetic capacity depends on the ability of plants to utilise assimilates in growth, metabolism or storage (ie on their sink capacity). Hence, the loss of photosynthetic capacity is often linked to a build up of non-structural carbohydrates in leaves. Any factor that reduces sink capacity will cause acclimation of photosynthesis to elevated CO_2.

A long-term study on the effects of CO_2 x temperature regimes on swards of ryegrass (*Lolium perenne*) supplied with ample levels of N, was conducted in the ITE Bangor Solardome Facility. During the first year of exposure, swards showed a 10–15% increase in shoot growth in response to elevated CO_2 or elevated temperature. This stimulation in shoot growth was not increased further in response to combined CO_2 + elevated temperature. However, continued exposure to elevated CO_2 diminished, and even reversed, the response in the third and fourth years of growth. Elevated temperature continued to stimulate growth in the later years of the experiment except in mid-summer when high temperatures may have induced heat or drought stress. In addition, there was some evidence for an increase in root biomass at elevated CO_2. There is a possibility that long-term exposure to elevated CO_2 may result in an increase in belowground storage of carbon.

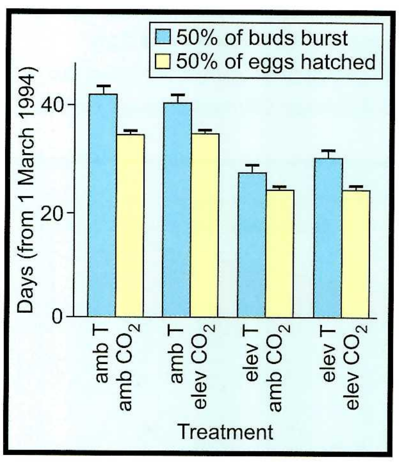

Figure 5. Time taken from 1 March 1994 for budburst in oak and egg hatch in winter moth in ambient and elevated temperature and CO_2 treatments. Elevated CO_2 has no significant effect, whereas elevated temperature accelerates both leaf and caterpillar emergence so that they remain synchronised

Plant-herbivore interactions

The interaction between plants and associated invertebrate herbivores might also be affected by climate change. For example, the synchrony between winter moth (*Operophtera brumata*) egg hatch and budburst of oak (*Quercus robur*) is believed to be critical for the moth's success (Hunter 1992). If the caterpillars are too early, there are no young leaves for them to eat. If they are too late the leaves are unpalatable. Elevated temperature is known to affect the relationship between winter moth and Sitka spruce (*Picea sitchensis*) (Dewar & Watt 1992). The effect of elevated temperature (+3°C) and CO_2 (doubled) on the synchrony between moth and oak to climatic change, has been tested in the solardomes at ITE Bangor. In early winter, moth eggs were attached near the buds on young oak trees in the domes, and egg hatch and budburst were monitored as spring approached. Although both occurred earlier at elevated temperature, the synchrony between moth and tree remained close (Figure 5). Elevated CO_2 levels had no effect on egg hatch or on budburst (Buse & Good 1996). Although temperatures did not change the synchrony, the earlier appearance might have an effect on the breeding success of birds that feed caterpillars to their young (van Noordwijk *et al.* 1995).

Static models of species distribution

The most direct approach to visualising climate change is by means of analogue climates. Here, the aim is not to find where particular species could live in future, but whether there are current climates that resemble predicted future climates. No two climates are the same in all respects. However, climates are biologically similar if the factors that are most important for organisms are similar. In Europe, the four most important macroclimatic factors are:

- summer warmth
- winter cold
- annual rainfall
- summer drought.

These can be measured approximately by the total heat sum, January mean temperature, annual precipitation and summer precipitation. When these variables are used to measure the degree of climatic similarity, we see that under a climate scenario (generated by the Hadley Centre of the UK Met Office), Dorset in 2065 will have a climate like that currently experienced in southern Brittany (Figure 6).

As a method of visualisation, analogue climates have the advantage that they do not require detailed modelling of a large number of species. All species that currently live in the analogue area are likely to be physiologically suited to the new climate. In particular, weeds, pests and diseases that are present in the analogue area can be expected to invade. Almost all such organisms have good dispersal and should arrive with only a short delay. There is, therefore, no reason to expect Dorset to experience particularly severe pest problems in future. The pests should be no worse than they are now in Brittany.

An alternative modelling approach is based on the assumption that species' climatic tolerances are largely fixed. Limits of tolerance can be set either directly by physiology or indirectly by ecological factors such as competition, insect outbreaks or failure of synchronisation between the availability of a food resource and the ability of an animal to use it. Static models of distribution work from the assumption that present climatic tolerances will continue to apply in future.

This approach was used by ITE to assess the impact of a range of future climate scenarios upon the distribution of rare species in Britain (Elmes & Free 1994). It was assumed that the climatic requirements of species remain the same, whereas changes in average rainfall, temperatures and continentality (difference between winter and summer temperatures) occur independently as predicted by the various scenarios. Given the present distribution of a species and a scenario of change, we can then map the locations where it could occur in the future. Only 22% of the 251 rare species considered would be unresponsive to climate change. A problem with this method is that the predictions are totally dependent upon which of several often conflicting scenarios are used. For example, the study used scenarios ranging from hotter drier conditions to significantly wetter and warmer conditions compared to the present. In the former instance 40% of rare species including a significant number of Red Data Book species at the northern edge of their range, are expected to benefit while a smaller number (12%) of northern humid species might decline. However, if the wetter scenario prevailed about 22% of rare species might decline, especially those associated with the dry conditions of south-east England.

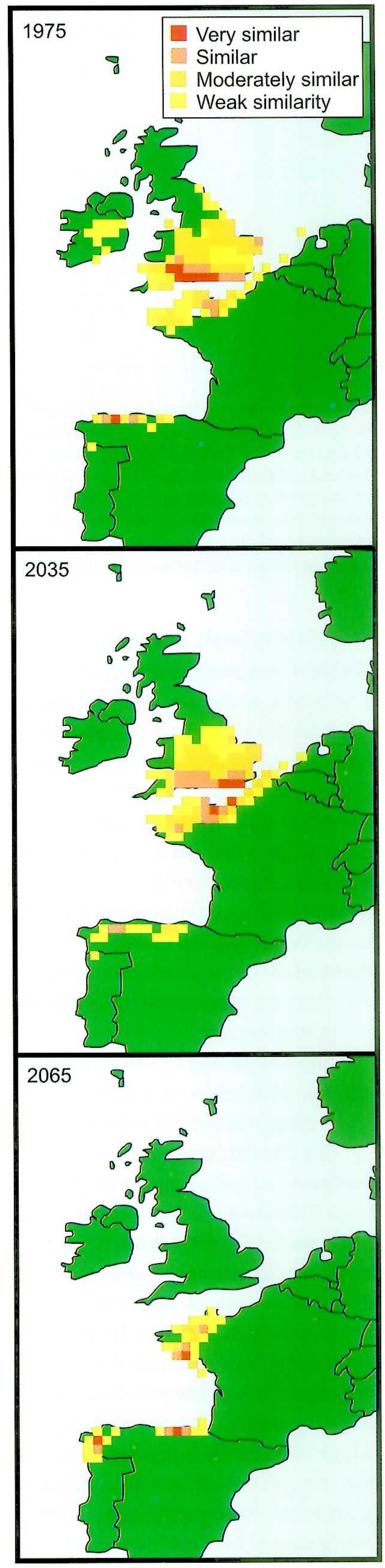

Figure 6. Present and future analogues of the present climate of Dorset, based on the UK Met Office Transient Scenario (1991). The scenario predicts the that the climate in 2035 will resemble the present climate of Sussex and Normandy, while in 2065 it will be like that of southern Brittany

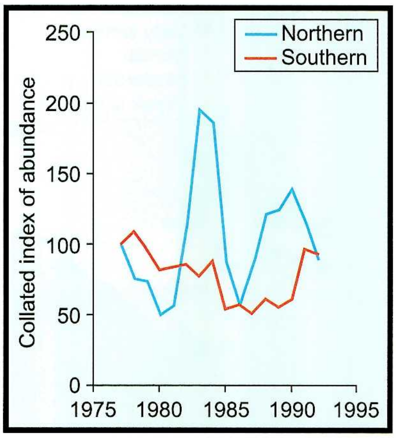

Figure 7. Annual variation in populations of the meadow brown butterfly (*Maniola jurtina*) at six northern and six southern monitored sites in Britain in 1972–92. Adapted from analysis of the Butterfly Monitoring Scheme data base by Thomas, Moss and Pollard (1994)

Dynamic models of single species

With the less mobile groups of organisms, including many species of vascular plants and non-migratory butterflies, the response to climate change will be delayed by slow dispersal. ITE has made dispersal models for a few plant species, including lizard orchid (*Himantoglossum hircinum*) and bristle bent (*Agrostis curtisii*). Parameters of the models include:

i. the potential rate of increase in a given locality
ii. the availability of suitable land
iii. the distance over which propagules are transported
iv. the climatic response.

Parameters i and ii can be estimated from field data. Parameter iii presents severe difficulties where there are occasional long-distance dispersal events. A plant of heathland such as bristle bent can extend its range in southern Britain only by moving between disjunct habitat patches. It has small seeds, which can readily be transported on the tyres of motor cars or in soil and gravel used for construction. The effectiveness of these means of dispersal is still hardly known. The climatic response (iv) is also often poorly understood. Bristle bent is a southern plant, ecologically similar to several other heathland grasses. The key ecological factor may be its response to fire, whose frequency and intensity may depend on human influences as much as on climate.

A simple dispersal model for bristle bent (United Kingdom Climate Change Impacts Review Group 1996) was based on the following assumptions.

- The potential rate of increase within a 1 km square is 40% per annum.
- Suitable land is moorland or lowland heathland.
- Propagules can be transported in small numbers up to 20 km.
- The species will be fully viable and able to spread as soon as the climate falls within its present European climatic niche.

Even with these generous assumptions, bristle bent is not predicted to spread north of Wales by 2100, although much of western Scotland will be climatically suitable. The species may need a millennium rather than a century to reach its climatic limits.

For butterfly species, ITE has shown that there is a tendency for populations living at the northern edge of their range to experience greater fluctuations (Figure 7) and hence to be more prone to local extinction than populations living central to the species ranges (Thomas *et al.* 1994). Many of the British butterfly species are close to the northern limit of their ranges. If climate change were to shift their potential limits northwards, then we would expect many populations to become more stable and local extinctions (excluding other anthropogenic factors) to become rarer. If this result is applied to insects more generally, we might expect local populations of species for which Britain forms a central or southern part of their ranges (largely the boreal and montane species), to become more variable and more prone to local extinctions.

Community based models

Communities are made up from populations of individuals belonging to different species that interact to various extents. Many communities consist of numerous interacting populations and can be very difficult to model. The problem can be simplified where there are small groups of species which interact very closely with each other, albeit within a wider community. This method has been applied to ITE's long-term study of oystercatchers (*Haematopus ostralegus*) and their principal prey, mussels (*Mytulus edulis*). Individual-based and behaviour-based models have been used to show how overwintering populations of the oystercatcher might respond to altered food supply caused by changing sea levels resulting from changing climate, as well as other anthropogenic impacts such as land-claim, shellfishing and disturbance (Stillman *et al.* in press).

Models of habitat and closely interacting populations can describe the dynamics of particular rare species of high conservation interest such as the large blue butterflies (*Maculinea* spp.). These species lay eggs on a special food plant species, but their larvae parasitize particular host ants (genus *Myrmica*) for most of their growth. ITE has developed a series of models that can be used to make predictions as to how local populations will behave under changing patterns of local habitat (eg Elmes *et al.* 1996, Thomas *et al.* 1998). The extent of which host ant species can use climatically altered habitat and compete with each other has been shown to be important in determining the robustness of large blue butterflies in the face of change. However, under the largely static climate of the recent past, local populations of the host ants appear to have experienced some selection of basal metabolism commensurate with the local climate. Southern populations are physiologically less active than northern populations of the same species. This might mean that even if populations can disperse to new habitats they might not be physiologically suited to them without some local selection over an indeterminate period.

A period of adjustment to new conditions would undoubtedly be required if the climate were to change abruptly. This is not expected to happen. Instead, communities will experience more frequent occurrences of conditions that are currently regarded as 'extreme events' According to many scenarios, southern Britain will experience more frequent and prolonged summer droughts Experiments conducted by ITE's collaborators under the TIGER thematic programme suggest that mature communities of long-lived perennial plants on nutrient-poor soils are well able to survive such events, whereas successional grasslands following intensive agriculture may lose their dominants When this happens, a transient phase with a high proportion of short-lived species intervenes

Conclusion

Climate change presents a challenge and an opportunity Given ITE's data bases and modelling experience, we can now give a fairly good indication of which species are capable of living at a given place in the future, using scenarios of change provided by climatologists The time-scale of adjustment remains elusive Birds may be able to track climate change by moving immediately to new sites as they become suitable, provided their prey populations are unaffected Many plants, on the other hand, may need millennia to reach their climatic limits Only for a few groups such as butterflies do we have a clear idea of limiting climatic factors and of how their population dynamics differ between the edge and core of their range Models of plant dispersal are still severely handicapped by lack of data on long-distance dispersal, and on how plants establish new colonies The data required to predict their future can be acquired only by persistent observation, long-term recording, and collaboration between field workers and modellers

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Future climate change research will focus on the effects of extreme events (particularly drought) and the factors controlling dispersal of species.