CLIMEX

Response of a Boreal Forest Ecosystem to Experimental Climate Change

CLIMEX

PART 1: SECTIONS 1-5

1. Strategic Relevance and Objectives

At the ministerial Conference on the Protection of Forests in Europe held in Helsinki (1993) following an earlier meeting in Strasbourg (1990) the Signatory States and the European Community made a general declaration of intent to implement the Rio Declaration, Agenda 21, the Convention on Biological Diversity and the UN Framework Convention on Climate Change as they apply to the forestry sector.

In making this declaration they recognised that human activities are substantially increasing atmospheric concentrations of greenhouse gases which will lead to climate changes that will occur over time periods considerably shorter than rotations of forest stands in Europe. These climate changes are likely to promote; (i) increased mineralisation of organic matter which will release CO_2, increase soil leaching, affect soil processes and lead to eutrophication of water; and. (ii) increased forest growth, for a certain time provided no soil changes adversely affect this, as a result of increased CO_2 in the atmosphere leading to sequestration of carbon.

It was recognised however that these and other potential impacts were highly uncertain as a result of complex ecosystem-climate interations including feedbacks and acclimatisation. As a consequence, the parties committed themselves to support further research into; (i) greater understanding of the linkages between climate change and forest ecosystems including feedbacks from the ecosystem to the climate; (ii) soil formation processes including the mineralisation of organic matter and leaching in response to climate change, and; (iii) development of process-based predictive ecosystem models applicable to the European scale and which may be used in comprehensive ways to integrate anticipated changes in the climate and their interaction with air pollution, with their effect on forest ecosystems and the fluxes of greenhouse gases.

CLIMEX offers a unique opportunity to contribute to this research agenda at a scale of study consistent with the ecosystem scale answers demanded. The observed impacts of climate change at whole ecosystem scale will be used to determine the nature and magnitude of changes and provide a basis for the construction and testing of impacts models.

1.1. Objectives

- To increase CO_2 and temperature to an entire boreal forest catchment ecosystems
- To determine whether the ecosystem is a net source or sink for carbon
- To determine the nutrient limitations on the net carbon flux in/out of the ecosystem
- To predict future response at the catchment scale and scale up predictions to whole regions
- To quantify the economic impact of global change on European forests

1.2. Scientific Background

Projected increases in atmospheric CO_2 and temperature can be expected to affect temperate and boreal forests ecosystems at many levels (Melillo *et al.* 1996). Predicting these effects is a considerable scientific challenge. At the individual plant level, increased CO_2 and temperature would be expected to increase growth and so increase the C/N content of litter. Increased temperature, however, will also increase evapotranspiration which may increase periods of soil drying and decrease plant growth. Mineralization should also be increased by temperature increases (Oechel *et al.* 1994), but only if the soils remain moist and if litter quality is not reduced by substantial increases in C/N ratios or by shifts in species composition. Mineralization in turn may release gases, including the greenhouse gases CH_4 and N_2O to the atmosphere (Van Breemen and Feijtel, 1990), and nutrients such as nitrogen and phosphorus to soil solution, surface waters and the marine environment (Schindler *et al.* 1990). Soil and water acidification and eutrophication of freshwater and marine ecosystems are possible results.

Forests are the most important carbon store on land and are generally assumed to be in steady state with respect to carbon balance. That is, their uptake of carbon is balanced by losses to respiration and leaching. Boreal regions comprise 20% of the world's forested area. The cold climate and short growing season in these regions cause low net primary productivity and decomposition and as a consequence, boreal forests represent a sizeable amount of the global C pool (Shugart *et al.* 1992). Boreal ecosystems may be quite sensitive to rising atmospheric CO_2 concentrations and increased temperatures (Eamus 1991) and because of this large stock of carbon and since it is likely that the largest changes in global climate during the next century will occur in high latitudes, quantification of the impacts of global change in boreal systems is especially pertinent (Pastor 1996).

Effects on plants often vary with species and the effects of individual processes in ecosystem biogeochemical fluxes may oppose each other, making it difficult to predict net effects at the ecosystem or landscape scale. Investigation of ecosystem-scale response requires ecosystem-scale experiments. Large-scale experiments with entire ecosystems offer a powerful scientific tool to investigate the effects of global change (Carpenter *et al.* 1995). Whole-ecosystem manipulation experiments represent the only tool by which ecosystem response can be measured and with which whole-ecosystem models can be tested. Such models are a key to future negotiations on CO_2 emissions control policy and yet they remain un-validated at a scale consistent with their structure.

Whole-catchment manipulations allow direct assessment of the effect of perturbations in the terrestrial ecosystem on runoff. The quantity and quality of runoff is to a large extent affected by processes occurring in the terrestrial catchment. Changes in terrestrial ecosystems will thus affect the aquatic ecosystems downstream. Whole-catchment experiments provide one of the few available tools to discover and quantify the response of aquatic ecosystems to future global change. CLIMEX (CLIMate change EXperiment) is unique to date in that it aims to provide a direct experimental link between terrestrial effects and aquatic effects.

CLIMEX (Plate 1) seeks to quantify the whole ecosystem response to both increased CO_2 and temperature. Other experimental approaches (Koch and Mooney 1996) such as open-top chambers, free-air-CO_2 enrichment experiments (FACE), and soil heating cables provide experimental data on the effects of CO_2 or temperature alone, over a shorter time period or on only parts of the forest ecosystem.

Plate 1. At KIM catchment a greenhouse encloses an entire 860m² forested catchment.

1.3. CLIMEX; Short term responses to treatment.

The CLIMEX experiment, located in southern Norway, utilises whole ecosystem manipulations to determine the impact of climate change. In one experiment, a 1200 m² forested catchment is enclosed within a greenhouse (Plate 2) and beginning in April 1994 has been subjected to increased CO_2 and temperature. After 3 years, observed treatment effects in the ecosystem (Table 1) relative to the experimental control are; increased leaf water use efficiency, reduction in stomatal density and increased rate of photosynthesis; increased biomass increment in *Calluna*; increased nitrogen mineralisation in soil; increased soil respiration and emission of nitrogen gases; and, increase in the flux of dissolved nitrogen at the catchment outflow.

A second experiment entails heating the soil of an entire catchment (Plate 3). Here results after 3 years indicate an increase in fine root biomass, no change in above ground biomass, but increased loss of nitrogen in the run-off water.

Table 1. CLIMEX project. Observed response after 3 years of treatment.

	plant response	soil response	water response
KIM catchment (clean rain, CO_2 and temperature)	increased stomatal density increased water use efficiency increased photosynthesis rate longer growing season increased biomass of shrubs	increased mineralisation	increased nitrate concentrations
EGIL catchment (acid rain, soil temperature)	no change	no change	increased nitrate and ammonium concentrations

The changes in leaf gas exchange were observed after the first year of treatment and changes in plant and soil dynamics were observed following the second and third years of treatment. The increase in catchment output flux of nitrogen is surprising given that the productivity of this ecosystem is thought to be limited by nitrogen. This heirarchy of responses was largely expected. Further treatment may cause changes in tree growth and nitrogen and carbon cycling. The key questions which remain relate to the new steady state relative to the new climate and how long this will take to occur. Of equal importance is to determine if the boreal forest ecosystem is a net source or sink for carbon under the new climate and to determine the controls of nutrient availability on the ecosystem dynamics controlling the carbon fluxes.

Plate 2. The forest in KIM comprises Pinus sylvestris and Betula pubescens and the dominant ground vegetation is Vaccinium myrtillus and Calluna.

1.4. Results of the International Review of CLIMEX

In September 1996, the European Commission conducted an independant evaluation of the CLIMEX project. The evaluation panel recommended;

- Continuation of the existing treatment regime for a minimum of two additional years.

- Ecosystem gas flux studies and coordinated detailed ecophysiological investigations be continued, and intensified. If possible, more detailed studies of how nutrient pools and fluxes interrelate should be undertaken, perhaps by incorporating stable isotopes as tracers.

- Documentation of tree growth and nutrition be continued with the classical approach by assessment of needle chemistry more closely linked to ecophysiological studies of the trees.

- Documentation of changes in ground vegetation, and the mechanisms responsible for the observed changes must be continued in order to fulfill the major objectives of the project.

- Synthesizing results of individual project components into models of sources and sinks of carbon, tree growth, nitrogen losses via streamflow, atmospheric exchange and water balance. In turn, these syntheses should provide the basis for scaling up results to regional and larger scales. Once accomplished, economic implications for boreal countries need to be considered.

These recommendations are largely followed in the formulation of this proposal to continue the CLIMEX experiment.

Plate 3. At EGIL catchment heating cables have been installed on the soil surface.

2. Work Content

This two-year proposed project builds on the previous three-years of experimental manipulation and attempts to address key questions relating to the medium term response of the C and N cycles within the catchment system.

2.1. The CLIMEX Experimental Facility

The CLIMEX project involves two separate forested headwater catchment manipulations. CLIMEX began in 1992 using the former RAIN project facilities at Risdalsheia near Grimstad, Norway (lat. 58° 23' N, long. 8° 19' E). Treatment began in April 1994. Three adjacent catchments, ROLF, CECILE and METTE serve as untreated references.

Experiment 1. CO_2 and air temperature are increased in a greenhouse (Figure 1) enclosing the KIM catchment (860m^2). In the lower 70% of the catchment area (KIM_T), CO_2 is increased to 560 ppm and temperature increased by 3°C above ambient in summer and 5°C above

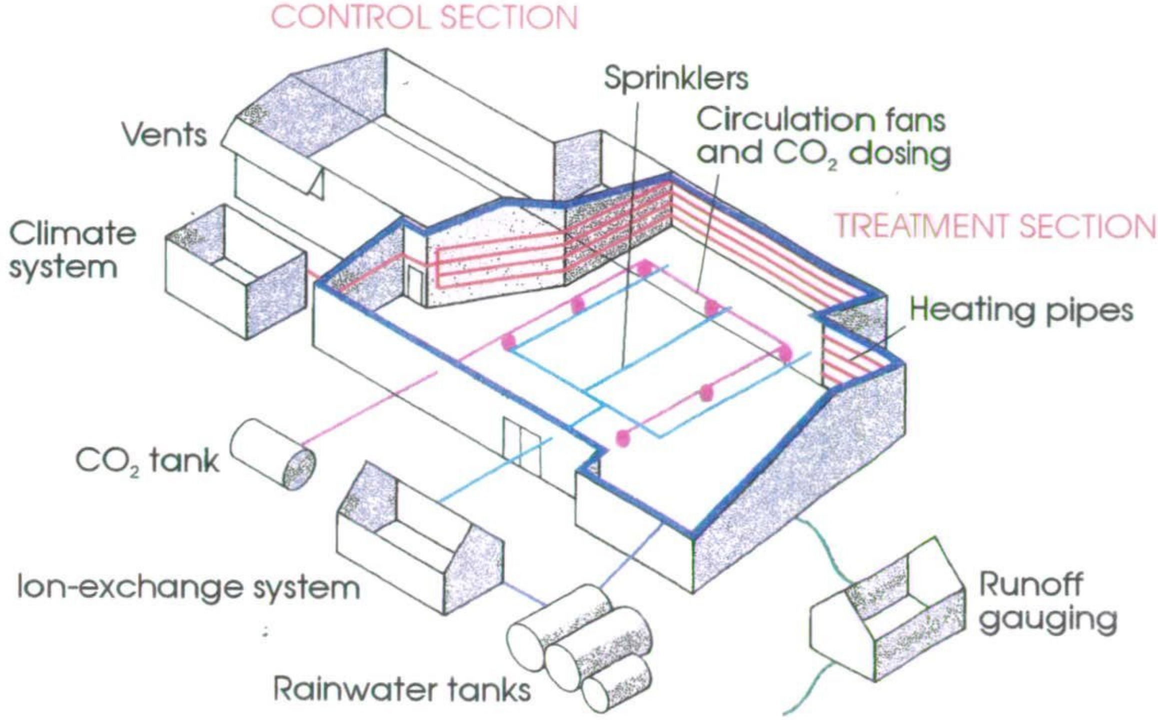


Figure 1. A schematic of the greenhouse installation at KIM catchment.

ambient in winter. The upper 30% of the catchment is separated by an impermeable wall and recieves no climate treatment (KIM_C). Since 1984, KIM catchment has received clean rain: ambient outputs of acid pollutants are removed from precipitation by means of ion-exchange and clean precipitation with neutral levels of seasalts re-added beneath the roof. KIM_T and KIM_C have similar plant species composition, hydrology and soils. Rainfall volumes are maintained at ambient level.

Experiment 2. At EGIL catchment ($400m^2$), soil temperature is increased to the lower 80% of the catchment area ($EGIL_T$) using the same variation through the year as at KIM_T. The upper 20% of the catchment remains untreated ($EGIL_C$). EGIL catchment receives ambient acid rain.

2.1.1. Experimental Design

At the ecosystem-scale CLIMEX is based on the multiple catchment design in which single catchments are manipulated while several similar adjacent catchments serve as untreated references (Figure 2). CLIMEX entails treatment at 2 catchments; KIM (clean rain, CO_2 and temperature) and EGIL (acid rain, soil warming). Catchment scale responses such as changes in run-off chemistry are revealed by (i) comparison of treatment catchments with the untreated references and (2) comparison of pre-treatment with post-treatment at each catchment.

At the level of plant and soil processes CLIMEX entails multiple plots within each treatment

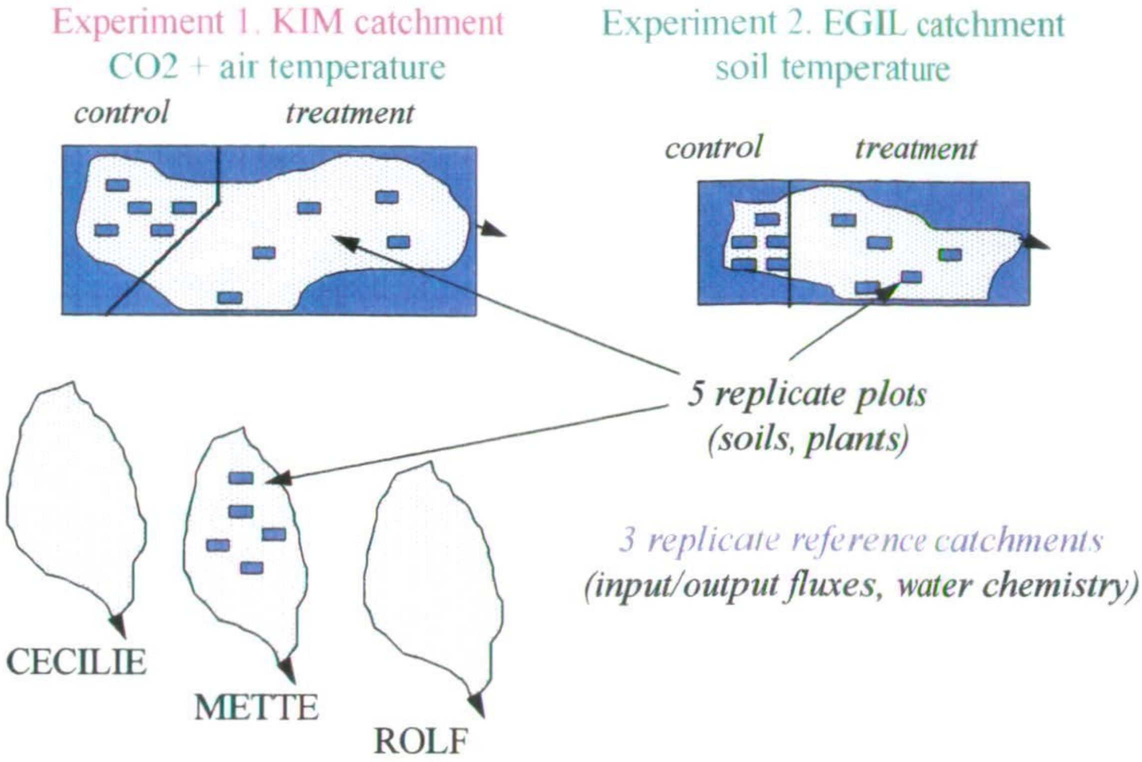


Figure 2. Schematic of the experimental design employed in CLIMEX.

and reference. The uppermost 20% of each catchment is reserved as untreated control. At KIM catchment this section is separated by a transparent wall such that the control part (KIM_C) is inside the greenhouse, receives clean rain but is not subjected to increased CO_2 and temperature. Similarly, at EGIL catchment, the upper 20% is not heated by cables.

At $EGIL_T$, soil warming is achieved using electric heating cables, a method successfully applied at 4 other forested sites in the USA and Sweden. This also allows intercomparison of scientific results of several soil warming experiments with a similar design but on different ecosystem types. Soil and plant monitoring is carried out using the same replicate sampling strategy as at KIM. The upper 30% ($EGIL_C$) serves as an 'unheated' control (without cables) and so enables comparison with $EGIL_T$ and with outside reference catchments.

2.1.2. Technical Design

At KIM catchment, CO_2 is added to the treatment area at 6 points to achieve the target value of 560ppm during the growing season (April - October). CO_2 concentrations are monitored in KIM_T, KIM_C and outside using infra-red gas analysers (Figure 1). Within KIM_T, CO_2 dosing, air heating and opening of the side panels of the greenhouse (ventilation and cooling) are computer controlled as a function of CO_2 concentration and temperature in KIM_T relative to KIM_C. Roof mounted fans circulate the air to prevent thermal stratification (Plate 4).

Treatment began in KIM_T in April 1994 with a step change in CO_2 and temperature and has continued until present. Ecosystem response to treatment will reflect the combined impact of increased CO_2 and temperature, simulating conditions predicted to occur around 2050 AD (IPCC 1995). This system has functioned satisfactorily for three years of treatment. For example, in the second year, the target CO_2 concentration of 560ppmv was achieved for 90% of the time (Figure 3) and KIM_C concentrations matched outside ambient levels. Acceptable performance was also achieved in the temperature regime (Figure 4). Relative humidity, though not controlled, has been generally similar in KIM_T, KIM_C and outside.

At EGIL catchment, electric heating cables in the lower 80% are placed on the soil surface about 10 cm apart. A seasonally-varying temperature difference between the control and heated areas of 5 °C in January and 3 °C in July is maintained. Temperature is monitored and controlled by 120 thermistors placed in different depths throughout the catchment. Treatment began in $EGIL_T$ in April 1994 with a step change in temperature and has continued until present (Figure 5).

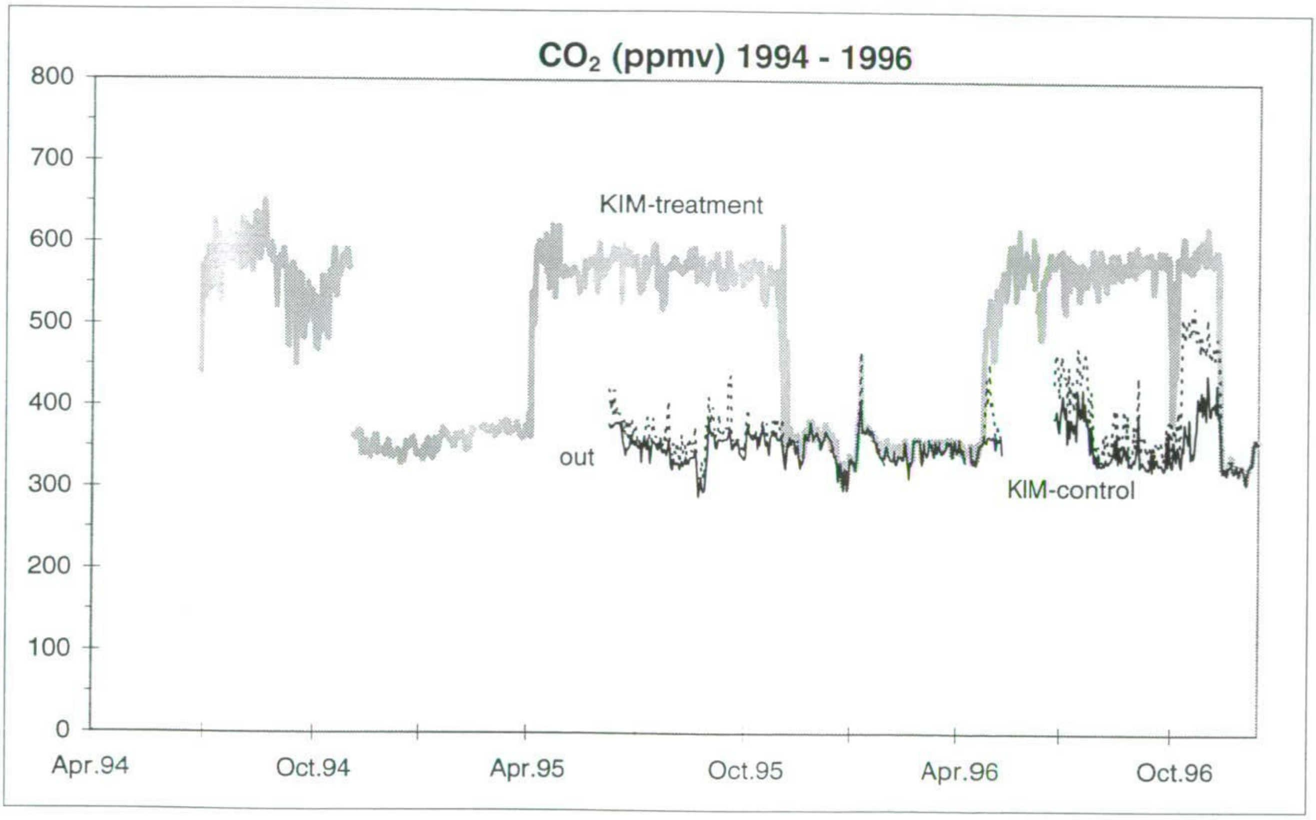
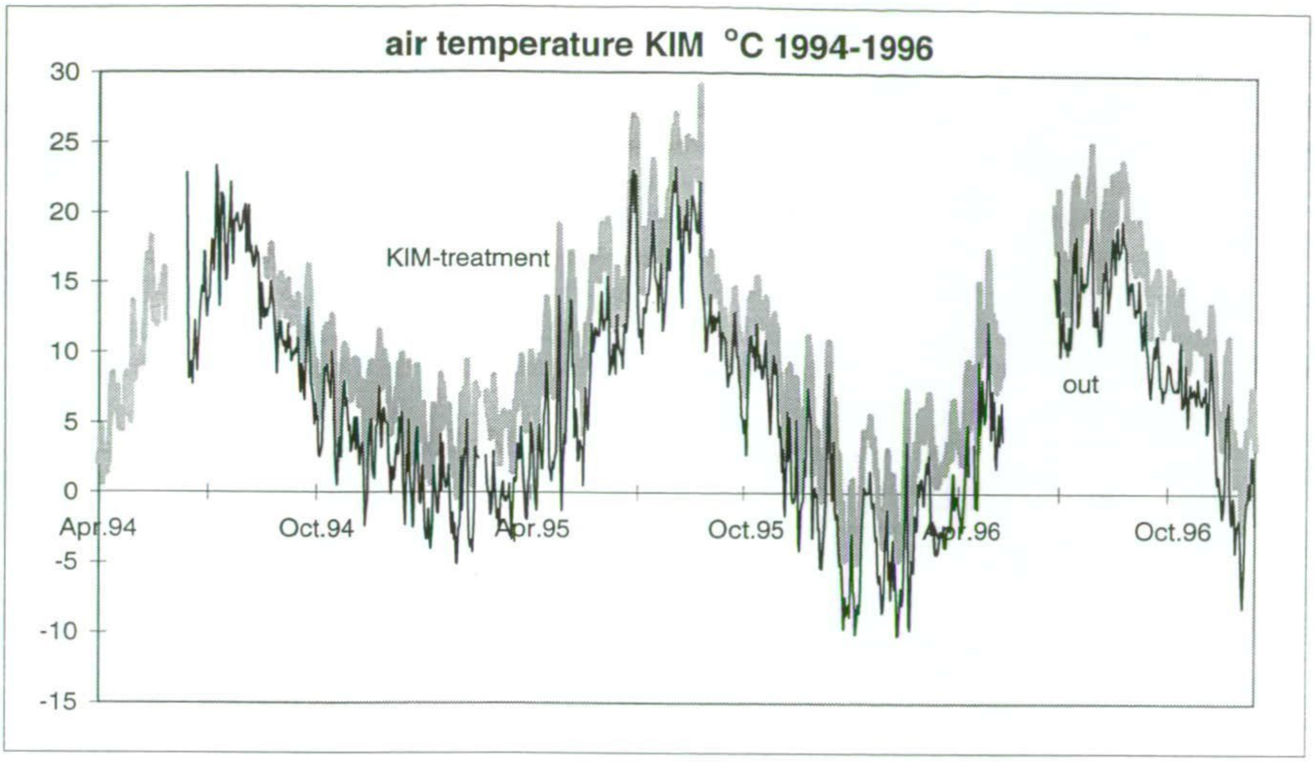


Figure 3. CO_2 concentrations in KIM_T, KIM_C and outside during 3 years of treatment. Note that the return to ambient CO_2 in KIM_T in September 1996 was deliberate to enable measurement of gas emissions.



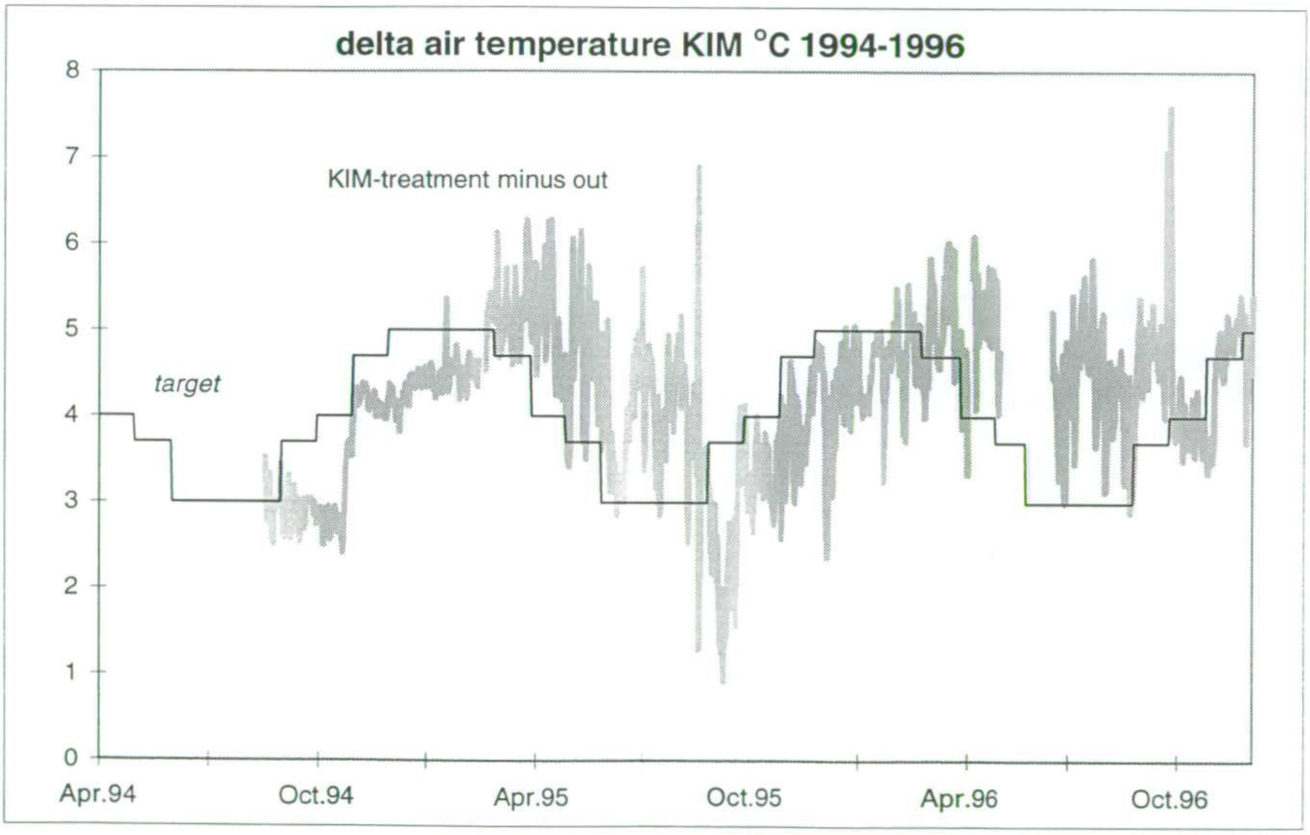


Figure 4. Air temperature in KIM_T and outside during 3 years of treatment. The lower panel shows the difference in temperature against the target.

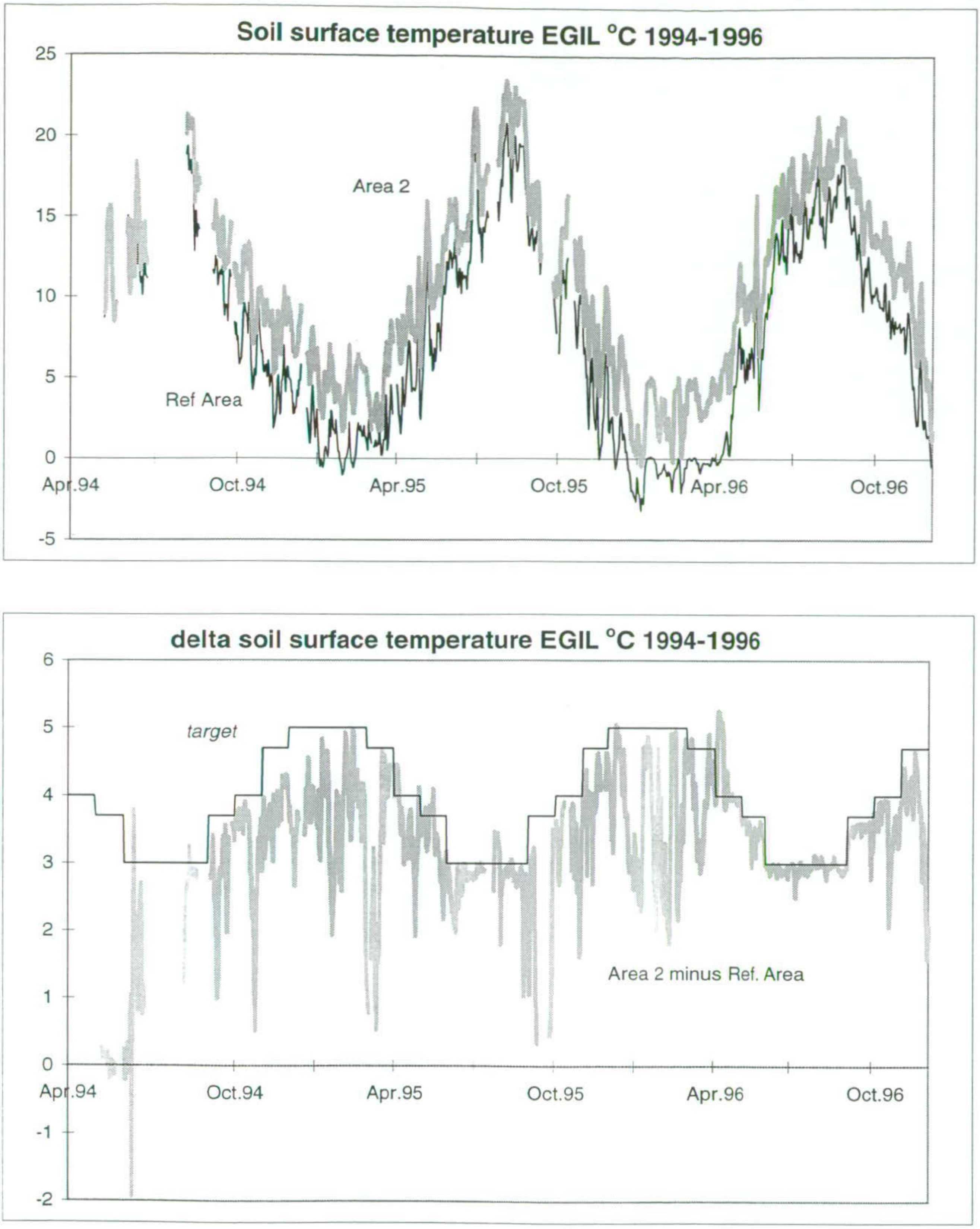


Figure 5. Soil surface temperature in $EGIL_T$ (Area 2) and $EGIL_C$ (Ref. Area) during 3 years of treatment. The lower panel shows the difference in temperature against the target.

Plate 4. Roof mounted fans circulate the air inside the KIM greenhouse and prevent thermal and CO_2 stratification.

2.2. Work Plan

This proposed continuation of CLIMEX focuses on two key questions; (1) Is the ecosystem a net source or sink for carbon ? (2) Is the carbon net flux limited by nutrient availibility ?

The potential for carbon sequestration from the atmosphere by the boreal forest ecosystem is dependant on the relative responses of the soils and vegetation to future changes in CO_2 and temperature. Transient conditions of increased growth of vegetation may allow net CO_2 fixation by the vegetation to exceed soil respiratory losses but this is unlikely to continue over the long term. Continued increase in soil nitrogen availibilty, however, may permit sustained stimulation of photosynthesis depending on the extent of down regulation by vegetation. This response may be critical and is largely unknown for mature trees since the majority of CO_2 experiments are confined to saplings and the interpretation of down regulation is confounded by the small rooting volume associated with pot-based experiments. CLIMEX offers the opportunity to overcome both of these issues.

Soil nutrient release and status could dictate the capacity of the vegetation to fix CO_2. Under conditions of nutrient limitation, plants grown in enriched CO_2 and increased temperature can down regulate (acclimate) the amount of Rubisco in their leaves. The extent of acclimation, in plants unconstrained by pot size, will be strongly dependent on soil N availibility.

The effect of 3 years of climate treatment on tree growth and carbon pools has been small.

This may indicate that temperature and CO_2 availibility are not the main limiting factors for growth in this catchment ecosystem. The effect of 3 years of climate treatment on growth of the dwarf shrubs has been an increase in total biomass and total nitrogen in the ground vegetation. However, nitrogen concentrations in the plants has not increased. Increased total nitrogen in biomass can be explained by the observed increase in rates of nitrogen mineralization presumably in response to increased temperature. This suggests that nitrogen is still a limiting factor in this system despite the increased availability in the soil. It is feasible that continued higher nitrogen mineralisation rate will in future result in higher plant nitrogen content. Higher nitrogen availability may also promote increased nitrogen loss from the system. Clearly, other nutrients may also limit growth in this system but the treatment effects on the availability of these nutrients is unknown. If any other macro-nutrient becomes limiting, relative to nitrogen, then plant nitrogen content and nitrogen loss from the system may increase at earlier point in time.

These questions will be addressed through the quantification of the ecosystem boundary fluxes of carbon and the major macro-nutrients; nitrogen, phosphorous and potassium (whole catchment gas emissions and water fluxes) and identification and quantification of the mechanisms controlling the carbon and macronutrient fluxes (uptake and cycling through vegetation and soils). These observations will be carried out simultaneously through two coordinated field campaigns each year (spring and autumn) and, where relevant, by continuous monitoring. In addition, a ^{15}N tracer experiment will be carried out to provide insight in the role of increased N mineralization in regulating carbon cycling at increased CO_2 and temperature.

The programme of work for two years consists of; (i) continued operation and maintenance of the CLIMEX treatments; (ii) scientific studies relating to the behaviour of boreal forest ecosystems in response to experimental climate change; (iii) interpretation of the data in a modelling framework, and; (iv) extrapolation of model outputs over space and time for preliminary economic assessment.

The scientific design focusses on; (1) developing an understanding of the processes operating within the ecosystem in response to the climate change; and (2) representation of this process understanding in mathematical models capable of prediction and extrapolation of climate change impacts in space and time and development of an economic assessment of the predicted future impacts across wide regions of Europe. Processes in the ecosystem will be studied by observation and experimentation within the greenhouse facility established as part of CLIMEX. Model development and application will draw upon observed data from this experiment as well as from other climate change experiments around the world.

2.2.1. Site Operation

Operation of the experimental facility

The ongoing experimental treatments at both KIM (CO_2 and temperature) and EGIL (soil warming) will be continued. This includes the maintainance of elevated temperature throughout the year at KIM_T and $EGIL_T$ and of elevated CO_2 at KIM_T during the growing season, April - October.

Hydrometeorological monitoring

Hydrometeorology will be monitored continuously within the treatment and control sections of both KIM and EGIL and outside at the untreated reference catchments. Temperature is a controlled variable but other parameters change as a function of temperature and as a result of the influence of the greenhouse structure itself. Monitoring of these variables in treatment, control and outside catchments aids the interpretation of observed responses and enables the effect of the treatment to be assessed with respect to the effect of the enclosure.

The monitoring includes; water discharge from five catchments (hourly); rainfall in the greenhouses and outside (hourly); solar radiation, air temperature and humidity in the greenhouses and outside (hourly).

2.2.2. Scientific Studies

Ecosystem gas fluxes

One of the key ecosystem responses to climate change is the net atmosphere - biosphere exchange of CO_2, H_2O and a range of reactive trace gases. Trace gases include CH_4, N_2O, NO, NO_2, CO, O_3 and VOCs. These trace gases strongly influence tropospheric ozone concentrations and the lifetimes of major pollutant gases. The unique properties of the CLIMEX experiment provide an opportunity to measure directly the net fluxes of CO_2, H_2O and many of these trace gases and to study differences in the fluxes between the high CO_2 treatment chamber (KIM_T) and the low CO_2 chamber (KIM_C). Furthermore, by developing methods to measure fluxes over very short time scales the responses of fluxes to radiation, temperature and soil water may be obtained.

KIM_C and KIM_T catchments can be treated as giant dynamic cuvettes for measuring the whole ecosystem source or sink of trace gases over several hours. Whereas other such studies of trace gas fluxes typically use small boxes (< $1m^2$) placed on the soil surface, the CLIMEX greenhouses allow fluxes to be measured at a scale 3 orders-of-magnitude larger and encompassing the entire ecosystem. Two sets of measurements made in 1996 indicate differences between KIM_C and KIM_T in the fluxes of CO_2 and CH_4. Both systems demonstrate the normal diurnal cycle of photosynthesis and respiration, but at ambient CO_2 concentrations (KIM_C) the net ecosystem rates of carbon fixation are smaller than in KIM_T, as a result of larger respiratory losses. KIM_T also has much larger rates of CH_4 oxidation. These results are preliminary and require quantification and further study.

The measurements to date are based on a tracer technique to determine rates of exchange of air within the chambers (KIM_T and KIM_C) to provide the relationships between effective ventilation rate and windspeed (with all windows and doors closed). The data show that very small fluxes of the trace gases (e.g. fluxes of 0.1 ng NO-N m^{-2} s^{-1}) can be quantified and subtle effects of the CO_2 and temperature treatments on soil-atmosphere losses of fixed nitrogen may be measured as well as the much larger net CO_2 fluxes from soils and vegetation.

The objective of the gas flux measurements is to quantify the ecosystem fluxes of CO_2, H_2O, CH_4, N_2O, NO, NO_2, SO_2 and O_3 and their response to CO_2 concentration and temperature treatments. The work will also be used as a part of the integration of the smaller scale studies and in this way help with upscaling the responses of individual species to provide the net exchange of the ecosystem. The work will also provide direct evidence of effects of the treatment on rates of decomposition of soil organic matter and on rates of denitrification averaged over the large area of the chamber.

The measurements will be made during 2 campaigns during each of the two years of the study. These campaigns will be made (1) in June, shortly after the leaves of deciduous species have completely expanded and (2) in September, shortly before senescence begins. The work will be timed to coincide with studies of leaf gas exchange to allow comparison and upscaling.

Fluxes of CO_2 and H_2O will be measured using a Licor 6262 IRGA with Licor 610 calibrator. Detection limits for fluxes of CO_2 under typical conditions will be 0.1 mmol m^{-2} h^{-1} and for water vapour 0.03 mol m^{-2} h^{-1}. Concentrations of CH_4 will be measured using a tunable diode laser (TDL) spectrometer capable of providing extremely high resolution of small concentration differences (*c.* 0.5 ppb in 1800 ppb). The detection limit for fluxes in this system is about 0.3 µmol CH_4 m^{-2} h^{-1}. Thermo Electron analysers will be used for the remaining species giving detection limits of 0.2 ng N m^{-2} s^{-1} for NO_x, 0.2 ng S m^{-2} s^{-1} for SO_2 and 8 ng m^{-2} s^{-1} for O_3.

Fluxes of all species will be obtained at ambient CO_2 concentrations, and fluxes of CO_2 and H_2O will be measured at CO_2 concentrations between ambient and 1500 ppm to allow comparison with leaf scale measurements of photosynthesis. Comparison will be made between these CO_2 and CH_4 fluxes and those obtained using small cuvettes (0.1 m^2 area) outside the catchments. This will allow the "chamber effect" of KIM_C to be quantified.

Solute fluxes

Runoff from the catchment represents an important pathway for loss of carbon, nutrients and other components from the ecosystem. Runoff is the result of the net effect of processes within the ecosystem and integrates the response over the entire catchment. Because both the volume and chemical composition of runoff can be measured quite precisely, change in runoff provides a sensitive signal of change within the terrestrial catchment ecosystem.

Runoff volume and chemical composition has been measured regularly for 13 years at catchments at the Risdalsheia site. Samples for chemical analysis are collected weekly and analysed for pH, major ions (Na, K, Ca, Mg, Cl, SO_4, F), Al-species (reactive-Al, non-labile Al), N-species (NO_3, NH_4, total-N), total-P, total organic C, and SiO_2. Analyses are made by modern state-of-the-art techniques (including ion chromatography, induced coupled plasma spectrophotometery and automated colorimetry) specially adapted to low ionic strength freshwaters, and the laboratory is certified under ISO 9000 standards. Runoff volume is measured continuously on site.

Changes in concentrations and fluxes as a result of the climate manipulation are tested by several statistical techniques. Random Intervention Analysis (RIA) uses paired samples from an untreated reference catchment and a treated catchment taken for a period prior to and after onset of treatment to test for significant changes in relative concentrations due to manipulation. Time series analysis offers another means of testing.

The concentrations and flux of TOC in runoff are expected to increase in response to the increased CO_2 and temperature. Two factors are important. The increased temperature should speed up decomposition of soil organic matter and result in increased release of dissolved organic matter. Increased temperature should cause increased evaporation and decreased runoff, such that the concentrations of TOC will increase. After 2 years of treatment the TOC concentrations have increased slightly at KIM_T relative to the 3 untreated reference catchments. Annual flux of carbon in runoff is about 1.0 mol C m^{-2} yr^{-1}.

The concentrations and fluxes of key nutrient species in runoff provide a sensitive indicator of changes in nutrient availability and cycling within the terrestrial catchment ecosystem. Boreal forest ecosystems such as those at Risdalsheia are typically limited by nitrogen supply. At Risdalsheia chronically high levels of nitrogen deposition have resulted in apparent nitrogen saturation as indicated by high levels of inorganic nitrogen in runoff. At the reference catchments over the 10-year period 1984-1993 ambient nitrogen deposition was 83 mmol N m^{-2} yr^{-1}, and runoff of inorganic nitrogen about 51 mmol m^{-2} yr^{-1}. At KIM catchment the nitrogen deposition has been dramatically reduced by the roof since 1984 to about 18 mmol N m^{-2} yr^{-1} during the period 1984-993 and down to nearly zero after the installation of air-tight walls (which exclude dry deposition) on the structure for CLIMEX. Compared with the other catchments at Risdalsheia, runoff from KIM in 1993 contained only 2 mmol m^{-2} yr^{-1} of inorganic nitrogen, a strong indication that the ecosystem is limited by nitrogen supply.

The increased CO_2 and temperature at KIM due to treatment have, as expected, resulted in increased growth of plants and increased biomass. The uptake of nitrogen by plants has apparently increased to provide the nitrogen for this biomass increase. The increased plant demand for nitrogen is thus expected to reduce the concentrations of nitrogen in runoff. On the other hand, increased temperature is expected to increase decomposition of organic matter in the soil, and so release additional nitrogen. This in turn should increase the amount of nitrogen in runoff. The change in concentrations of nitrogen in runoff will thus reflect the net result of these two processes and could be either positive or negative.

Results from the first 2 years of treatment indicate that nitrate concentrations and perhaps also ammonium concentrations in runoff from KIM have increased slightly since the onset of treatment (from <2 to 7 - 14 mmol inorganic N m^{-2} yr^{-1}) The ecosystem data together thus suggest that increased mineralisation of organic matter has increased sufficiently to both supply the extra demand by the plants as well as leave some left over to be lost in runoff. Flux and concentrations of organic nitrogen have not changed significantly (20 mmol organic N m^{-2} yr^{-1}).

The measurement programme also encompasses other key nutrients such as phosphorous and potassium. As yet there have been no significant changes in the fluxes of these elements that can be ascribed to the climate change treatment of CLIMEX. The flux of phosphorous from the catchments in 1995 ranged from 0.13 - 0.35 mmol m^{-2} yr^{-1}. The flux of potassium from the catchments in 1995 ranged from 2-7 mmol m^{-2} yr^{-1}.

Vegetation dynamics

After 3 years exposure to elevated CO_2 and temperature changed amounts of Rubisco and its activation state in vegetation have not been observed. Leaf photosynthetic rates are generally higher in KIM_T compared to KIM_C indicating the potential for increased photosynthetic carbon fixation. This capacity may increase further if soil mineralisation rates continue to supply increased nitrogen to the plants.

Measurement of leaf gas exchange rates of two dominant tree species (*Pinus sylvestris* and *Betula pubescens*) and the ground shrub *Vaccinium myrtillus* will be measured using an IRGA. Measurements will be taken hourly to characterise daily variation through two periods in the growing season; mid- and late-season. Plant respiration rates have not yet been adequately quantified in CLIMEX and these may be critical for determining the net carbon balance of the vegetation alone. Therefore, leaf respiration rates will be quantified and partitioned into growth and maintenance components following the approach of Wullschleger (1993). Stem respiration rates of mature pine and birch trees will be measured using an IRGA and following the approach of Edwards and Hanson (1996). At the same time soil respiration rates will be determined at several locations around the catchment. Soil respiration rates will be measured using a portable soil respiration chamber at several different locations within the treatment and control sections of KIM and in an outside reference catchment.

These data will be combined with estimates of the total stem area, canopy development and leaf area, as well as total soil area measurements for each catchment to produce gross carbon budgets for the treated and untreated areas of KIM during each of the two field measurement campaigns. The catchment carbon budgets will then be used to partition shifts in the source/sink relations of the whole ecosystem identified by the CO_2 gas flux measurements made over the same periods as the vegetation measurements. The approach will, however, be unable to quantify the contribution of fine root respiration to the ecosystem carbon budget since this is integrated into the soil respiration.

To characterise the extent of down regulation in leaf photosynthesis in the dominant tree and shrub species, mesurements of leaf assimilation versus CO_2 response, leaf carbon and nitrogen contents and direct enzyme assays of Rubisco amount and activity will be undertaken on replicate plants in the control, treatment and outside reference catchments. These measurements will be taken during the two field campaigns in mid- and late growing season.

The extent to which the capacity of vegetation to fix CO_2 is affected by the treatments will be examined by (i) constructing photosynthesis (A) versus intercellular CO_2 concentration (c_i) response curves (A/c_i curves) on leaves of the dominant tree species (*Pinus sylvestris* and *Betula pubescens*) and the ground shrub *Vaccinium myrtillus* together with measurements of leaf carbon to nitrogen ratios, and (ii) direct assays of the amount of Rubisco and its activation state of leaves of mature individuals for the same species as (i). These measurements will be performed on individuals of each species in the treated and control sections of KIM and on plants in the outside reference catchment. Leaf A/c_i curves will be constructed using an IRGA and the sampling strategy for each species as set out previously.

Rubisco content will be determined by PAGE (polyacrylimide gel electrophoresis) separation and Western blotting and quantification (Nie *et al.* 1995). As in previous monitoring at the site, leaves will be collected for each species from individuals in KIM to obtain representative measurements for each species. This suite of measurements will permit an understanding of the extent to which Rubisco amount and activity has changed in response to the CLIMEX treatment. Given that Rubisco requires substantial investment of nitrogen by the plants, a reduction in Rubisco amount would be indicative of some degree of nutrient limitation.

With respect to vegetation growth, the initial hypothesis is that nitrogen availability is the main factor limiting plant growth, especially in KIM_C and KIM_T where nitrogen deposition has been extremely low since 1984. Increased temperature will increase nitrogen mineralisation which will initially be the main regulator of the growth response to the manipulation. The main supply of nitrogen to support this increased growth is hypothesised to be decomposed organic matter and further, it is expected that the increased temperature and CO_2 will increase the internal cycling of nutrients, especially potassium.

For the ground vegetation, total carbon in the biomass has been calculated as part of the earlier experiments. Using growth measurement data the amount of carbon in biomass before treatment can be reconstructed. By continuing the growth measurements and through vegetation mapping, future changes in the ground vegetation carbon pool will be estimated.

Growth of ground vegetation will be monitored by marking and measurement during the first visit to the site in mid-June (after full leaf development) and measurement and harvesting in mid-August (before senescence). Plant species composition will also be recorded during mid-August (to maintain comparability with previous years measurements). Measurements of productivity and plant biomass turnover will be carried out in each of the treatment and reference areas. Production and turnover of leaves, flowers and stems of the dominant species in the ground vegetation will be estimated by measuring labelled plants and harvesting shoots.

Root turnover will be measured in mini-rhizotrons using a camera attached to an endoscope. Photographs will be taken during the growing season in five mini-rhizotrons per treatment, at fixed positions within each mini-rhizotron. Length of living and dead roots will be measured, and the life-span of roots will be estimated by following individual roots in time.

With respect to tree growth, it is hypothesised that; (i) increased temperature and CO_2 will initially increase the tree growth, and; (ii) that increased assimilation of CO_2 in the canopy will initially increase the C/N ratio due to nitrogen limitation.

Tree growth, biomass and element concentrations in tree biomass were estimated in 1996 and will be determined again after a further 2 years of treatment in 1998. The carbon pool in tree roots, needles/leaves, stems, bark and branches of the major tree and ground vegetation will be quantified to determine changes in growth and allocation of carbon within the plants. For the trees this will be done by combining measurements of tree diameters at breast height and tree height with general biometric relationships for pine and birch trees in Nordic countries. The biometric relationships will be tested and adjusted to local conditions from cutting and fractionation of single trees at the site outside the experimental plots. From these measurements and calculations total biomass and allocation of carbon to the different tree pools and the relative growth rates will be estimated.

Fluxes of carbon will be determined in litterfall sampled by ten randomly placed litterfall collectors. The litterfall will be separated into pine needles, birch leaves and a "rest fraction" (small branches, dust, buds, etc.). Based on existing measurements of seasonal and spatial variation and distribution the yearly fluxes will be separated into monthly fluxes. Throughfall will be collected in 5 funnels per plot placed under canopies and carbon (TOC) and element cycling (TON, N, P, K) will be calculated from measurements in throughfall. Litterfall samples from KIM_T, KIM_C and METTE will be pooled and analysed for C, nutrient and major ion content annually. This system will be replaced/supplemented with smaller funnel collectors with a more well defined canopy cover above and the measurements will be upscaled to the plot and ecosystem scale.

Chemical analysis of the produced plant material from trees and dominant ground vegetation (C, N, starch, lignin, cellulose) will be carried out to determine the effects of the different treatments on chemical composition and decomposability of the litter that is produced.

Soil dynamics

Field observations indicate that in KIM_T the soil body is shrinking where it wedges out thinly over the granite surface forming the rim of the watershed. By monitoring the soil/granite boundary (from earlier soil data, existing photographs and new photographs) and marking the boundary between soil and granite (starting winter 1996/97) and appropriate sampling and analysis of carbon and nitrogen in KIM_C, KIM_T and METTE, this process will be quantified. To further describe soil carbon dynamics, determination of mineralization rates of litter will be continued in 1997-98 and 1998-99 using (1) litterbags with standard pine litter in KIM_T,

KIM_C and METTE (2) litterbags using high and ambient CO_2 grown litter from CLIMEX plots, and (3) cellulose stubs. During the final treatment year soil nitrogen mineralization will be monitored every six-eight weeks as has been done done in past 4 years, in KIM_C, KIM_T and METTE.

Soil moisture and hydrology

Soil moisture content is monitored at several locations in KIM and EGIL (4 hourly) using Time Domain Reflectometry. A semi-permanent water table exists in KIM during wetter periods and the level of this is monitored using a piezometer (hourly). The soil moisture measurements are combined with a hydrological model and by kriging techniques to provide estimates of catchment soil water storage and evapotranspiration over short time periods (4 hourly for example). Assessments of hydrological response times and runoff characteristics will also be undertaken annually using chemical tracers to indicate changes in dominant flowpaths.

A ^{15}N pulse labelling experiment

A ^{15}N pulse labelling study will be carried out in KIM_C , KIM_T and METTE during the growing season of 1997. The fate of the label will be followed in the major and most dynamic plant and soil pools. A process-based carbon and nitrogen isotope model (NICCCE) (Van Dam and Van Breemen 1995) will be used to describe transformation rates of C, ^{14}N and ^{15}N. The objective of the ^{15}N study is to calibrate the NICCCE model, so as to (i) test the hypothesized increase in plant nitrogen uptake from increased mineralization of soil nitrogen (that cannot be achieved with conventional methods), and (ii) indicate the source of the observed increase of nitrogen in runoff in KIM_T. The ^{15}N study will thus provide insight into the role of nitrogen in regulating carbon cycling at increased CO_2 and temperature.

Experiments with ^{15}N enrichment at manipulated plot or catchment scale have been carried out frequently in recent years (Nadelhoffer *et al.* 1995, Buchmann *et al.* 1996, Koopmans *et al.* 1996). Quantitative conclusions from such experiments are often limited to the fate of the applied ^{15}N in a certain ecosystem pool or flux after a certain time period. Here we will use ^{15}N enrichment to estimate transformation rates of dynamic C and N pools with a process-based simulation model (Tietema and Van Dam 1996). Such a model is fitted to the data by an optimization routine, yielding the unknown rates and parameter values (Koopmans and Van Dam. in press).

The NICCCE model has been successfully applied to describe the transformations of carbon and nitrogen stable isotopes in two coniferous forest ecosystems. (Koopmans and Van Dam, in press). As a first step, in February and March 1997, before the 1997 growing season, the NICCCE model will be calibrated on available non-^{15}N data collected during the previous 3 years of the CLIMEX project. This calibrated version of the model will then be used to simulate the effects of a pulse addition of ^{15}N. The model exercise will aim to:

i. determine the most reactive pools and fluxes, and the optimal size of tracer addition and frequency of sampling. The most reactive pools require the highest measuring effort.

ii. determine the necessary amount of ^{15}N (expected to be less than 1% of the total atmospheric N input) to be added to obtain measurable enrichments in even the largest pools. The use of NICCCE to answer this question has been described before by Kjønaas *et al.* (1993).

One ^{15}N pulse will be given in late April or early May 1997 just before bud break, as ammonium sulphate or -chloride added to the rain in the KIM catchments, and sprinkled by hand in METTE. Pre-treatment ^{15}N contents in relevant pools and fluxes will be measured on existing samples and, if neccessary, samples taken before the labelling. This serves two goals; (i) knowledge of the initial natural abundance of ^{15}N in the various ecosystems is required to set the initial conditions of the model; and (ii) differences in ^{15}N natural abundance in vegetation and soil are known to be correlated with nitrogen status of the ecosystem (Emmett *et al.* in press) and observations will indicate the degree of nitrogen saturation in KIM_T.

^{15}N will be monitored for at least two years. It is expected that the relatively small pools, like the forest floor, soil microbial biomass and freshly produced plant biomass (needles, leaves, roots), will be most reactive and will be sampled most frequently. Initially, nitrate leaching out of the catchment will probably be the most reactive flux. Other, less reactive pools and fluxes that will be measured occasionally are mineral soil, older needles and wood. To indicate the source of the most labile N pool the ^{15}N content will be determined in N mineralized in mineralization tubes in the last treatment year.

2.2.3. Prediction and assessment of climate change impacts

A key focus of this proposal is the interpretation of the observed responses to treatment in CLIMEX within a modelling framework. This enables the prediction of continued response to treatment and aids in the development of models for other ecosystem types. The models will be dynamic and process based and will be used to extrapolate across wider regions. Model results can then be linked to an economic assessment of climate change impacts and so provide information of direct policy relevance. The models will be designed to be sufficiently robust to enable scenario assessment and to provide tools which may be used in conjunction determination of CO_2 emissions control policies within Europe.

Vegetation modelling - NUCOM

The NUCOM model (Berendse 1994) simulates the interaction between soil organic matter accumulation, changes in nutrient mineralisation and the competition between plant species in heathlands. The model has been adapted to simulate vegetation succession from drift sand to forest under different climatic conditions, atmospheric CO_2 concentrations and nitrogen deposition levels (DRIFT model). In this model plant populations compete for light, nitrogen and water. Carbon assimilation at different CO_2 levels is calculated on the basis of intercepted irradiation, temperature and the nitrogen concentration in photosynthetic tissues. Direct and indirect effects of climate change on evapotranspiration, soil moisture content, decomposition and nitrogen uptake are also simulated.

The model calculations are performed for each species in the vegetation, and the species interact through shading and competition for nitrogen and water. Changes in the availability of nitrogen, water and light during succession will result in shifts in the plant species composition. The direction of these changes will depend on the driving variables (CO_2 concentration, temperature and nitrogen deposition). With NUCOM we will be able to predict changes in species composition, as well as effects on the carbon and nitrogen cycles in this ecosystem for different climate change scenarios.

The dominant species in CLIMEX (*Calluna*, *Vaccinium*, *Pinus* and *Betula*) are also important species in these models, and many species parameters are therefore available. For CLIMEX, the NUCOM model will be extended to simulate ^{15}N and ^{13}C fluxes, using separate ^{15}N and ^{13}C budgets, and also the spatial distribution of species will be modelled. Validation of the model will be carried out using data collected during the first four years of CLIMEX and data which will be gained from continued monitoring of plant growth and species composition.

Catchment scale modelling - MERLIN

A major advantage of catchment-scale experiments such as CLIMEX is that the flux of chemical components in runoff provides a highly sensitive indicator of change within the ecosystem. Process-oriented models at the catchment scale can exploit this sensitivity by linking key processes operating within the ecosystem in a mathematical model and then testing the model by predictions of runoff chemistry with observations. Several such catchment-scale, process-oriented models will be evaluated using data produced by CLIMEX.

MERLIN (Model of Ecosystem Retention and Loss of Inorganic Nitrogen) (Cosby *et al.* In press) is a catchment-scale mass-balance model of linked carbon and nitrogen cycling in terrestrial ecosystems that was specifically designed to predict and simulate leaching losses of nitrogen. MERLIN has been successfully used to simulate changes in nitrogen leaching due to changes in forest cover and nitrogen deposition at the NITREX experimental site at Aber, Wales, UK (Emmett *et al.* in press). MERLIN has also been applied to other NITREX sites and to similar large-scale manipulation experiments in North America.

MERLIN offers potential as a means by which future response to global change can be quantitatively evaluated. Much of the focus of CLIMEX is on carbon and nitrogen cycling, and MERLIN provides the mathematical framework into which the experimental data can be placed in a systematic fashion. The experimental data from can be used to calibrate the model, and the calibrated model can then be used for scenarios studies and to scale up in space and time. This work will be coordinated with the DYNAMO project, a 3-year project (1996-98) funded in part by the European Commission, with a focus on the modelling the interactions between global change, atmospheric deposition and land-use change at the catchment-to-regional spatial scale and decade-to-century time scale.

Landscape Scale Modelling - Sheffield Vegetation-Biogeochemistry Model

Dynamic global vegetation - biogeochemistry models are required to predict the likely response of the terrestrial biosphere to anticipated future global environmental change and for improved representation of an active vegetation surface within general circulation models of the Earth's global climate system. Testing the predictions of such models is an essential part of their development prior to their use in a predictive capacity.

Process-based ecosystem models are required to investigate the impact of future global environmental change on the terrestrial biosphere. In addition, models capable of realistically simulating the vegetation-mediated exchange of energy and momentum between the Earth's surface and the atmosphere are required within general circulation models (GCMs) of the Earth's global climate system (Woodward *et al.* 1995). The absence of an active and realistic vegetated surface within GCMs will lead to inaccurate forecasts of future climates. As part of a coordinated research effort (Steffen *et al.* 1992) several such models have been developed (Prentice *et al.* 1992, Running and Gower 1992, Woodward *et al.* 1995) but rigorous testing of the predictions has remained limited to data from plants grown in small-scale experiments (e.g. Woodward *et al.* 1995, Rastetter 1996). Data collected as part of CLIMEX provide the only means to test the predictions of these models at a relevant spatial scale.

The predictive capacity of these models will be assessed by comparing predicted and measured CO_2 and water vapour fluxes from leaves of mature trees growing within the treated and control sections of the CLIMEX greenhouse. The integrated ecosystem response to the CO_2 and temperature treatments in CLIMEX is revealed in soil-solution and runoff carbon concentrations, and measurements of these are used for comparison with model predictions based on historical records of climate. The model is used to predict the likely responses of several ecosystem processes (photosynthesis, net primary productivity (NPP), carbon concentration in soil-solution and runoff) and structural features (leaf area index (LAI)) to future global environmental change and to separate the effects of temperature and CO_2 on the responses.

The proposed modelling procedure begins with the University of Sheffield global primary productivity model (Woodward *et al.* 1995). This model incorporates the biochemical processes of photosynthesis and the dependence of gas exchange on stomatal conductance, which in turn depends on temperature and soil moisture. Soil water loss by evapotranspiration is controlled by canopy conductance. Nitrogen uptake to leaf layers is proportional to irradiance, and respiration and maximum assimilation rates are set as functions of nitrogen uptake and temperature. Total nitrogen uptake is assumed to be temperature dependant and is derived from soil carbon and nitrogen. Long-term average annual carbon and hydrologic budgets are used to set canopy leaf area. Although observations constrain soil carbon and nitrogen, the distribution of vegetation types is not specified by an underlying map. Preliminary modelling results indicate that at scales from biochemical processes to the whole canopy simulated variables agree favorably with experimental results for both current and elevated CO_2 atmospheres. Simulated global distributions of leaf area index and annual net primary productivity are sufficiently realistic to demonstrate that the model can be used to investigate vegetation responses to global environmental change.

The NPP computed by the vegetation model will then be used in the biogeochemistry-decomposition model CENTURY (Parton *et al.* 1993, VEMAP 1995). CENTURY simulates the C and N dynamics of vegetation and predicts soil organic matter (C and N) from predictions of NPP for any given climate and atmospheric CO_2 concentration and has been extensively and successfully tested against global observational data on soil nutrients (Post *et al.* 1985). The newly-derived soil nutrient status is then used to drive the vegetation model and the iteration continued until equilibrium values of LAI and NPP are achieved.

Initial attempts to predict the future response of the catchment ecosystem at Risdalsheia (KIM) to increased CO_2 and temperature treatment using the Sheffield vegetation-biogeochemistry model suggest that NPP increase will occur ahead of any large increase in LAI. This is in accordance with other experimental data from water limited and/or nutrient limited ecosystems, such as the boreal forest (Field *et al.* 1995). In this case, the model predicts that as the CLIMEX treatment continues at KIM catchment only small changes in annual runoff will be observed since plant growth has effectively increased for the same precipitation regime. Clearly, further work is now required to refine these model applications and ultimately to test the predictions against observed response to the continued climate treatment.

Forest production and economic assessment - SUAS Model

Economic analysis of impacts of climate change on economics of forests production and forest products trade are rare. Perez-Garcia *et al.* (in press) have carried out analyses on the effect of climate change on forest growth, production, consumption, prices and trade up to the year 2040. Their results show that coniferous timber production will decrease in European producer countries like Finland and Sweden, but increase in Canada. There is a similar impact on non-coniferous timber production. The overall net economic impact of climate change is predicted to be positive with a net present value increase between US$11 and US$16 billion (in 1980 prices), for the global forest sector.

On the other hand, Burton *et al.* (1995) predict minimal economic impacts in the US from climate change. They predict the change in the economic welfare will be less than 1% (positive under some conditions and negative under others). The IPCC estimates that climate change alone would be responsible for a 1-9% increase in land suitable for forests, with the largest gains in temperate and boreal regions, up to the year 2050.

Most predictions of global climate change are very general in nature and it is difficult to model the economic implications of this change in all countries. A variety of primary and secondary economic effects may result from changes in tree distribution, growth rates and wood quality. These changes could result from differences in timber yields, forest product yields, product quality, industrial structure or regional employment.

Scenarios for forest development in Scandinavia will be derived from the SUAS-model. These scenarios will describe the potential supply of roundwood from Scandinavian forests. The potential change in international trade in forest products will then be estimated to determine whether or not a country will gain or lose when the forest resources are impacted by climate change.

The SUAS model was developed at the Swedish University of Agricultural Sciences (Sallnäs 1990) and was later used in the IIASA Forest Study (Nilsson *et al.* 1992). The model uses matrix-type simulation calculating at five-year intervals. It generates projections of growing stock, increment and timber harvest volumes over time by country, species and age class. For each forest type, it requires data on area, growing stock and annual increment per age class. This data is held on the European Forest Resource Database. At the moment the SUAS model can simulate scenarios of total harvest level per species group, thinning and final felling regimes per species, regeneration rates, and afforestation rates. Furthermore, the growth of the forest can be adjusted according to assumed effects of forest decline.

To incorporate the effects of climate change on the Scandinavian forest resource for the next 100 years the response of the trees will be modelled using estimated and measured growth changes (% of stem increment and allocation changes resulting in changing whole tree/stemwood biomass ratio) and natural mortality rate changes. Scandinavia has been chosen as the maximum upscaling level because this region covers a large part of the economically important part of the European forest resource and because CLIMEX is located in the boreal forest. In addition, much research has been carried out on possible impacts of climate change on these forests.

A harmonised set of variables describing the impacts on the forest ecosystem will be set up in order to incorporate the impacts at the appropriate level and with a standard methodology. The required information will be generated by the CLIMEX experiment, from literature (e.g. Kellomäki 1995, Kellomäki and Pohtila 1995, Landsberg *et al.* 1995, Sykes and Prentice 1995, Sykes *et al.* 1996, Talkkari and Hypen 1996) and from the catchment scale models *(MERLIN* and the *Sheffield* model). Also, information from other EU funded projects (e.g. ECOCRAFT and EUROFLUX) will be used. A set of functional forest types will be assessed from the database which now includes 622 forest types for the three Scandinavian countries. This will reduce the number of responses to be assessed to approximately 20 functional forest types.

To incorporate the effects of climate change a new methodologywill be developed. Based on the CLIMEX data and the intermediate upscaling approaches, information will be available on transient responses of the tree species. Such responses will be incorporated by adapting the growth curves and then stemwood volume can be converted to whole tree biomass and carbon. This will enable changes in allocation due to climate change to be accounted for and an assessment of the future carbon balance of the forest resource.

The model produces output for variables such as distribution of forest area over volume and age class at the national level and by tree species during the simulation period, mean volume development during the simulation, mean age development during the simulation at the national level and by tree species, the actual harvest from thinning and final felling at the national level and by region and tree species.

We will use two methodologies to estimate economic consequences of climate change on forest products markets in different countries in Europe: ETTS V-framework (ECE 1996) and Phelps-model (Zhang *et al.* 1993). The ETTS V-study (ECE 1996) provides the best and most up-to-date starting point for this analysis.

3. Project Milestones and Deliverables

Milestones

-- The technical operation of the experiment will be assessed annually at the completion of each full year of treatment (February 1998 and 1999).

-- The ^{15}N tracer addition will be undertaken in April/May 1997 following collection of samples.

-- Intensive field monitoring campaigns will take place in May/June and August/September 1997 and 1998.

-- The evaluation of all data collected will take place at annual project meetings to be held in February 1998 and 1999.

-- Modelling workshops will be held in May 1997 and April 1998 to address model validation, linkage and extrapolation issues. Members of other relevant EU programmes will be invited to participate.

Deliverables

Deliverables from CLIMEX will be primarily in the form of reports and publications of the scientific information resulting from the project in international, peer-reviewed journals. All will be public documents, open without restriction.

Project reports will include the following:

-- annual report of technical aspects of the project, including data on climate conditions and an integrated report of the main scientific findings of the experiment and modelling approaches.

-- articles in the peer-reviewed scientific literature; presentations at scientific conferences.

-- a final report summarising the responses of the whole catchment ecosystems to experimental change over a 6-year period.

In addition the CLIMEX site at Risdalsheia will be open to visitors. In previous years up to 1000 persons have visited Risdalsheia annually. As the world's largest single climate change experiment CLIMEX attracts interest from many groups including politicians, environmental policy-makers, scientists, and the general public. CLIMEX has been featured by television, radio and the press.

4. Benefits

The whole-ecosystem experiment is now a well-established tool in ecological research (Carpenter *et al.* 1995). Experiments have been carried out in terrestrial, aquatic, wetland and marine ecosystems. Such experiments provide direct information on ecosystem response to perturbation and help identify driving processes and dynamics of ecosystem change. Results of ecosystem experiments are highly relevant to environmental policy. Data from such experiments provide important means by which predictive models of ecosystem response can be developed and evaluated.

In global change research as in all other ecological research there is a place for experiments at many scales. The advantages of large-scale whole-ecosystem experiments obviously include such things as minimised edge effects, ability to encompass interactions between species and different components of the ecosystem, and ability to integrate feedbacks between different ecosystem processes. The major disadvantages include the high costs and lack of replicates. Whole-ecosystem manipulations, however, provide perhaps the only means by which the validity of small-scale experiments can be assessed. As Schindler (1991) points out, in some cases the results from small-scale experiments are indeed corroborated by whole-lake experiments, but in other cases the results although statistically significant are in fact simply an artefact of the experimental design. CLIMEX can be used to evaluate results from such small-scale experiments.

The complexity of ecosystems is such that laboratory and small plot experiments are difficult to interpret (or may even give misleading results) when scaled-up to the whole ecosystem. Laboratory experiments are also usually of short duration and thus also difficult to extrapolate in time to the years and decades required for most ecosystems to respond to environmental perturbation. Environmental monitoring while providing data from intact natural systems does not help with determining dose-response relationships except "after the fact". Thus whole ecosystem experiments fill the gap between smaller-scale, short-term laboratory experiments and environmental monitoring.

The experimental design at KIM involves simultaneous increases in CO_2 and temperature which reflect the conditions predicted to occur around 2050 AD (IPCC 1995). Clearly, it will not be possible to differentiate between effects of CO_2 and effects of increased temperature alone in the interpretation of the observed ecosystem responses. This experimental design, however, was deliberately chosen to provide the science community with a unique experiment. The GCTE operational plan calls for large scale manipulation experiments but focuses on FACE technology because the technical aspects of raising CO_2 and temperature to a boreal forest are considerable. CLIMEX offers a solution. Almost all other experiments conducted using other technologies (and mostly at smaller scale) attempt to determine the effects of CO_2 and temperature alone. Results from these can be used to supplement and augment the results from CLIMEX.

The experimental facility is built around a pre-existing experiment at the site which incorporates removal of S and N deposition to study reversal from acidification. The advantages of building onto this design are mainly financial in that the roof structures already existed. Building new greenhouses of this scale from "scratch" would involve a capital expenditure of around ECU 1 million. Scientifically, the great advantage of this setup is the excellent database, particularly of surface water chemistry and soil chemistry, which has been continually measured since 1984. This long monitoring history permits separation between natural year-to year variation and the effect of a treatment, and establishes a baseline for water and soil chemistry against which the effects of the CLIMEX manipulations will be clear. Considerable advantage is also gained from the use of staff with more than 10 years experience working with the facility. A further advantage of siting the experiment in this area arises from the fact that the site is located at the southern limit of the boreal forest in N. Europe and this is a vegetation type predicted to change in response to climate change. There is also considerable interest in the role of the boreal forest as a C sink.

CLIMEX is of European scale and global relevance. CLIMEX is relevant to the setting of emissions levels for CO_2 and other greenhouse gases. CLIMEX provides direct information of the ecosystem-scale effects of in creased atmospheric CO_2 (and other greenhouse gases) and the interaction with other atmospheric pollutants and thus contributes to scientific base upon which emissions policies for major gases (CO_2, SO_x, NO_x, NH_4) are decided.

CLIMEX represents a major EU contribution to IGBP (International Geosphere-Biosphere Programme). Indeed CLIMEX has been accepted as a Core Project under GCTE (Global Change -- Terrestrial Ecosystems) as part of Core Research Category 1 (Steffan *et al.* 1992). Results from CLIMEX provide a unique basis for evaluating predictive models of ecosystem response to future global change. The data can be used to test dynamic global vegetation models (DGVM) as part of the IGBP activities under GAIM (Global Analysis, Interpretation and Modelling). Indeed results from CLIMEX and similar whole-ecosystem manipulations with other types of ecosystem are one of the few means by which such models can be "ground-truthed".

CLIMEX is best carried out at the European level. The boreal forest ecosystems of CLIMEX are found in many northern European countries, and indeed at high latitudes over much of the northern hemisphere. The results are thus of pan-European significance. Because the ecosystem processes affected by the climate change manipulations at Risdalsheia function in many types of terrestrial ecosystems, the results are also relevant to other ecosystems as well. Finally the terrestrial-aquatic link provided by these whole-catchment experiments are of significance for freshwater ecosystems as well.

5. Economic and Social Impacts

Not applicable.

CLIMEX

PART 2: SECTIONS 6-10

6. Project Management Structure

The project management structure has evolved over 4 years of successfull operation. The project coordinator, site manager and lead scientists have considerable knowledge of the site and expertise in their science areas. In this respect, CLIMEX brings together many of the leading scientists in ecosystem and global change research. The formal structure of the project management is shown in Table 2 and the work responsibilities of each participant within each task is indicated. Project review meetings are held each year and these will be supplemented by workshops dedicated to evaluation and reporting of modelling techniques and advances. In addition, all fieldworkers meet at the site during the field campaigns and this encourages free transfer of data and ideas and provides an ideal forum for multi-disciplinary cooperation. The scheduling of the tasks and of major meetings and deliverables is given in Figure 6.

	Partners Involved
1. Project Coordination (JENKINS IH)	
2.1. Site Coordination (WRIGHT NIVA)	
2.1.1. Site Operation HOGBERGET (NIVA)	2
2.1.2. Hydrometeorology Monitoring COLLINS (IH)	1,2
2.2. Scientific Coordination (JENKINS IH)	
2.2.1. Ecosystem Experiments VAN BREEMEN (WAU-SSG)	
2.2.1.1. C Sink/Source FOWLER (ITE)	1,2,3,4,5,6,7
2.2.1.2. N Limitation BERENDSE (WAU-TENC)	1,2,3,4,5,6,7
2.2.1.3. N15 Experiment VAN DAM(WAU-SSG)	2,3,4,6
2.2.2. Modelling and Extrapolation JENKINS (IH)	
2.2.2.1. Catchment Models WRIGHT (NIVA)	1,2
2.2.2.2. Soil/Vegetation Models RASMUSSEN (RISOE)	1,3,4,5,6,8
2.2.2.3. Regional Assessment PAIVINEN (EFI)	6,8

Table 2. The management structure, breakdown of tasks, task coordinators and partners involved in each task.

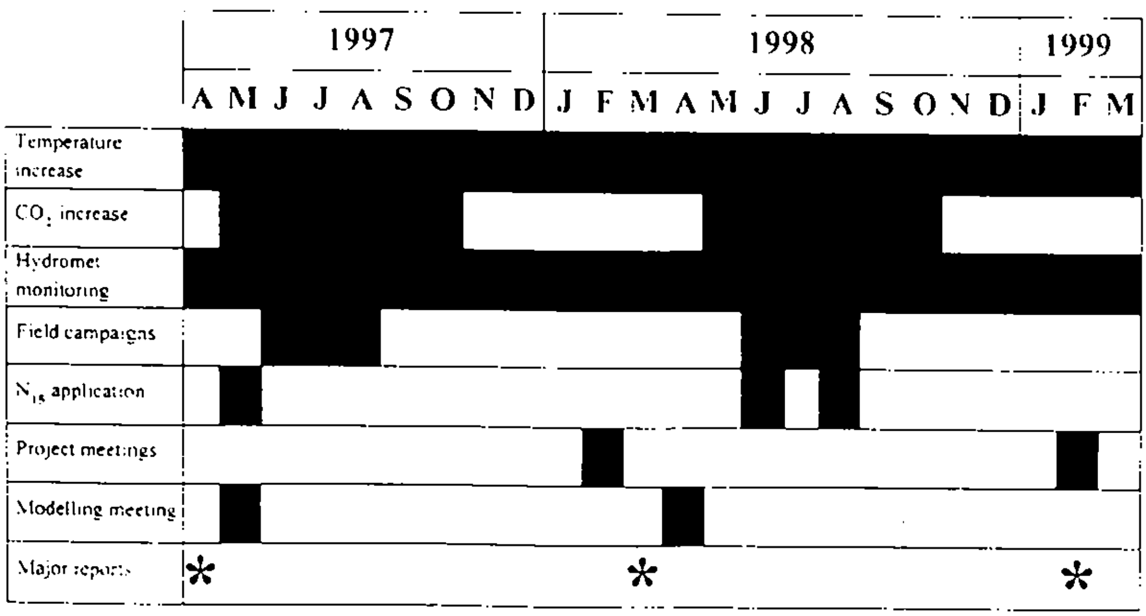


Figure 6. The scheduling of the main tasks and of major meetings and deliverables.

7. The Partnership

Partner Number; **01**
Laboratory; **Institute of Hydrology (IH), UK.**
Principal Investigator; **Dr. Alan Jenkins**
Scientists Involved; Mr. Rob Collins

IH has been at the forefront of hydrological and environmental research since its establishment as the only dedicated hydrological research laboratory in the UK in 1962. IH has undertaken research into global change modelling and impacts assessment at national and international level. These include; improving the representation of land-surface hydrology within GCM models; regional assessment of the potential impact of future climate change on evaporation and runoff in the UK, Europe and Africa; assessment of the potential impacts of climate change on water quality in the UK; and, assessment of the impacts of climate change on water resources management in the UK. IH are currently involved in several EU research programmes the most relevant to this area are GRAPES (Groundwater and River Resources Action Programme on a European Scale), LAPP (Understanding Land Surface Physical Processes in the Arctic) and DYNAMO (Dynamic Models for Scaling Up the Impacts of Environmental Change on Biogeochemical Systems).

Experience;

Dr. Alan Jenkins is currently the Head of the Water Quality Division at IH. He has managed and led several large modelling programmes directed at assessing climate change and land use effects in catchment ecosystems in the UK. His expertise lies in the development and application of catchment scale hydrochemical models and their use in scenario assessment. His work is widely published in international journals. Dr Jenkins has been the coordinator of CLIMEX since its inception in 1992.

Relevant Publications;

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Cosby, B.J., Ferrier, R.C., JENKINS, A., Emmett, B.A., Wright, R.F. and Tietema, A. (1997) Modelling the ecosystem effects of nitrogen deposition: Model of Ecosystem Retention and Loss of Inorganic Nitrogen (MERLIN). Biogeochemistry. In Press.

Arnell, N., JENKINS, A. and George, D.G. 1994. The Implications of Climate Change for the National Rivers Authority. UK National Rivers Authority R&D Report 12. HMSO. London

Partner Number; **02**
Laboratory; **Norwegian Institute for Water Research (NIVA), Norway.**
Principal Investigator; **Dr. Richard F. Wright**
Scientists Involved; Dr. Anke Lükewille, Mr. Jarle Håvardstun, Mr. Rolf Høgberget, Ms. Mette Lie, Mr. Tore Sørvåg, Ms. Ann-Kristin Buan

NIVA is Norway's largest and leading research organisation dealing with freshwater ecosystems and water pollution. NIVA's analytical laboratory has an international reputation for high quality analyses of freshwaters. The effects of climate change on aquatic ecosystems and the interaction of acidic deposition with climate change are identified as important and urgent research fields both at NIVA and within Scandinavia. The Norwegian Institute for Water Research (NIVA) has over 20 years of research experience in the fields of acid deposition, global change and effects on aquatic ecosystems. A central part of this research has focused on the terrestrial-aquatic interface, and the impact of changes in terrestrial ecosystems on water quality. NIVA has conducted several large-scale whole ecosystem experiments with terrestrial, aquatic and marine ecosystems, including the RAIN project (acid rain exclusion to whole catchments), NITREX project (whole-catchment additions of nitrogen) and the HUMEX project (whole-lake acidification experiment), and now most recently the CLIMEX project (whole catchment manipulation with CO2 and temperature), These facilities were supported in 1994-96 in part by a grant from the European Commission ("Human capital and mobility programme -- access to large-scale facilities"). NIVA's research in this field is interdisciplinary and internationally oriented, and the institute has infrastructure and experience from similar large international projects.

Experience;

Senior scientist Richard F. Wright will conduct the work at NIVA. He has over 20 years experience in hydrochemical research including field study, experimental and modelling research. He has 13 years experience in running the experimental facilities at Risdalsheia, first as the RAIN project (1984 - 1994) and then as the CLIMEX project.

Relevant Publications;

Wright, R.F., Lotse, E. and Semb, A. 1993. RAIN project: results after 8 years of experimentally reduced acid deposition to a whole catchment. Can. J. Fish. Aquat. Sci: 50, 258-268.

Carpenter, S.R., Chisholm, S. W., Krebs, C.J., Schindler, D.S., and Wright, R.F. 1995. Ecosystem experiments. Science 269: 324-327.

Wright, R.F., and Schindler, D.W. 1996. Interaction of acid rain and global changes: effects on terrestrial and aquatic ecosystems. Water Air Soil. Pollut. 85: 89-99.

Lükewille, A., and Wright, R.F. In press. Experimentally increased soil temperature causes release of nitrogen at a boreal forest catchment in southern Norway. Global Change

Partner Number; **03**

Laboratory; **Wageningen Agricultural University, Dept of Soil Science and Geology (WAU-SSG), NL.**

Principal Investigator; **Prof. Dr. Nico Van Breemen**

Scientists Involved; Dr. Peter Buurman, Dr. Douwe van Dam, Dr. Hugo Denier van der Gon, Fayez Raiesi Msc, Ir. Paul Verburg, Ir Esther Kockkoek, Mr. Eef Velthorst.

The soils departments at the WAU, together with those from the neighbouring Agricultural Research Institutes in Wageningen, form one of the largest concentrations of soils expertise in the world. The Department of Soil Science and Geology has more than 15 years of experience in studying the effects of changing environmental conditions on the chemistry of soils, soil solution, groundwater and sediments (e.g. NITREX and EXMAN EU Projects).

An important ongoing activity of the research group is the study of the impacts of climate change (in particular elevated temperature and CO_2) on cycling and sequestration of C in terrestrial ecosystems (CLIMEX and BERI EU Projects). Research on effects of land use change on greenhouse gas emission is carried out mainly in the tropics: studies on effects of deforestation on C and N cycling in Costa Rica and studies on the effect of agricultural management on emission of methane from rice fields in the Phillipines, China and Indonesia. The common approach in these studies is to apply a combination of monitoring of biogeochemical processes and modelling.

Experience;

Nico van Breemen will supervise the work at SSG-WAU. He has over 25 years of experience in soil process research, both in the tropics (SE Asia and Central America), in Europe and the USA. Since 1980 he has been involved in a large number of projects on relationships between soils and large-scale environmental problems, such as acidification and climate change, often as initiator and project leader. He has been responsible for soil studies in CLIMEX since 1992. Dr Douwe van Dam is an expert in the modelling of C and N isotopes in terrestrial ecosystems. He has cooperated in ^{15}N studies at different spatial scales, ranging from microcosm to plot-scale.

Relevant publications;

VAN BREEMEN, N. 1995. Nutrient cycling strategies. Plant and Soil 168/169, 321 - 326.

Van Dam, D., and VAN BREEMEN, N. (1995) NICCCE: a model for cycling of nitrogen and carbon isotopes in coniferous forest ecosystems. Ecological Modelling 79, 255-275.

Wesselink, L.G., VAN BREEMEN, N., Mulder, J. and Jansen, P.H. 1996. A simple model of soil organic matter complexation to predict the solubility of aluminium in acid forest soil. Eur. J. Soil Science 47, 373-384.

TIETEMA, A. & D. van Dam 1996. Calculating microbial carbon and nitrogen transformations in acid forest litter with ^{15}N enrichment and dynamic simulation modelling. Soil Biology and Biochemistry 28, 953-965.

Partner Number; **04**
Laboratory; **Wageningen Agricultural University, Dept of Terrestrial Ecology and Nature Conservation (WAU-TENC), NL.**
Principal Investigator; **Prof. Dr. Frank Berendse**
Scientists Involved; Dr. Wim Arp

The department of Terrestrial Ecology and Nature Conservation of WAU is the largest university department in the Netherlands that focuses on the dynamics of the species compositions and nutrient cycles in natural ecosystems. In the department expertise is combined on systems ecology, plant ecology, plant-soil and plant-herbivore interactions. The department runs a very well equipped analytical laboratory, where most chemical analyses of plant and soil material can be carried out. The department participates in the Dutch National Programme on Climate Change and within this research programme develops models that simulate the interaction between nutrient cycling and plant population processes. These models have been found to be appropriate tools to predict effects of climatic change on plant species composition and diversity on a time scale of several decades. The department also participates in the EU funded BERI and CANIF projects.

Experience:
Professor Frank Berendse will be responsible for the research conducted at TENC-WAU. He has 20 years experience of running field and greenhouse experiments and the development of models for plant competition and nutrient cycling. He has been responsible as a principle investigator in three EU-funded projects. Dr. Wim Arp has for the last ten years participated in large scale experiments studying the effects of elevated CO_2 on natural ecosystems. The group has been responsible for studies of ground vegetation in CLIMEX since 1992.

Relevant publications:

Arp, W.J. and Berendse, F. 1993. Plant growth and nutrient cycling in nutrient-poor ecosystems. In: Climate change: crops and terrestrial ecosystems (van de Geijn, S.C., et al., eds.). Agrobiologische Thema's 9: 109-123, AB-DLO, Wageningen.

Berendse, F. and Jonasson, S. 1992. Nutrient use and nutrient cycling in northern ecosystems. In: Arctic ecosystems in a changing climate (F. Chapin et al. eds.). Academic Press, San Diego. pp. 337-356.

Berendse, F. (1993). Ecosystem stability, competition and nutrient cycling. In: Biodiversity and Ecosystem Function (Schulze, E.-D. and Mooney, H.A., eds.). Ecological Studies 99; 409-431. Springer Verlag, Heidelberg.

Berendse, F. (1994). Competition between plant populations at low and high nutrient supplies. Oikos 71; 253-260.

Berendse, F., Schmitz, M. and de Visser, W. (1994). Experimental manipulation of succession in heathland ecosystems. Oecologia 100; 38-44.

Partner Number; **05**
Laboratory; **University of Sheffield, UK**
Principal Investigator; **Dr. David J. Beerling**
Scientist Involved; Mark A. Wills

The University of Sheffield has one of the largest centres for research in Animal and Plant Sciences of all the British Universities and is a major world centre for plant ecological research. Research in this area encompasses fundamental studies of; plant growth and distribution; mycorrhizal symbioses and their importance in ecological processes; effects of global change both in the past and the future on arctic, temperate and tropical ecosystems. The department currently participates in several EU sponsored projects including CLIMEX, BERI (Bog Ecosystem Research Initiative), CANIF (Carbon and nitrogen cycling in forest ecosystems) and BIODEPTH (Biodiversity and ecological processes in terrestrial herbaceous ecosystems). The National Environment Research Council funded Unit of Comparative Plant Ecology is an integral part of the Department. Financial support for research also comes from the Research Councils, Royal Society, BP International Ltd, Shell Research, Fisons plc, the water industry, English nature and Broads Authority. Staff serve on the boards of over 30 learned journals. Institutes of Photosynthesis, Endocrinology and Environmental Sciences and Technology facilitate interdisciplinary research programmes involving staff in other departments.

Experience;
Dr. Beerling has been extensively involved with the measurements and modelling of the vegetation responses in relation to the CLIMEX treatments over the past 4 years. Over the past 5 years, his research has been funded in part by the Natural Environment Research Council, UK. In 1996, he was elected a Fellow of the Linnean Society and is currently a Royal Society University Research Fellow and honorary lecture in the Department of Animal and Plant Sciences, University of Sheffield. His research is widely published in international peer-reviewed journals.

Relevant pulications;

Beerling, D.J. (1994) Modelling palaeo-photosynthesis: late Cretaceous to Present. *Philosophical Transactions of the Royal Society (Series B) B346*, 421-432.

Beerling, D.J. and Quick, W.P. (1995) A new technique for estimating rates of carboxylation and electron transport in leaves of C_3 plants. *Global Change Biology 1*, 289-294.

Beerling, D.J. (1996) Ecophysiological responses of woody plants to past CO_2 concentrations. *Tree Physiology 16*, 389-396.

Beerling, D.J. and Woodward, F.I. (1996) *In situ* gas exchange responses of boreal vegetation to elevated CO_2 and temperature: first season results. *Global Ecology and Biogeography Letters 5*, 117-127.

Beerling, D.J., Heath, J., Mansfield, T.A. and Woodward, F.I. (1996) Drought - CO_2 interactions in trees: mechanisms and observations. *New Phytologist 134*, 235-242.

Partner Number; **06**
Laboratory; **Risoe National Laboratory, (RISO), DK.**
Principal Investigator; **Dr. Lennart Rasmussen**
Scientists Involved; Dr. Claus Beier

The Environmental Science and Technology Department has a staff of 130 scientists and technicians. The department has many years of experience in soil chemistry and plant nutrition and it has great expertise in the use of stable and radioactive isotopes in research projects. During recent years the department has participated in both national and international forest ecosystem research, including biogeochemical cycling and impact of air pollution on forests.

Experience;

Employed as associate professor at the Laboratory of Environmental Sciences and Ecology, Technical University of Denmark, 1978-92. From 1992 to January 1996 Head of Department of the Department of Forest Health and Forest Ecosystems, Danish Forest and Landscape Research Institute. Now senior scientist, project leader of Risoe Environmental Risk Assessment Facility (RERAF) at Risoe National Laboratory. Research area on air pollution and biogeochemical cycling of elements in forest ecosystems, with special emphasis on acid rain problems and heavy metal deposition. Previous coordinator of two EU projects (EXMAN - Experimental manipulations of forest ecosystems in Europe, and APOS - The influence of different air pollution levels on the degree of forest soil acidification and forest stability). Danish participant in two other EU projects (NITREX - Nitrogen saturation experiments, and NIPHYS - Nitrogen physiology of forest plants and soils). Leader of the Danish Centre for Terrestrial Ecosystem Research, member of several international scientific committees, and member of editorial boards and referee of several international scientific journals. The group have been responsible for tree studies in CLIMEX since 1995.

Recent publications

Beier. C. & Rasmussen. L. (1994). Effects of whole-ecosystem manipulations on ecosystem internal processes. Tree 9. 218-223.

Rasmussen, L., Brydges, T. & Mathy, P. (Eds.). (1993). Experimental manipulations of biota and biogeochemical cycling in ecosystems - Approach, methodologies, findings. - Commission of the European Communities, Brussels. Ecosystem research report 4.

Beier. C. & Rasmussen, L. (Eds.). (1993). The EXMAN project. Experimental manipulation of forest ecosystems in Europe. - Commission of the European Communities, Brussels. Ecosystem Research Report 7.

Beier. C., Gundersen, P., Hansen, K. & Rasmussen, L. (1995). Experimental manipulation of water and nutrient input to a Norway spruce plantation at Klosterhede, Denmark. II. Effects on tree growth and nutrition. Plant and Soil 168-169. 613-622.

Partner Number; **07**
Laboratory; **Institute of Terrestrial Ecology, UK (ITE)**
Principal Investigator; **Prof. David Fowler**
Scientists Involved; Dr K J Hargreaves, Mr R Storeton-West, Ms J MacDonald.

The Institute of Terrestrial Ecology, comprising six research stations is the largest environmental research organisation in the UK, and the research station in Edinburgh has specialized in research on air pollution and global climate issues for over 20 years. Topics of research include measurement of ozone and acidic deposition and their effects on vegetation. New techniques to measure fluxes of pollutants and trace gas exchange between terrestrial ecosystems and the atmosphere have been developed for O_3, NO_x, NH_3, SO_2, CH_4, N_2O. The work includes continuous measurements at a few sites and in short-term field campaigns at a range of sites in the UK and Europe frequently as part of a large, often multi-national consortium..

The group is also deeply involved in global change and the developement of global budgets for radiatively active gases. The emission of these gases, methane, nitrous oxide, carbon dioxide and other species from wetlands, have been measured on a local scale in Northern Scotland and Lapland and on a national scale through the use of aircraft over the past 3-5 years. The group possesses the necessary equipment for the measurements of frequently small concentrations of gases. These activities have been supported by the UK National Envionmental Research Council and the European Community and will be partially supported by the UK Deparatment of the Environment in 1997-98.

Experience:
The senior scientist, David Fowler, together with Ken Hargreaves, will conduct the measurements in the CLIMEX chambers. David Fowler has over 20 years experience in environmental physics particularly in the measurement of concentrations and deposition of trace gases in the atmosphere. Both scientists have 5 years experience of measuring radiatively active gases under the TIGER programme in the UK, and in Lapland as part of the LAPP project, and have already carried out 2 measurement campaigns in the CLIMEX project.

Relevant Publications:

Fowler, D., Hargreaves, K.J., Skiba, U., Milne, R., Zahniser, M.S., Moncrieff, J.B., Beverland, I.J. and Gallagher, M.W. (1995). Measurement of CH_4 and N_2O fluxes at the landscape scale using micrometeorological methods. Phil. Trans. Royal Soc., London,A 352, 339-356.

Fowler, D., Hargreaves, K.J., Choularton, T.W., Gallagher, M.W., Simpson, T. & Kaye, A. (1996). Measurement of regional CH_4 emissions in the UK using boundary layer methods. Energy Conversion and Management, 37, 769-775.

Hargreaves, K.J. & Fowler, D. (1995). Micrometeorological measurement of net summer carbon fluxes to northern wetlands and the potential effects of global warming. Annales Geophysicae, Supplement II to Vol. 13.

Fowler, D., MacDonald, J., Leith, I.D., Hargreaves, K.J. & Martynoga, R. 1995. The response of peat wetland methane emissions to temperature, water table and sulphate deposition. In: *Acid rain research: do we have enough answers?* edited by G.J.Heij & J.W. Erisman, 485-487. Amsterdam: Elsevier.

Partner Number: **08**
Laboratory: **European Forest Institute, (EFI) FI.**
Proncipal Investigator: **Dr. Risto Päivinen**
Scientists involved: Dr. Chijien Lin, Prof. Birger Solberg, Ir. Gert-Jan Nabuurs

The European Forest Institute is an independent and non-governmental research body, conducting problem-oriented and multidisciplinary forest research at the European level in order to serve the needs of policy making and decision making bodies in Europe. EFI specialises in European-level studies on forestry and international forest research projects. EFI has excellent abilities to execute the task of the proposed project. Through its member network (67 forest research organisations throughout Europe) it can efficiently put up a team of the best experts for a given task. Several of EFI's ongoing projects are funded by the European Union, as an example, EFI is currently coordinating a project on creating a forest information system for the EU (European Forest Iinformation and Communication System - EFICS).

EFI has the best available European-level database on forests, including time series of forest inventory data from European countries from the past four decades, which can be used for the purposes of this study. One of the key priorities in EFI's research is to make prognoses on the future development of European forests with the help of scenario models. EFI has developed the so-called EFI-SUAS model for European-level forest scenario modelling. The model includes 2500 forest types, and can be used for upscaling the effects of climate change to Scandinavian forests.

Experience

Dr. Risto Päivinen is Deputy Director of EFI and will lead the work at EFI. He is one of the world's leading experts in forest inventory and spatial forest information systems. He is involved in the planning of the Global Forest Resource Assessment 2000, and is also the coordinator of the EFICS study. Professor Birger Solberg is Professor in forest economics at the Agricultural University of Norway and the Norwegian Forest Research Institute, and Associate Researcher at the EFI. He is one of the world's leading experts in forest economics. One of his main study areas are the economic aspects of carbon balance in the forest ecosystem.

Relevant publications

Nabuurs, G. J and Päivinen, R., 1996, Large Scale Forestry Scenario Models - A Compilation and Review, European Forest Institute Working Paper No.10, Joensuu, Finland

Nabuurs, G.J. and Mohren, G.M.J. 1995. Modelling analysis of potential carbon sequestration in selected forest types. Canadian Journal of Forest Research 25, 1157-1172.

Paivinen, R. and Halinen, M. 1995. A strategic planning system for large forest area. Lesnietvi Forestry 41, 147-150.

Solberg, B. and H.F. Hoen (1995) Economic aspects of carbon sequestration - some findings from Norway. In, Apps, M.J. & Price, D.T. (Eds) Forest Ecosystems, Forest Management and the Global Carbon Cycle. Springer-Verlag, Berlin.

8. Financial Information

The budget for CLIMEX can be separated into 2 major parts (Table 4), the *site operation* costs which are necessary to carry out the experiment itself (Table 5), and the costs for the *scientific investigations* (Table 6). Matching funds for CLIMEX are national financing from Norway, the UK and NL as well as industry support from NORSK HYDRO A/S.

Table 4. A breakdown of the costs (ECU 1000's) for CLIMEX for 24 months, April 1997 - March 1999.

Site operation costs:	Partner	Total	From EU
	NIVA (02)	432	216
	AUW-TENC (04)	200	200
TOTAL RUNNING COSTS		**632**	**416**

Scientific investigation costs:

	Partner	Total	From EU
Project coordination	IH (01)	40	20
Soil hydrology	IH (01)	103	51
Integrated modelling	IH (01)	147	74
Input-output budgets	NIVA (02)	284	142
Soil chemistry	WAU-SSG (03)	382	382
Ground vegetation	WAU-TENC (04)	367	367
Plant gas exchange	US (05)	173	173
Tree growth and nutrition	RISOE (06)	356	178
Gas emissions	ITE (07)	162	81
Forest and economic modelling	EFI	216	108
TOTAL SCIENCE COSTS		**2255**	**1576**
TOTAL COST		**2887**	**1992**
% From EU			69%

Table 5. Breakdown of CLIMEX site operation costs for 2 years. All costs in ECE 1000's.

	Total	From EC
CO_2 gas		
NIVA (2)	62	31
AUW-TENC (4)	102	102
CO_2 tank rental		
NIVA (2)	50	25
AUW-TENC (4)	25	25
Electricity		
AUW-TENC (4)	68	68
Other		
NIVA (2)	40	20
Labour (incl. overhead)		
NIVA (2)	280	140
TOTAL RUNNING COSTS	**627**	**411**

Table 6. Breakdown of CLIMEX budget by partner. All costs in ECU 1000's.

Participant No.	01	02	03	04	05	06	07	08
Personnel	106	246	150	176	88	150	52	118
Man Months	*30*	*60*	*42*	*40*	*36*	*30*	*18*	*18*
Durable Equipment	5	6	0	15	35	0	12	0
Sub-contracts	0	0	12	0	5	0	0	0
Travel/Subsistence	21	11	15	15	9	16	16	10
Consumables	10	152	185	267	12	50	6	12
Overhead	148	301	20	94	24	140	76	76
Total	290	716	882	567	173	356	162	216
Requested from EU	145	358	382	567	173	178	81	108
% of Total	50%	50%	100%	100%	100%	50%	50%	50%

9. Exploitation Plans

Results of CLIMEX will be published in peer-reviewed scientific journals and widely reported through participation in international conferences and workshops. This will ensure and maintain scientific credibility and also make the results exploitable for support of EU and international policy regarding environment and climate change. Reports will be published to ensure accountability and will be written in a manner as to be easily interpretable and usable by policy decision makers. The results and model predictions from CLIMEX will be of relevance to other ongoing EC funded programmes in which lead scientists in CLIMEX are also involved (eg. DYNAMO, BERI, CANIF, ECOCRAFT, EUROFLUX) and this will promote European collaboration. Results will also be disseminated within the framework of IGBP-GCTE to promote and support international collaboration. A full list of publications from CLIMEX to date is incl;uded in Appendix 1.

10. Ongoing Projects and Previous Proposals

CLIMEX was established as a project forming part of the 3rd EC Framework programme for the ENVIRONMENT (contract no. EV5V-CT91-0047) for 24 months starting December 1992. This contract was amended by supplementary agreement no. 1 in December 1994 to extend the project to 30 months and increase the contribution from the Commission from 990,660 to 1,149,660 ECU. A proposal for continuing funding (CLIMEX Phase II) was submitted in July 1993 to the ENVIRONMENT Programme (proposal no. PL931388), received a 2 rating, but was not funded. A further proposal for continuation was submitted to the 4th Framework programme for ENVIRONMENT and CLIMATE in April 1995. This proposal was succesfull (contract no. ENV4-CT95-0185) and was funded for 12 months from 1st February 1996.

Capital investment for the RAIN project (in 1983) was about 2.4 million NOK and for CLIMEX (in 1993) about 3.0 million NOK. The installation at Risdalsheia is one of the world's largest and technically most ambitious environmental manipulation facility, and has been recognised as such by a grant from the EU under the Human Capital and Mobility, Access to Large-Scale Facilities Programme (1994-96).

Appendix 1. CLIMEX Publications

Jenkins, A., Schulze, E.D., van Breemen, N., Woodward, F.I. and Wright, R.F. 1992. CLIMEX - climate change experiment. p. 359-366, In: Teller, A., Mathy, P. and Jeffers, J.N.R. (Eds) Responses of Forest Ecosystems To Environmental Changes. Elsevier, London, 1009 pp.

Arp, W. and Berendse, F. 1993. Plant growth and nutrient cycling in nutrient-poor ecosystems. In, Van de Geijn, S.C., Goudriaan, J. and Berendse, F. (Eds) Climate Change; Crops and Terrestrial Ecosystems. Agrobiologische Thema's 9, CABO-DLO, Wageningen, The Netherlands.

Jenkins, A., Wright, R.F., Berendse, F., van Breemen, N., Brussaard, L., Schulze, E.D. and Woodward, F.I. 1993. The CLIMEX project - climate change experiment. p. 71-77, In: Rasmussen, L., Brydges, T. and Mathy, P. (eds) Experimental Manipulations of Biota and Biogeochemical Cycling in Ecosystems. Ecosystems Research Report 4, Commission of the European Communities, Brussels, 348 pp.

Jenkins, A. and Wright, R.F. 1993. The CLIMEX project - raising CO_2 and temperature to whole catchment ecosystems. p. 211-220, In: Schulze, E.D. and Mooney, H.A. (Eds) Design and Execution of Experiments on CO_2 Enrichment. Ecosystems Research Report 6, Commission of the European Communities, Brussels, 420 pp.

Beerling, D. J. and Woodward, F.I. 1994. The climate change experiment (CLIMEX): Phenology and gas exchange responses of boreal vegetation to global change. Global Ecology and Biogeography Letters 4, 17 - 26.

Jenkins, A. (Ed) 1995. CLIMEX Climate Change Experiment: Progress Report December 1992 - June 1993. Climate Change Research Report 1/95, Norwegian Institute for Water Research, Oslo, 12 pp.

Jenkins, A. (Ed) 1995. CLIMEX Climate Change Experiment: Progress Report July 1993 - December 1993. Climate Change Research Report 2/95, Norwegian Institute for Water Research, Oslo, 31 pp.

Dise, N.B. and Jenkins, A. (Eds) 1995. The CLIMEX Project: Whole Catchment Manipulation of CO_2 and Temperature. Climate Change Research Report 3/95, Norwegian Institute for Water Research, Oslo, 130 pp.

Jenkins, A. and Wright, R.F. 1995. The CLIMEX Project: Performance of the Experimental Facility During the First Year of Treatment. p. 323-327. In: Jenkins, A., Ferrier, R.C. and Kirby, C. (Eds) Ecosystem Manipulation Experiments: Scientific Approaches, Experimental Design, and Relevant Results. Ecosystem Research Report 20. Commission of the European Communities, Brussels, 374 pp.

Lükewille, A., Arp, W., Verburg, P., Jenkins, A. and Wright, R.F. 1995. The CLIMEX soil heating experiment at Risdalsheia, Southern Norway. p. 331- 334, In: Jenkins, A., Ferrier, R.C. and Kirby, C. (Eds) Ecosystem Manipulation Experiments: Scientific Approaches, Experimental Design, and Relevant Results. Ecosystem Research Report 20. Commission of the European Communities, Brussels, 374 pp.

Verburg, P., and van Breemen, N. 1995. Effects of climate change on decomposition of soil organic matter in a boreal ecosystem. p. 557-560, In: Zwerver, S., van Rompaey, R.S.A.R., Kok, M.T.J., and Berk, M.M. (Eds.) Climate Change Research: Evaluation and Policy Implications. Studies in Environmental Science 65A. Elsevier Science, Amsterdam, 674 pp.

Jenkins, A. (Ed) 1995. CLIMEX Climate Change Experiment: Final Report on Phase 1 the first year of treatment May 1994 - December 1994. Climate Change Research Report 4/95, Norwegian Institute for Water Research, Oslo, 47 pp.

Wright, R.F., Indrøy, A-S., Høgberget, R., Lükewille, A., Sørvåg, T., and Willbergh, M. 1995. CLIMEX Project: Climate Data for the First Year of Treatment April 1994- March 1995. Climate Change Research Report 5/95, Norwegian Institute for Water Research, Oslo, 21 pp.

Beerling, D. J. and Woodward, F.I. 1996. *In situ* gas exchange responses of boreal vegetation to elevated CO_2 and temperature: first season results. Global Ecology and Biogeography Letters 5, 117-122.

Beerling, D. J., Heath, J., Woodward, F.I., and Mansfield, T.A. In review. Drought - CO_2 interactions in trees: observations and mechanisms. New Phytologist.

Lükewille, A., and Wright, R.F. In press. Experimentally increased soil temperature causes release of nitrogen at a boreal forest catchment in southern Norway. Global Change Biology.

Jenkins, A. (Ed) 1996. CLIMEX project: Report on the second year of treatment May 1995 - December 1995. Climate Change Research Report 6/96, Norwegian Institute for Water Research, Oslo, 74 pp.

Wright, R.F., and Lükewille, A. In press. CLIMEX project: Response of runoff chemistry after 2 years of elevated CO_2 and temperature. Climate Change Research Report 7/96, Norwegian Institute for Water Research, Oslo.

Collins, R., and Jenkins, A. 1996. CLIMEX project. Soil moisture monitoring and hydrological response. Climate Change Research Report 8/96, Norwegian Institute for Water Research, Oslo.

Appendix 2. References Cited in the Proposal

Buchmann, N., G. Gebauer and E.-D. Schulze. 1996. Partitioning of ^{15}N-labelled ammonium and nitrate among soil, litter, below- and above-ground biomass of trees and understory in a 15-year-old *Picea abies* plantation. *Biogeochemistry 33*: 1-24.

Carpenter, S.R., S.W. Chisholm, C.J. Krebs, D. W. Schindler and R.F. Wright. 1995. Ecosystem experiments. *Science 269*: 324-327.

Cosby, B.J., Ferrier, R.C., Jenkins, A., Emmett, B.A., Wright, R.F. and Tietema, A. (1997) Modelling the ecosystem effects of nitrogen deposition: Model of Ecosystem Retention and Loss of Inorganic Nitrogen (MERLIN). Biogeochemistry. In Press.

Eamus, D. 1991. The interaction of rising CO2 and temperatures with water use efficiency. *Plant Cell Environ. 14*: 843-852.

Emmett, B.A., O.J. Kjõnaas, P. Gundersen, C.J. Koopmans, A. Tietema and D. Sleep. 1996. Natural abundance of ^{15}N in forests along a nitrogen deposition gradient. *Forest Ecology and Management* (in press)

Emmett, B.A., Cosby, B.J., Ferrier, R.C., Jenkins, A., Tietema, A. and Wright, R.F. 1996. Modelling the ecosystem effects of nitrogen deposition: Simulation of nitrogen saturation in a Sitka spruce forest, Aber, Wales, UK. *Biogeochemistry* (In press).

Field, C.B., Jackson, R.B. & Mooney, H.A. (1995) Stomatal responses to increased CO_2: implications from the plant to the global scale. *Plant Cell Environ.* **18**, 1214-1225.

IPCC. 1995. *Climate change 1995. The science of climate change* (ed. by J.T. Houghton, L.G. Meira Filho, B.A. Callander, N. Harris, A. Kattenberg and K. Maskell), pp. 449-481. Cambridge University Press, Cambridge.

Kellomäki, S. 1995. Computations on the influence of changing climate on the soil moisture and productivity in Scots pine stands in southern and northern Finland. *Climatic Change 29*: 35-51.

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Appendix 3. The CLIMEX International Review Report

Excerpts from the report to the Commission of the European Communities on the evaluation conducted in September 1996 by Prof. Folke Andersson, Swedish University of Agricultural Science, and Prof. David Schindler, University of Alberta, Canada.

3. RELEVANCE OF CLIMEX TO THE UNDERSTANDING OF GLOBAL CHANGE

We find the CLIMEX research to be highly relevant to understanding global change. The project has also been accepted as a part of GCTE Core Research, Category 1. It is relevant for several of the four foci and for several of the activities and tasks within individual foci. In focus 1 activity the use of large scale experiments is stressed, and the importance of warming at high-latitude ecosystems is pointed out. Implied is the need for large-scale experiments in which both CO_2 and temperature are manipulated.

CLIMEX also addresses other GCTE-issues:

- it determines the interactive effects of increased temperature and changes in nutrient availability on carbon, nutrient pools and fluxes across transition from boreal forest to tundra;

- it provides ecosystem-scale information which will be used to test, modify and develop ecosystem-models of carbon, nutrient and water cycles.

- it attempts to predict the effects of change in climate and atmospheric composition on the growth and function of forest crops.

- it provides relevant data for determining the impact of global change as expressed at plant physiology, vegetation and ecosystems level, on soil organic matter dynamics.

5. EXPERIMENTAL DESIGN, FIELD INSTALLATIONS AND PROJECT PERSONAL

Experimental design

Strength and weaknesses of whole ecosystem experiments
Whole ecosystem experiments have both unique shortcomings and advantages. The large scale of such projects precludes extensive replication, often leading to criticism from those who are trained in conventional scientific methods. Yet experiments at smaller than whole-ecosystem scales often sacrifice spatial and temporal reality and heterogeneity in order to obtain statistically- precise results. Detailed comparisons of replicated smaller scale experiments with whole ecosystem experiments have shown that the former often provide precise documentation of processes and effects that are artifacts of whole ecosystem responses (Schindler 1991; Likens 1992; Levine and Schindler 1992). Recently, statistical approaches applying randomized intervention analysis (Carpenter et al. 1989) and comparing observations in experimental ecosystems to multiple reference sites (Schindler 1991) have overcome some of these criticisms. It is now widely agreed that whole-ecosystem experiments provide a necessary step between laboratory and experimental plot-scale approaches and applications to management of whole ecosystems (Carpenter et al. 1995; Jenkins 1995).

The small number of experimental enclosures and the large number of processes that must be studied in each whole ecosystem treatment also limit the number of potential facets and interactions of "global change" that can be tested. Of the many available options, the combination of increased temperature and CO_2 concentrations expected in approximately 50 years was an excellent choice for the main experimental treatment, providing the potential for a "reality check" on changes predicted from climate models, which rely heavily on assumed interactions that are often unverified by data.

The choice of CLIMEX sites
Similarly, the choice of boreal catchments for such large-scale experiments is an excellent one. At 12 million km^2, the boreal landscape may be the largest economically-important biome to be heavily impacted by global change. Steady-state climate models predict the near-disappearance of boreal forests in many regions (Hengeveld 1991). Together, boreal forests, wetlands and lakes are the largest global carbon pool (Kurz et al. 1995; Gorham 1991; Dillon and Molot 1996). Boreal regions may be an important "missing sink" in the global carbon budget (Schindler & Bayley 1993) and a major source of methane to the atmosphere (Matthews and Fung 1987). Even small changes in the growth of boreal forests or their magnitude. Also changes in the magnitude of the boreal forest as a net sink for carbon have major economic implications: the former for countries containing boreal ecosystems and the latter for the entire earth.

Unique features of CLIMEX
International considerations. The CLIMEX project and its predecessor RAIN are internationally-recognized as being at the forefront of whole-ecosystem approaches. The site was one of five internationally-recognized whole-ecosystem projects featured in a "Frontiers in Science" issue of Science devoted to whole-ecosystem experiments (Carpenter et al. 1995). The project design includes several desirable features, by allowing inclusion of investigations at several scales, from physiological approaches to studies of whole-system biogeochemical processes and of both individual taxa and whole-community interactions. At the ecosystem scale, both randomized intervention analysis and inclusion of multiple reference catchments are being used to minimize the handicaps provided by lack of treatment replication.

CLIMEX is one of the few large-scale projects to include the potential for of long-temporal scales in its design. It has often been shown that the responses of ecosystems or whole catchments to chemical, biological or physical stressors are delayed, with full steady-state responses not observed for several years (Schindler 1991; Likens 1992). In fact, the RAIN project, conducted at the same sites, provides one of the best examples of the long times required for full ecosystem responses (Wright and Hauhs 1991). In what follows, we will highlight several examples where we believe that key processes and linkages must be studied longer in order fully examine consequences of high CO_2 and temperature at the ecosystem scale.

Field sites and installations. The major factors contributing to the choice of Risdalsheia as an object for experimental global change investigations were the existence of 11 years of background data and that substantial investments in the facility in earlier years reduced construction costs. The research site was already competently managed. Access to several suitable reference areas was another advantage.

The Risdalsheia site of CLIMEX has been well-planned, efficiently and cleverly engineered, and carefully and economically managed. The basic experimental structures had proven that they were robust and reliable during the RAIN project. The capital costs of imposing a modified climate to whole catchments were reduced substantially by reusing the RAIN roofed catchments. Modifications to the original facilities in order to raise temperatures and gas concentrations were operating reliably within weeks of initial installation. Technical details are given in Wright (1996).

The design has a number of shortcomings, most notably reduced light intensities, wind velocities, fog and dryfall deposition, and variation in types of precipitation events when compared to outdoor ecosystems (Jenkins and Wright 1996). We believe that these are more than balanced by the opportunity to obtain empirical, ecosystem-scale data under a climatic regime similar to that expected fifty years in the future.

The fact that several years of input-output chemical budgets were available for the experimental and one of the reference catchments also provides an unprecedented opportunity to compare the results of climate modification with those caused simply by inter-annual variation is climate and other local factors.

Project personnel. The CLIMEX scientific team is a near ideal mix of disciplines and age groups. The scientific leaders are internationally-recognized for their ability to lead scientists from many disciplines and countries in performing ecosystem-scale experiments that have important bearing on environmental management and policy. An entire new generation of young scientists has been included in CLIMEX. Most appear to be very able, and the interdisciplinary experience provided by CLIMEX may be one of the project's most important long-term products.

The technical staff of CLIMEX include people with a decade of experience with the facility as the result of the RAIN project, a major advantage when operating such a complex facility.

For the plant and soil studies the drawback of not having true replicates has partly been overcome with the use of five pseudo-replicates. The tree growth and production studies will however be hampered by the low number of trees and absence of true replicates. The growth response must be studied rather at the individual rather than the stand level. Information from various observations on the changes of canopy structure/architecture is recommended to be used derived from inside and outside the enclosure.

7. RECOMMENDATIONS

Based on facts presented in documents for the review and accompanying discussions we give the following recommendations:

- introduce "event" experimentation and coordinated measurement campaigns.

- continue the existing treatment to KIM catchment for at least two years

- investigations of whole ecosystem metabolism measured by gas fluxes are recommended coordinated with ecophysiological measurements

- coordinate and intensify studies of major ecosystem elemental fluxes

- continue input-output budgets

- continue studies of tree growth and biomass accumulation

- continue studies of forest nutrition, linking it more effectively to ecophysiological studies

- continue documentation of changes to ground vegetation and soil nutrient pools

- explore possible new approaches to hydrological assessment

- discontinue studies of soil fauna ecology

- look for interaction phenomena such as the occurrence of the Calluna beetle or other "surprises" that have potential to greatly modify the effect of climate change

- evaluate results of root and mycorrhiza studies. Modify or delete if they are not contributing to overall project objectives

- consider possibilities for future experiments in the experimental catchments

- synthesize results to develop models of sources and sinks for carbon and nitrogen, tree growth and water balances

- develop appropriate models for scaling results of the experiments to regional and global aspects of climate change

- address socio-economic concerns resulting from project findings

- ensure that bridge funding is in place so that the collection of critical data is not disrupted during the period in 1997 before future funding is decided

Rationale for recommendations

Overall, we recommend continuation of the existing treatment regime to KIM catchment for a minimum of two additional years. Premature termination of the experiment after such a large capital investment would be very short-sighted, for it is probable that many of the short-term observations will prove to be unreliable on medium to long time-scales. Whole ecosystems are often notoriously slow to respond to stresses, for redundancies in species composition and functional components often protect the whole system to some degree after damage to individual processes or species has been noticed (Schindler 1987, 1990). While some responses to the climate treatment in KIM seem clear, others appear to be only beginning following 2 1/2 years of treatment.

Some changes do, however, need to be considered to redirect effort and funding to the understanding of changes that occur.

We recommend that the ecosystem gas flux work and coordinated detailed ecophysiological investigations be continued, and intensified. If possible, even more detailed studies of how nutrient pools and fluxes interrelate should be undertaken, perhaps by incorporating stable isotopes or radioisotopes as tracers, to determine how the relative sizes and relationships of nutrient pools and fluxes might change.

The imposed climatic change has both direct implications for the cycling of nutrients other than N and C, and potential indirect effects via modifications to nitrogen and carbon cycling. In particular, we believe that studies should be expanded to include phosphorus, because of its vital role in forest nutrition and water pollution.

We recommend that documentation of tree growth and nutrition be continued. It would be desirable to have the classical approach to nutrition by assessment of needle chemistry more closely linked to ecophysiological studies of the trees.

Similarly, continued documentation of changes in ground vegetation, and the mechanisms responsible for the observed changes must be continued in order to fulfill the major objectives of the project. Enough flexibility should be incorporated in the project re-design to study the potential effect of "surprises" such as the Calluna beetle outbreak on the outcome of plant community interactions.

We recommend that new methods be explored for determining the response of the hydrology of the treated catchment to the newly-imposed climatic regime. For example, using piezometer water level to index antecedent moisture of soils and differences in the ratio outflow:precipitation following precipitation events of known size in both pretreatment and treatment periods might allow better evaluation of the effects of the imposed climate change on the hydrologic budget.

In order to accomplish the above objectives without significant increases in funding, some aspects of CLIMEX may have to be discontinued, or investigated less intensively. We believe that a detailed analysis of existing data should precede proceeding with studies of soil ecology, soil chemistry, and root biomass studies, for it is not presently clear that they are contributing effectively to major objectives of the study. Some aspects might be discontinued, while others may require modification of approaches taken.

We believe that the CLIMEX facility is too valuable to be discarded after this set of experiments. In order to maintain the integrity of ecosystems for future experiments, it is necessary to consider possible options for new experiments now, so that current sampling regimes do not cause irreparable damage.

We suggest that one future experiment to be considered is to continue the current climatic experiment while superimposing nitrogen addition. The current design effectively considers the effect of climate warming in isolation from other chemical insults to global ecosystems. The possible effect of increased nitrogen deposition on carbon cycling, is another issue of great importance to global change, for it has potential to alter the importance of the terrestrial biosphere as a global carbon sink. Galloway et al. (1995) predict that nitrogen deposition will increase up to four-fold for some regions of the world by the year 2020.

Results are now sufficient to begin synthesizing results of individual project components into models of sources and sinks of carbon, tree growth, nitrogen losses via streamflow and atmospheric exchange, and water balance. In turn, these syntheses should provide the basis for scaling up results to regional and larger scales. Once this is accomplished, economic implications for boreal countries, global climates and global populations need to be considered.

One difficulty faced by the project has been to bridge the period between past funding cycles. This caused some disruption of experiments in an earlier phase of the experiment. The potential for similar disruptions, including loss of key staff, appears to be possible in 1997. WE strongly recommend that the necessary measures be taken to see that bridge funding is in place to ensure that critical data are not lost during the period in 1997 when new funding is decided.