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Modelling Climate Change Impacts on Biogeochemical and Ecological Systems: Core Model Project

3rd progress report, for the year to December 1993.

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Executive Summary

The DoE Core Model Project has been running for three years. This report summarizes the the progress made in the third year of study.

A seminar on the work at the Core Model Programme was held at Monkswood in April 1993. This outlined the work of the Core Model Project to an invited audience. Following the seminar further discussions have taken place between ITE and IH about ways of further integrating the two groups and sub-contractors. Two proposals are currently under discussion.

The linked model is now complete. Each of the modules describing water balance, grass-land, nitrate and evapotranspiration are presented. The methods used to integrate the models and incorporate them within the GIS framework are described. The validation and simulation of the grass-land module is described. The very high computational demand of the linked model and the problems this causes, are highlighted.

The GIS framework has undergone continued development, with the link to the Oracle database now completed and the increased functionality of the software.

Work on available datasets has continued, to make new datasets accessable from the GIS framework. Problems still exist in interpolating the base-line climate data into a usable format, from mean monthly values to daily values.

Work to be continued in the final year of the study includes; the application of the linked model to the sites where the grass-land model was validated, a regional application of the linked model, further development of the grass-land model and preparation for the end of project seminar.

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1.0) Introduction

Climate changes are expected to be manifest as a rise in mean annual temperature, together with perturbation of rainfall patterns, alongside a continuing increase in atmospheric CO_2 [18,19]. A number of scenarios have been proposed for the UK climate over the next 40 years. Based on the 'business as usual' scenario of greenhouse gas emissions [9] the average U.K. summer season temperature will rise by 1.4°C and mean winter temperature by between 1.5 and 2.1°C, and precipitation during the winter will on average increase by about 5%.

Following such a change in climate there will inevitably follow a change in the hydrology and consequently hydrochemistry of UK catchments. The changing rainfall, temperature, radiation and humidity will effect the amount of evapotranspiration and the flow characteristics of the rivers. Soils which may become drier will cause a change in the flow paths of water and hence the hydrological response time will change. The changing hydrology of the UK catchments will in turn effect the hydrochemistry. The composition, for example, of the cations and anions in the soil may change because of changing weathering rates related to temperature. The increased rates of mineralization by bacteria in soils may cause changing nitrate levels in the soil water and river.

Such a future climate scenario could also have a profound effect on the agricultural ecosystems of the UK. Almost three quarters of all agricultural land in the UK (about 13 million hectares) is covered by grassland and grazing land. This land use completely dominates the landscapes of the north and west of the country. Therefore, predicting how this large area of managed ecosystem will respond to global environmental change as a result of the burning of fossil fuels and emission of greenhouse gases is an important current and national concern [9,12].

1.1) Aims

The research programme has been initiated to assess the likely impact of future climate change on biogeochemical and ecological systems, it has three main objectives;

1) To provide core models for predicting the impacts of climate change on biogeochemical and ecological systems.

2) To provide models which run for both equilibrium and transitional climates.

3) To couple the models with a GIS to examine the impacts spatially across the UK.

1.2) Integration of research groups

ITE and its sub-contractors have now formulated a frame work which describes how land-use places constraints on future habitat distribution, which in turn places constraints on future species distribution. Amongst other factors, hydrology also places restrictions on the possible future land use and habitats. IH and ITE have been in discussion regarding possible links between the two groups. Two proposals are currently under discussion. The IH linked model (section 2), amongst other results, will produce a map of GB, or a sub-section, showing grass-land productivity under a present or future climate. This result could be used to assist in the calculation of a future land-use map. There are three constraints on this proposal from the IH perspective. The first is the availability of daily climate data (see section 5.0), the second is the computing constraint (see section 5.0) and the third is that the linked model, compared with the individual modules as a whole, has yet to be validated and its behaviour is not yet known.

The second possible collaboration, is to use TOPMODEL [13] or a similar distributed model, to show, for example, the distribution of the percentage time a grid square, within a catchment, is saturated. TOPMODEL can predict, given a climate scenario, the soil moisture content and how it is distributed over a catchment. The water content of a soil has a direct effect on the growth of given species. Plants with high water requirements, may be constrained more than plants with low water requirements under a drier climate. Thus a particular species may be constrained to a particular part of a catchment or may not be present at all. This would place constraints on future habitat distributions and could be used to predict future species distributions. Again this idea is still being developed.

1.3) Publication of Core Model Programme

A final end of project seminar will be presented at Newcastle University on 14-15th December. With the end of contract seminar in mind a "trial" seminar was given in April 1993 to an invited audience of possible future funders. The seminar was generally well received with the exception that the integration across the two main research groups and the sub-contractors was thought to need further development. To this aim there have been a number of meetings between ITE and IH and with sub-contractors in order to further combine the approach into a final package. Section 1.2 describes the changes that took place to further integrate the programme.

Throughout the year IH staff have continued to promote the work of The DoE Core Model Project. Alan Jenkins, William Sloan and Andrew Eatherall gave papers at the DoE Core Model Seminar in May at Monkswood. Andrew Eatherall presented a paper at the 'Prediction of Species Distribution in Relation to Climate' conference, Monkswood. A paper will be published in April in the journal IWEM outlining a methodology of linking a non-point source pollution model and a geographical information system.

1.4) Core model applications

The linked model and the catchment hydrochemistry model will be able to ask a number of questions about the possible effects of climate change. These include;

1) What are the "climate thresholds" of the ecosystem? *i.e.* to what extent can the climate change before there will be a perceived change in the ecosystem.

2) What will be the response of nitrate concentration in streams to climate change?

3) What will be the response of grass-land productivity across GB in response to

climate change?

4) What will be the response of evaporation or flow across GB?

5) How will the hydrochemistry of a particular catchment respond?

6) Are there important feedback processes operating within an ecosystem which might further enhance or ameliorate the impact of climate change? Can these effects be quantified?

Some of these questions will be broached by the application of the linked model to a number of sites in the GB, during the coming year. Others will have to be addressed by future projects.

2.0) Linked model and GIS

2.1) Introduction

Model simulations of particular aspects of an ecosystem are usually considered in isolation from other aspects of the same system. For example, a model simulating the growth of a particular plant species might have driving variables such as; rainfall, temperature, soil water and nitrate concentration in the soil water. Under an equilibrium experiment these driving variables would be supplied to the model *i.e.* it is know how the driving variables will change (if at all) over time.

A problem arises when these models are used to predict what will happen under a changing climate, because a climate change will effect all processes (physical, chemical and biological) within an ecosystem, including the driving variables. *i.e.* the value of the driving variables will not be known and can not be predicted intuitively, because of the non-linearity of the systems involved. Thus any results taken from such a model, run in isolation from other parts of the ecosystem (the driving variables), may be inaccurate.

The philosophy behind the linked model is to begin to close this gap and to allow dynamic models to be coupled with other dynamic simulations of parts of the ecosystem to build a model which will begin to simulate the whole ecosystem response to a changed climate.

The linked model will be applied on a regional scale. This regional application necessitates a need for spatial data across GB for input to the model. Hydrologists generally work on a catchment scale, because the catchment defines an easy unit in which to measure water balances. However most regional data is in a grided format, which causes the hydrological modeller some problems as the data usually has to be converted. In this case the hydrological modelling is based on the water balance of a particular grid square. This means that all the results of the modelling are based upon a single grid square, so although the model is able to calculate the flow of water from a given grid square it is unable to predict flow within a stream. In order to do this a catchment would have to be defined as a group of grid squares and the water would have to be routed through all of the grid squares.

Spatial data for GB comes in varying scales and consists of very large data sets. To handle such large data sets, with relative ease, a Geographic Information System (GIS) has to be used. Arc/Info, besides providing the usual GIS tools, also allows models to be incorporated into the macro language of the package. This makes the handling of the spatial data a great deal easier and for this reason part of the linked model has been encoded within the GIS.

2.2) Development of the linked model

The linked model is separated into four modules, two of which are encoded into Arc/Info and two which are programed in FORTRAN. There are also a number of smaller FORTRAN programs which are used to transfer data from the Arc/Info models to the FORTRAN models and *vice versa*. The whole linked model is run and controlled from Arc/Info.

The four modules of the linked model are shown in Figure 1. They consist of; the evaporation model (section 2.3), the water balance model (section 2.4), the nitrate model (section 2.5) and the grass-land model (section 2.6). The water balance and evaporation models are coded in Arc/Info Macro Language (AML) while the grass-land and nitrate models are coded in FORTRAN.

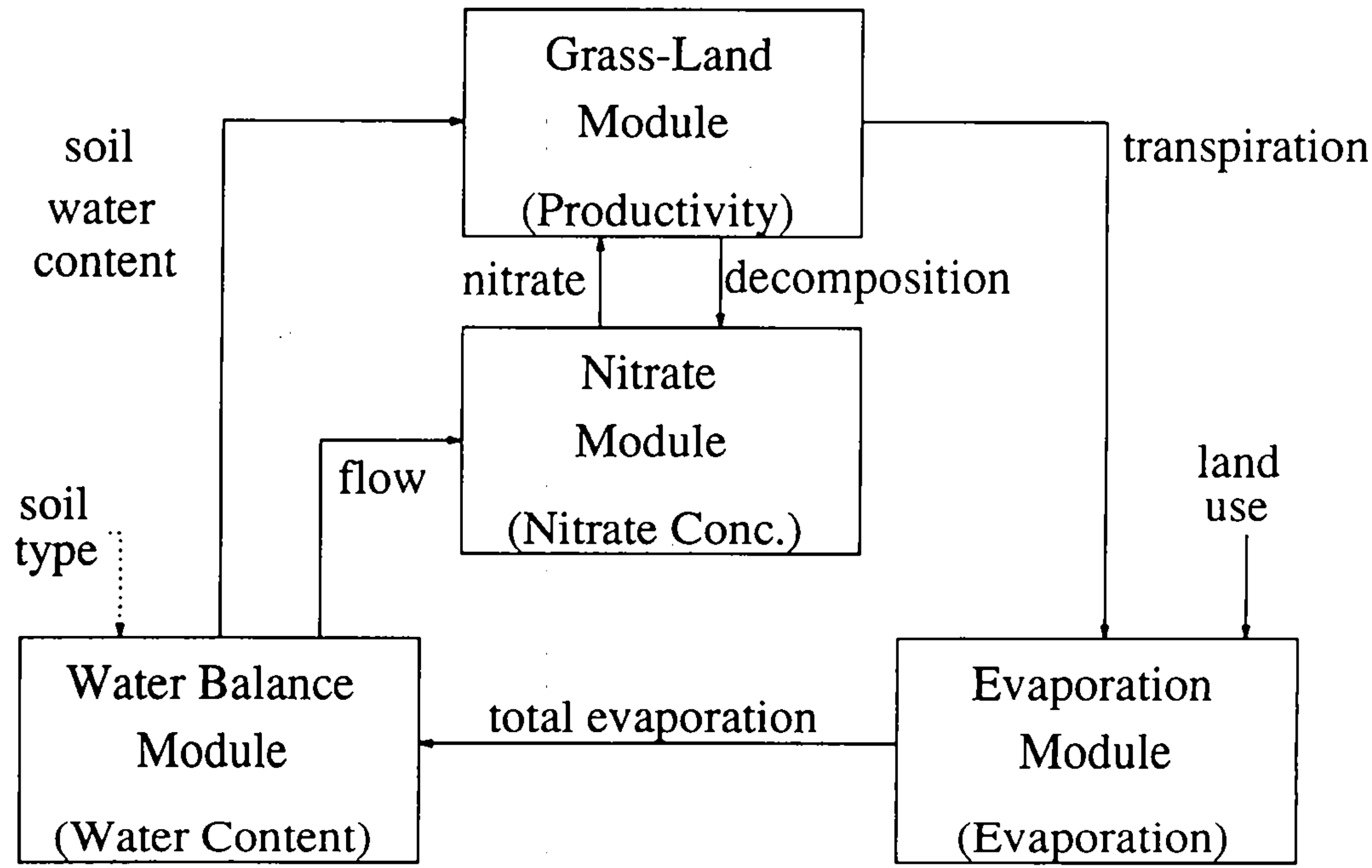
In order for the linked model to be applied on a regional scale the simulation treats each grid square as a catchment, so that results are given for each grid square. At present there is no lateral movement of water or nutrients between grid squares. The size of the grid square is based upon the largest scale of all the input data sets.

2.3) The Evaporation module.

The Evaporation model is based upon the daily evaporation model of Hall and Harding [15]. This model was developed to simulate the evaporation from vegetation in the Balquhidder catchment, Scotland. The catchment predominantly consists of upland grass, heather and coniferous forest. The 1978 land-use data set (ITE), which is used for this study and covers the area of GB, was degraded into three land use types; grass, heather and forest (Table 1). The proportion of a given grid square covered by one of the three land use types was then used to weight the results of the evaporation module.

For the heather and forest land-use types evaporation is separated into two parts, interception and transpiration. Heather (T_h) and forest (T_f) transpiration;

$$T_h = \beta_h E_T (1 - \omega_h) \qquad \textbf{Eqn 1}$$



* Each module requires climate parameters.

·······▸ Can be used when data becomes available.

() Ouput variable

Figure 1

$$T_f = \beta_f E_T (1 - \omega_f)$$ **Eqn 2**

Where β_f and β_h are transpiration factors, ω_f and ω_h are 'wet canopy time' factors and E_T Penman evaporation.

Table 1

ITE 1978 Land-use	Re-Classified
Upland grass	Grass
Permanent grass	Grass
Leys	Grass
Cultivated land	Grass
Built up	Grass
Miscellaneous Natural	Grass
Bog	Grass
Moorland	Heather
Heath/Shrub	Heather
Coniferous woodland	Forest
Broadleaf woodland	Forest

Heather (I_h) and forest (I_f) interception;

$$I_h = \gamma_h [1 - \exp(-\delta_h P)]$$ **Eqn 3**

$$I_f = \gamma_f [1 - \exp(-\delta_f P)]$$ **Eqn 4**

Where γ_f, γ_h, δ_f, and δ_h are interception parameters and P is daily rainfall.

Only transpiration is considered for the grass land-use type and is replaced in this model by the results from the grass-land model (section 2.6). The grass, heather and forest evaporation terms are then weighted for area. All the evaporation terms are then summed to give the total evaporation for each grid square and for each day.

The above equations describing transpiration are driven by E_T which in turn is calculated from climate variables. Thus under a changed climate the equations would by driven by the differing variables that make up E_T *i.e.* Temperature, humidity, wind speed *etc.* The equations for interception are driven by the amount of rainfall that falls in a given day and thus this would be the driving variable under a changing climate.

Figure 2 shows an example of the Hall and Harding model [15] applied across GB on an annual basis for 1984, forest evaporation. The Figure shows the approximately 250,000 grid squares of the land-use data set. The transpiration and interception terms are added and weighted for the area cover by forest in each grid square. It is acknowledged that the model has not been tested on lowlands and thus results may be inaccurate. Ideally a model (similar to the grass-land model) would be run for each land-cover type, in this case a model for forest and one for heather similar in structure to the grass-land model described in section 2.6. This is not yet possible so the above methodology is used.

2.4) The water balance module.

The grass-land model (section 2.6) has an in built routine for calculating the soil water content. This was inadequate for the purposes of the linked model so a more realistic routine was written. The new model uses the saturated storage capacity and field capacity of a generic soil to keep account of the water content of the soil and to calculate flow on a daily scale for each grid square. Figure 3 shows a schematic of the water balance model. This module is encoded in Arc/Info.

Figure 4 (Reproduced from Principles of Hydrology, eds. R.C. Ward and M. Robinson. Pubs, McGraw-Hill Book Company, 1990) shows the general relationship of total porosity, field capacity and wilting point for a number of soil types. The wilting point is defined as the minimum water content of a soil at which plants can extract water. Field capacity is defined as the quantity of water remaining in the soil after draining by gravity has ceased. Porosity is the amount of air-space within a soil and is equivalent to the saturated water content of a soil. Unfortunately these parameters were unavailable from the HOST data set and so a generic soil was used, derived from Figure 4. The soil has a defined field capacity and saturated water content in units of mm of water.

The net rainfall is first calculated by subtracting the evaporation away from the total daily rainfall. The evaporation is provided from the results of the evaporation module (section 2.2). The new water content is then calculated as the old water content plus the net rainfall. If the new water content exceeds the saturated level for the soil, which is assigned a value of 0.09 mm then the difference is assigned to excess flow. Whether excess flow occurs or not there is also a drainage term which describes the loss of water out through the bottom of the soil. The drainage term is dependent upon the field capacity of the soil and the linear function of drainage verses water content. The drainage term and the excess flow terms are then added to produce the flow from that grid square. The new water content of the soil is also

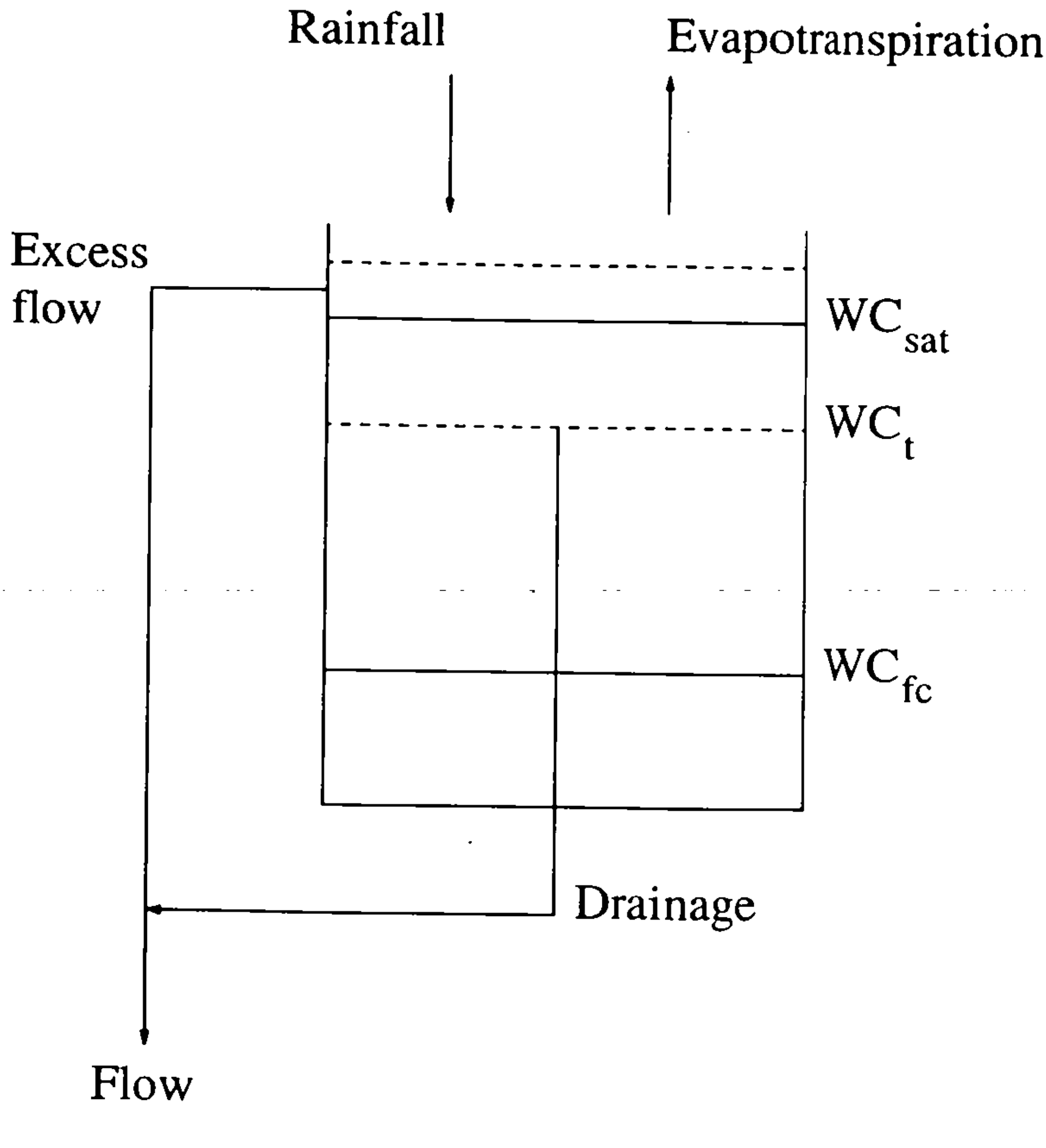
Annual Evaporation 1984 (Forest)

Key

- 0 - 72 mm
- 72 - 144 mm
- 144 - 216 mm
- 216 - 288 mm
- 288 - 360 mm
- 360 - 432 mm
- 432 - 504 mm
- 504 - 576 mm
- 576 - 648 mm
- 648 - 720 mm

Figure 2

Water Balance Model



* Drainage is dependent upon water content

Figure 3

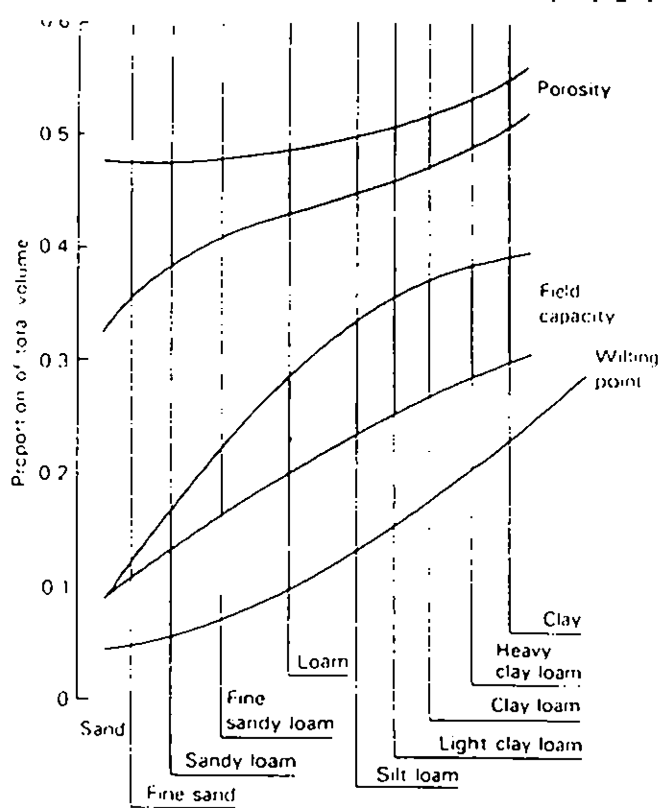


Figure 4. Change in water content with changing soil type.

calculated.

$$P_n = P_T - E_A \qquad \textbf{Eqn 5}$$

$$WC_t = WC_{t-1} + P_n \qquad \textbf{Eqn 6}$$

$$WC_{diff} = WC_t - WC_{sat}\;; \qquad WC_t > WC_{sat} \qquad \textbf{Eqn 7}$$

$$WC_{drain} = 1/(WC_{sat} - WC_{fc}) * WC_{sat}\;; \qquad WC_t > WC_{sat} \qquad \textbf{Eqn 8}$$

$$WC_{drain} = 1/(WC_{sat} - WC_{fc}) * WC_t\;; \qquad (WC_{sat} - WC_{fc}) < WC_t \le WC_{sat} \qquad \textbf{Eqn 9}$$

$$WC_{drain} = 0\;; \qquad WC_t \le (WC_{sat} - WC_{fc}) \qquad \textbf{Eqn 10}$$

$$Flow = WC_{drain} + WC_{diff} \qquad \textbf{Eqn 11}$$

Where; P_n - net daily rainfall, P_T - Total daily rainfall, E_A - Actual daily evapotranspiration, WC_t - Water content of soil on day t, WC_{t-1} - Water content of soil on day t-1, WC_{sat} - saturated daily soil water content (0.09 mm), WC_{diff} - excess daily water flow from soil, WC_{drain} - Water daily draining from soil, WC_{fc} - field capacity of water (0.03 mm). All units are mm. Soil depth is assumed to be 0.3 m. Each of these variables represents a grid of 1 Km^2 grid squares over the land surface the module is ran.

2.5) The nitrate model

This component of the linked model is a simple extension of a lumped catchment model developed for simulating the nitrate concentrations in a stream in an upland forested and moorland catchment [39]. The original model does not attempt to separate the various processes within the terrestrial nitrogen cycle. Knowledge of how the concentration of nitrate in a stream varies seasonally along with how it reacts to change in land use were used to develop its structure.

The model is continuously defined by the first order differential equation,

$$\frac{dN}{dt} = k_1(Q_R N_R - QN) + \frac{d}{dt}(-k_2 T + I(k_3 T - k_4)) \qquad \textbf{Eqn 12}$$

where,

N = Nitrate concentration in the stream (mg-NO_3/l)
Q_R = Rainfall (mm/day)
N_R = Nitrate concentration in the rainfall (mg-NO_3/l)
Q = Stream flow (mm/day)
T = Stream temperature (°C)
I = A positive index indicating changes in the biomass
k_1 = Constant mm^{-1}
k_2 = Constant mg-NO_3/(l °C)
k_3 = Constant mg-NO_3/(l °C)
k_4 = Constant mg-NO_3/l

Changes in the biomass index, I, are assumed to be proportional to changes in the biomass. So if there was no significant vegetation change in the catchment during the period of the simulation the value of I would remain constant. If, however, the biomass doubled the magnitude of I would double.

The first part of equation 12 describes the contribution of nitrate to the system by atmospheric deposition and its removal by leaching. The form of this expression is typically used in mass balance models assuming a completely mixed tank.

The second part of equation 12 describes the combined effects of the biologically mediated processes operating within the terrestrial parts of the catchment. It is dependent on temperature and the biomass change index. The structure is derived from three observed phenomena in upland forested and moorland catchments [2,26,41]. These are, firstly; a seasonal oscillation in the concentration of nitrate in the stream which appears to be inversely proportional to temperature; secondly, an increase in the amount of nitrate leached during and after a period of deforestation, and; thirdly, after such an event the amplitude of the oscillation increases.

If I is held constant for the period of simulation, indicating no disruption in the biomass, then ($-k_2 + Ik_3$) remains constant, hence the contribution to nitrate concentration by this part of the equation is proportional to the temperature. If I is reduced indicating a reduction in the biomass ($-k_2 + Ik_3$) becomes more negative and $-Ik_4$ becomes less negative. Hence the amplitude of the seasonal oscillation increases and there is an overall increase in the mean nitrate concentration in the stream.

The model described is dependent on four parameters which cannot be attributed to the rate at which any single process occurs, hence they must be estimated on the basis of observed data. Having estimated these parameters it is possible to make a speculative split of the model into two of the nitrogen processes which are known to occur, mineralization and plant uptake , provided no major change in uptake occurs. This is a necessary extension to the original model if it is to be used as a component of the linked model described earlier.

The net effect of mineralization and nitrification can be described by a first order, temperature dependent, rate equation [3], which could be approximated by dN/dt = cT, where c is a constant (mg/(1 day °C)) and T is temperature (°C). However, this ignores the fact that in late summer and autumn the rate of mineralization is likely to be greater than for spring and early summer at a similar temperature due to the increased availability of organic nitrogen from litterfall. This can be accounted for by subtracting a term which is dependent on the rate of change of temperature,

$$\frac{dN}{dt} = c_1 T - c_2 \frac{dT}{dt} \qquad \text{Eqn 13}$$

where c_1 is a constant (mg-NO_3/(1 day °C)) and c_2 is a constant (mg-NO_3/(1 °C)). dT/dt > 0 in the spring and dT/dt < 0 in the autumn, therefore, the rate of change of nitrate concentrations due to mineralization and nitrification is greater in autumn than in spring for the same temperature. Similarly for uptake the rate of transpiration is greater in the spring than in the autumn for the same temperature and hence the rate at which nitrogen is taken up by vegetation is greater. This can be described in an analogous manner,

$$\frac{dN}{dt} = c_3 T + c_4 \frac{dT}{dt} \qquad \text{Eqn 14}$$

where c_3 is a constant (mg-NO_3/(1 day °C)) and c_4 is a constant (mg-NO_3/(1 °C)). Combining these representations of mineralization and uptake with deposition and leaching terms results in,

$$\frac{dN}{dt} = k_1(N_R Q_R - NQ) + (c_1 - c_3)T + (c_2 + c_4)\frac{dT}{dt} \qquad \text{Eqn 15}$$

where k_1, N_R, Q_R, and Q are the same as in equation 12. If $c_1 = c_2$, then annual uptake and mineralization are in balance and equation 15 reduces to the simplified form of equation 12. It is this form of the model which is used in the linked model.

2.6) A model for predicting temperate grassland responses to changes in climate and CO_2

2.6.1) Introduction

The primary environmental variables which define the limits to growth and production of plants and govern changes in their geographical distribution are solar radiation, temperature, water, soil and nutrients. In general the variations in climate for the U.K. are in mean temperature (decreasing by about 3°C from south to north), solar radiation (decreasing by about 40% from south-west to north-east) and rainfall (decreasing by at least 50% from west to east) [9]. Apart from rough grazing land most annual crops and grassland are fertilized to minimize limitations from mineral nutrition [9].

Temperature is the strongest factor in the U.K. influencing the development and canopy expansion of annual crops and it is also the main constraint on the productivity of perennial ryegrass. Whereas for determinate crops (*e.g.* cereals) increased temperature decreases yields by shortening the duration of the growing season over which the crops intercept light, the yields of indeterminate crops such as grassland tend to increase as temperature rises because they continue to produce leaves and grow as long as the prevailing temperature remains suitable [40].

Drought can be a limiting factor to crops in the south and east of the UK where irrigation systems are inadequate to sustain sufficient soil moisture reserves [9].

Atmospheric CO_2 is an additional variable critical to crop growth. Most plants, particularly C_3 species, growing in atmospheric CO_2 levels higher than ambient exhibit increased rates of net photosynthesis [7,8], often with reduced stomatal apertures [44]. Elevated CO_2 can therefore lead to an increase in water use efficiency, reducing transpiration per unit leaf area while promoting photosynthesis. Experimental effects of CO_2 levels on crops have been reviewed by Acock and Allen [1] and Cure [11]. Compilation of greenhouse and other experimental studies by Kimball [20] estimates an increase in crop yield of 33±6% for a doubling of CO_2 concentration from 300 to 600ppm.

Crop growth models that simulate the responses of agricultural plants to climate may be used with climate change scenarios to evaluate the consequences for yields and phenology. Such models are usually developed from relationships among current climate variables and crop responses [28], but these relationships may or may not hold under differing climate conditions introducing uncertainty into the predictions of crop responses to climate change. However, a single crop model may be used over a range of sites with differing climatic conditions to study potential crop responses to climate change. For example, the predicted changes in climatic conditions in the UK over the next 40 years lie well within the range of environmental conditions already experienced by crops in this country. Since increasing CO_2 concentration is the primary cause of the anticipated climate changes both the direct and climatic effects of increasing CO_2 levels should be incorporated into crop growth models.

The most generally used grassland model is CENTURY which is a computer model of plant-soil ecosystems which was originally designed to simulate the biomass and soil organic matter dynamics of grassland ecosystems [29,30,31,32,35]. CENTURY is an ecosystem model rich in its capacity to simulate nutrient cycling but without a design to incorporate mechanistically the effects of CO_2 and temperature on basic plant processes such as photosynthesis and transpiration. A grassland model is described here with the capacity to respond mechanistically at the leaf and canopy level to changes in temperature and CO_2 in the range expected for the UK over the next 50 to 100 years.

The work described here aims to predict, in response to scenarios of environmental change, the dynamics of grassland vegetation within a catchment, using a physiologically based model of plant and canopy processes [37]. This model contrasts strongly with CENTURY which is an aggregated ecosystem model with little emphasis on physiological mechanisms. The physiological approach has been selected because of the greater capacity to make realistic predictions in new environments than empirical correlation models [43].

The grassland model has the capacity to simulate morphological and physiological processes of grass growth and adapt automatically to changes in the environment (solar radiation, temperature, humidity, rainfall and CO_2 concentration). The model is tested using observed field data of dry mass production from a range of sites in the UK and the Netherlands. The model is used for predicting the effects of future climatic change scenarios on the patterns of growth of temperate grassland.

2.6.2) The grassland module

An original grassland model [37] is being expanded for use as a general grassland model, suitable for predicting forage yields, particularly by harvesting and in the UK (Figure 5). The grassland model has been described in detail [14]. Each of the model routines are computed for 1 m^2 of ground area. Maximum rooting depth of the grass crop is assumed to be 0.3 m [37]. Calculations of photosynthesis, respiration and growth are in weights of carbohydrate (CH_2O) which for grasses is equivalent to dry weight because 40% of grass dry weight is carbon, the same proportion as in CH_2O [36].

The model uses arrays to track each portion of leaf area and leaf, stem and root weights produced each day. Each day some tissue weight loss occurs by temperature-dependent maintenance respiration [22,23,34]. On the day of formation portions of leaf have a photosynthetic capacity and specific leaf area assigned to them according to the mean temperature and light levels in the canopy. Leaf area index and biomass of plant components are totals of the relevant arrays. In the model the starting values for leaf, stem and root dry weights are 20, 100 and 400 g m^{-2}, based on field observations by Sheehy and Peacock [38].

The daily inputs of climatic variables required by the model are solar radiation, air temperature, soil temperature, fractional day length and relative humidity.

2.6.3) Validation

Validation of the grassland model has been mainly based on datasets collected from the joint Agricultural Development and Advisory Service (ADAS)/Grassland Research Institute (GRI) grassland manuring trial GM20 of perennial ryegrass (S.23) during the years 1970 to 1973 [24]. Five sites were chosen from across the UK with differing climatic regimes ranging from Northumberland in the north-east to Devon in the south-west (Table I). The swards were harvested (CUT) at regular intervals throughout the season. The field trial swards were each given an annual rate of nitrogen fertilizer of 150 g m^{-2}. The results of the growth data for the field trials and the predicted values generated by the model are summarized in Table II. A graphical example of the model output for the site in Devon is shown in Figure 6. All dry masses are for shoot growth only and are the averages of four years data (1970-1973). Correlation between the real and simulated data is clearly evident with the model predictions of dry masses at each cut at worst within ±25% of the field trial data, and the totals for all sites within ±10%, apart from High Mowthorpe which was 17% higher than the field data. A graph of the predicted versus the actual values of dry mass from individual cuts is presented in Figure 7. The regression line in Figure 7 is not significantly different (P=0.05) from the 1:1 line thus emphasising the validity of the model.

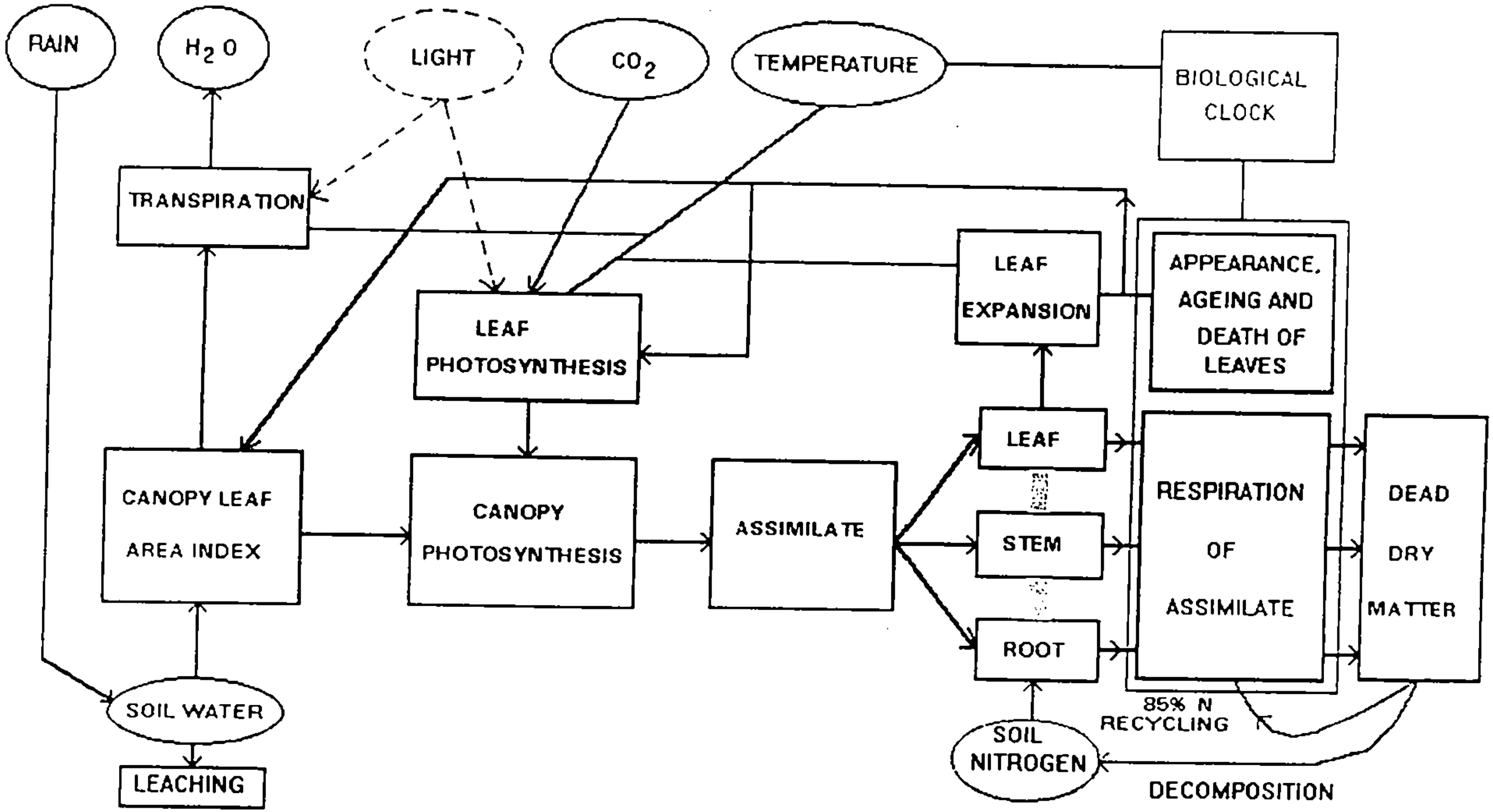


Figure 5 Schematic diagram of the grassland model.

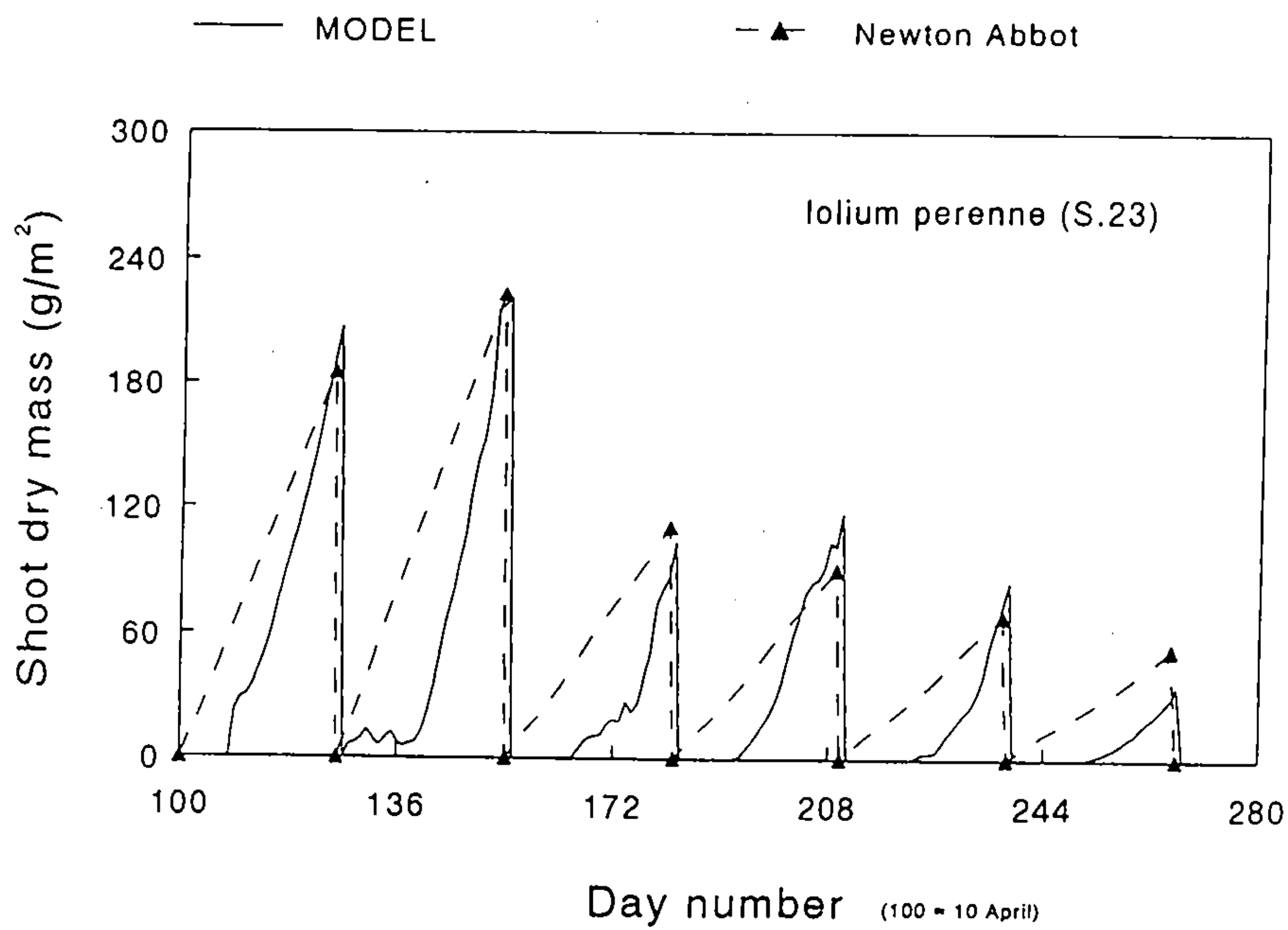


Figure 6 Model simulation of sequential harvests and actual growth data from Newton Abbot ADAS/GRI field trial GM20 (1970 - 1973).

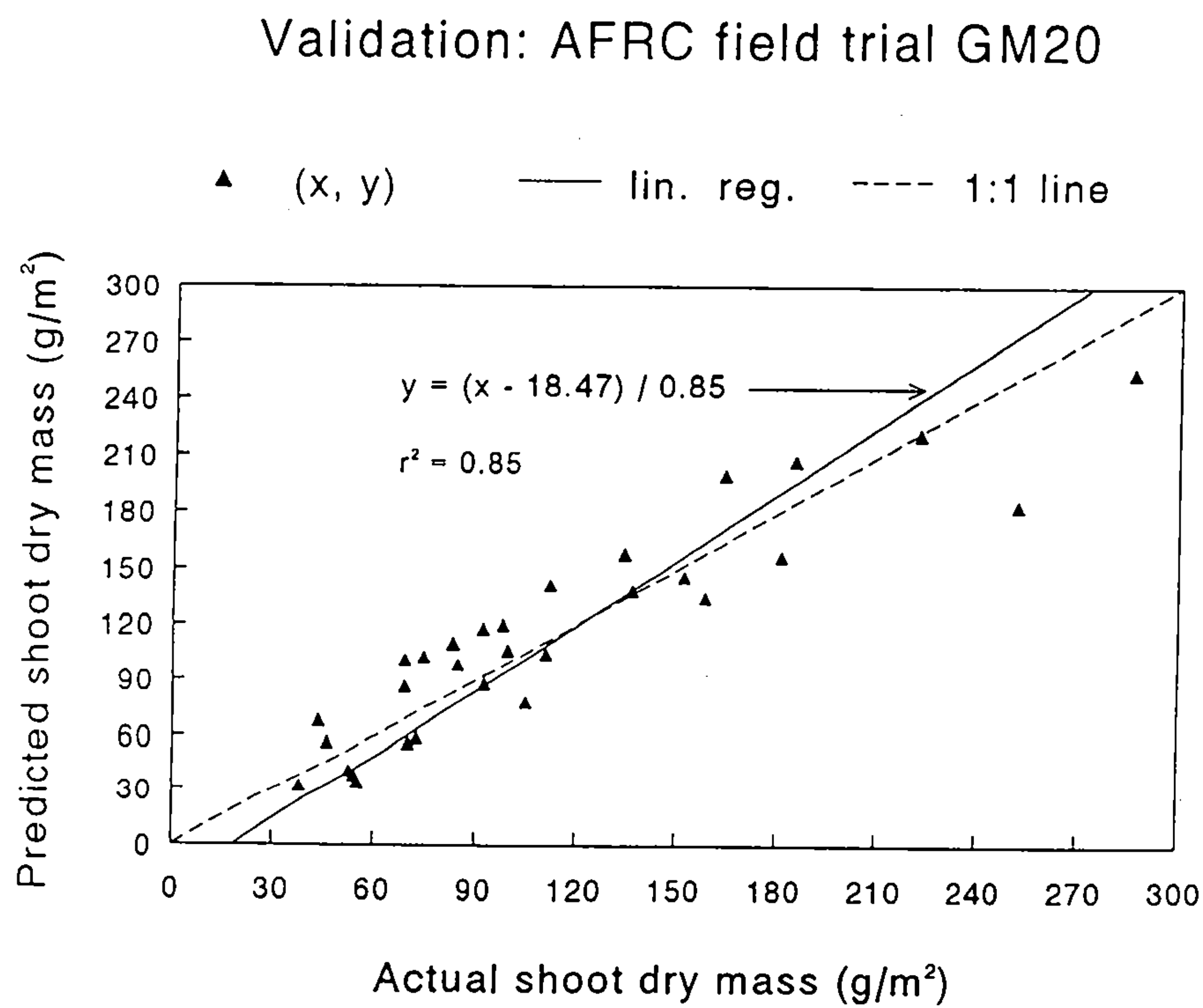


Figure 7 Comparison of model predictions of dry matter production with actual field data collected from the ADAS/GRI field trial GM20 (1970 - 1973) (see Table II).

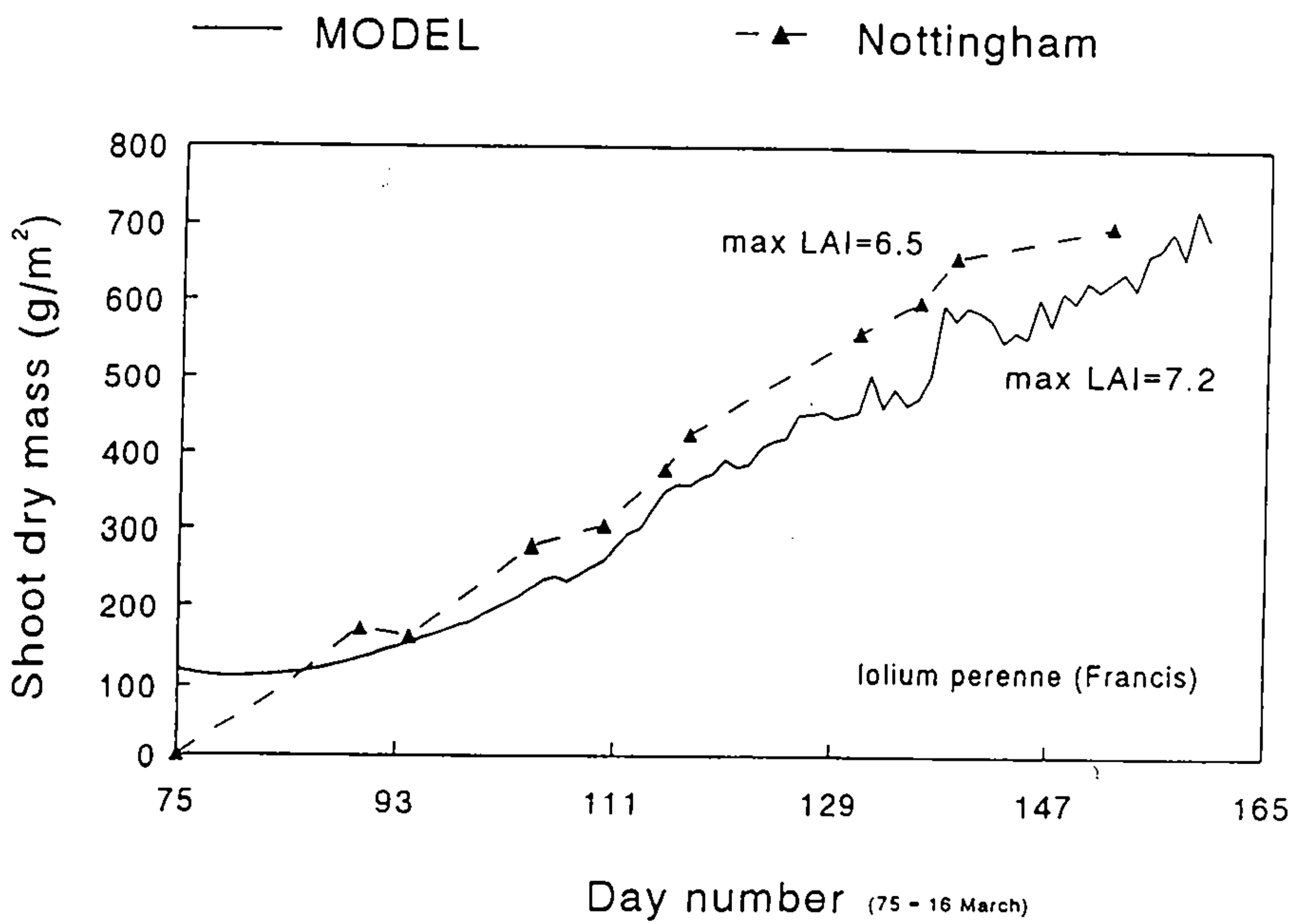


Figure 8 Time courses of dry matter production for model and actual field data at Sutton Bonington, Nottingham (1988).

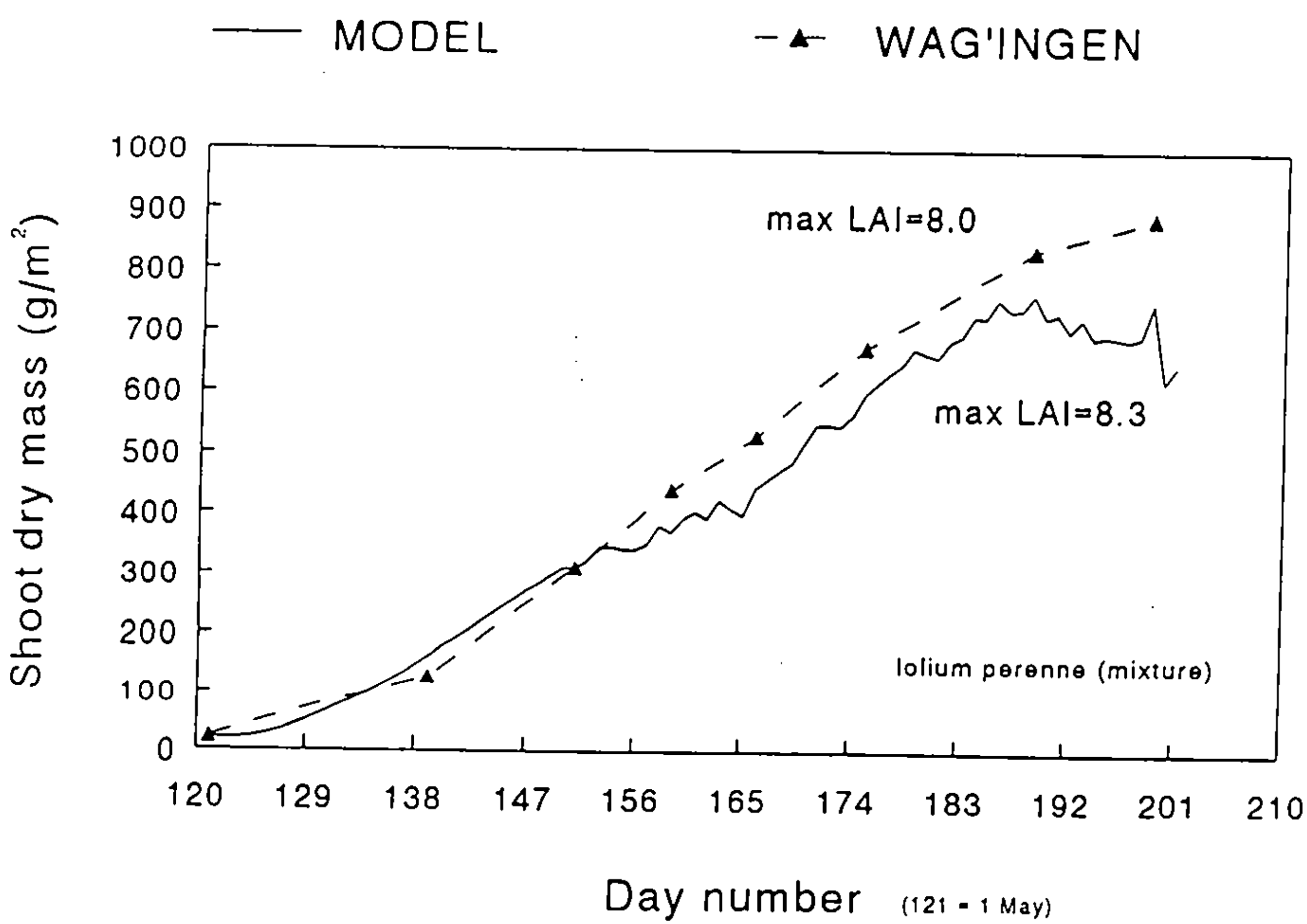


Figure 9 Time courses of dry matter production for model and actual field data at Wageningen, Netherlands (1960 - 1966).

Table I. Seasonal mean values of solar radiation, air temperature and total rainfall, during years 1970 1973, for the five sites in the UK used to validate the grassland model.

Location	1	2	3	4	5
Solar radiation ($MJ/m^2/d$)	7.12	7.09	7.98	8.02	8.14
Air Temperature (°C)	11.74	11.89	12.86	13.53	13.69
Total Rainfall (mm)	309.9	298.0	322.5	323.2	337.4

Location

1: Cambo (OS NZ0387), Morpeth, Northumberland.
2: High Mowthorpe Experimental Husbandry Farm (OS SE8868), North Yorkshire.
3: Rosemaund Experimental Husbandry Farm (OS SO4756), Preston Wynne, Hereford.
4: Somerset College of Agriculture and Horticulture (OS ST2539), Cannington, Somerset.
5: Seale Hayne (OS SX8273), Newton Abbot, Devon.

Additional validation data from the U.K. [Cullen, M. and Hand, I.S., University of Nottingham; personal communication] and the Netherlands [5] are presented in Figures 8 and 9. The field and meteorological data for Nottingham are for the 1988 season whereas those for Wageningen are the means for years 1960 to 1966 (see Table III). The shoot dry masses for the field swards were estimated from the cumulative dry masses of sequentially harvested subplots. In both Figures 8 and 9 the correlations between the field and model data are very good during the main phase of canopy expansion, model predictions being within ±25% of the field data. In these tests no cuts have been taken demonstrating the capacity of the grassland model to follow natural trends of grass growth. However, at both sites rapid accumulation of dry mass towards canopy closure appeared to be sustained longer in the field than predicted by the model. This phenomenon might be explained by the fact that whereas the dry mass of field swards probably contains dead tissue, that generated by the model does not.

2.6.4) Simulation

The model is now used to investigate the effect of climatic change, such as is indicated earlier for the UK for about the year 2030. Figures 10 and 11 illustrates the predicted effects of a 1.5°C increase in mean temperature and a 200 ppm enrichment of atmospheric CO_2 content (560 ppm) above ambient (360 ppm) on LAI and dry matter production for two contrasting sites in the U.K. (Morpeth and Newton Abbot). The seasonal mean air temperatures and total rainfall figures for Morpeth and Newton Abbot are 11.54 and 13.14°C and 379 and 352 mm, respectively. The temperature difference of 1.6°C has been specifically chosen to provide a test for the validity of the model when responding to a 1.5°C warming. In such a case the response of grasslands to a 1.5°C warming should be similar to Newton Abbot under current conditions.

Table II. Comparison of mean shoot dry mass data from ADAS/GRI GM20 field trials and the grassland model for five sites across the U.K. The values of dry mass are for years 1970 to 1973.

Shoot drt mass yield of individual cuts (g/m^2)							
CUT	1	2	3	4	5	6	Total
Morpeth, Northumberland:							
Day Number	136	164	192	220	248	276	
Field	152	252	134	136.5	105	72.5	852
Model	146	183.5	158.3	138.4	77.8	59	763
High Mowthorpe, North Yorkshire:							
Day Number	134	162	190	218	246	274	
Field	83	164	69	84.5	70	38	508.5
Model	109.9	199.8	101.1	98.5	56.2	31.9	597.4
Preston Wynne, Herefordshire:							
Day Number	130	158	186	214	242	270	
Field	158.5	286.5	98	99.5	92.5	52.5	787.5
Model	134.5	254.2	119.8	106.4	87.8	41	743.7
Cannington, Somerset:							
Day Number	128	156	184	212	240	268	
Field	112	181	74.5	43.5	46	55	512
Model	141.2	156.9	102.7	67.9	56.6	34.1	559.4
Newton Abbot, Devon:							
Day Number	126	154	182	210	238	266	
Field	185	222.5	111	92	69	54	733.5
Model	207.3	221.3	104.5	117.8	86.4	38.2	775.5

Table III. Seasonal mean values of solar radiation, air temperature and total rainfall for Netherlands and UK sites used for validation of the grassland model.

Location	1	2
Season	1960-66	1988
Solar radiation (MJ m^{-2} d^{-1})	15.3	12.8
Air Temperature (°C)	14.3	9.8
Total rainfall (mm)	223.8	121.4

Location

1: Institute for Biological and Chemical Research on Field Crops and Herbage, Wageningen, Netherlands.

2: University of Nottingham School of Agriculture, Sutton Bonington, Nottingham, UK.

The regimes used are:

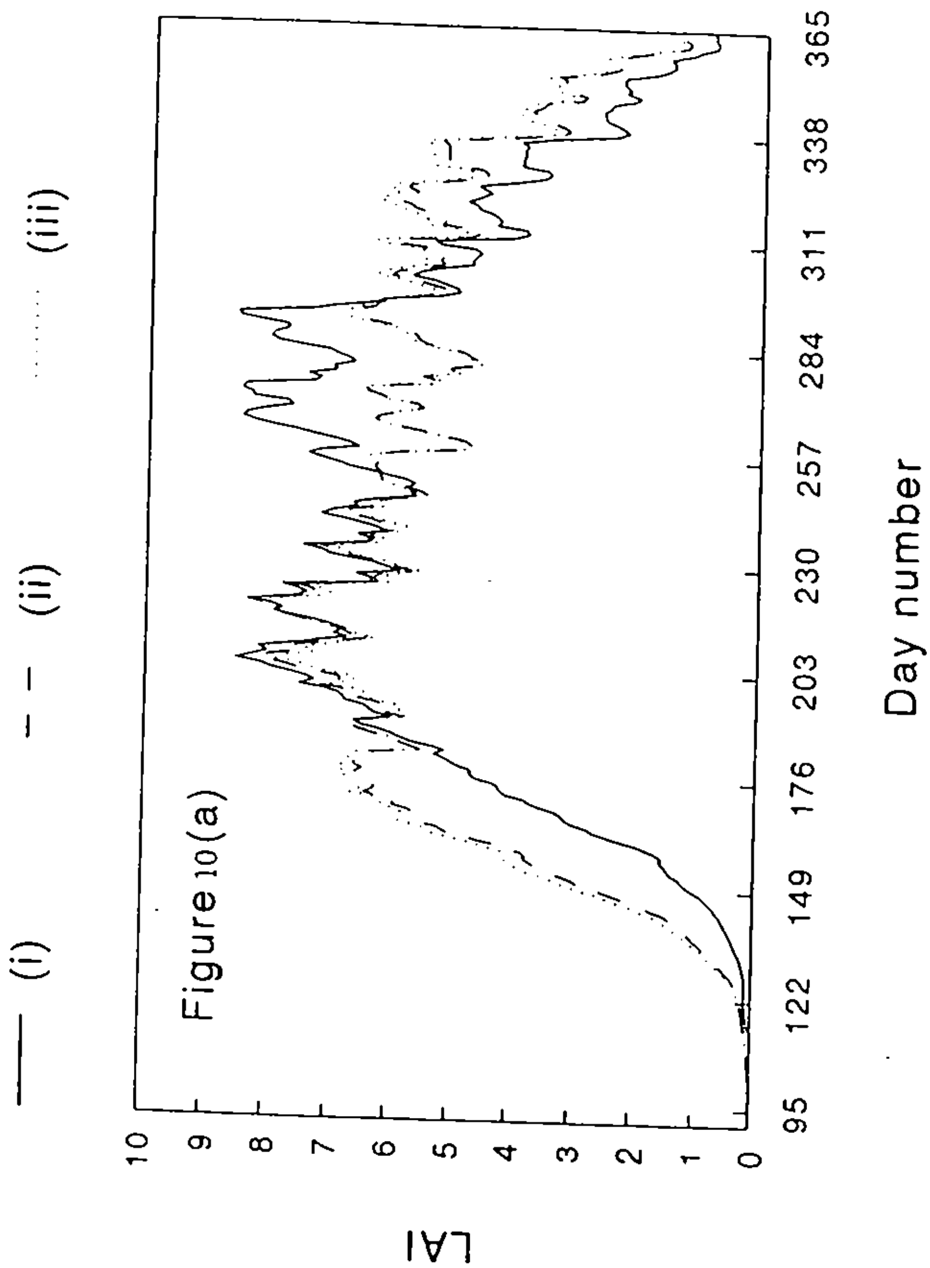
(i) Normal temperature / 360ppm [CO_2].
(ii) Temperature+1.5°C / 360ppm [CO_2].
(iii) Temperature+1.5°C / 560ppm [CO_2].

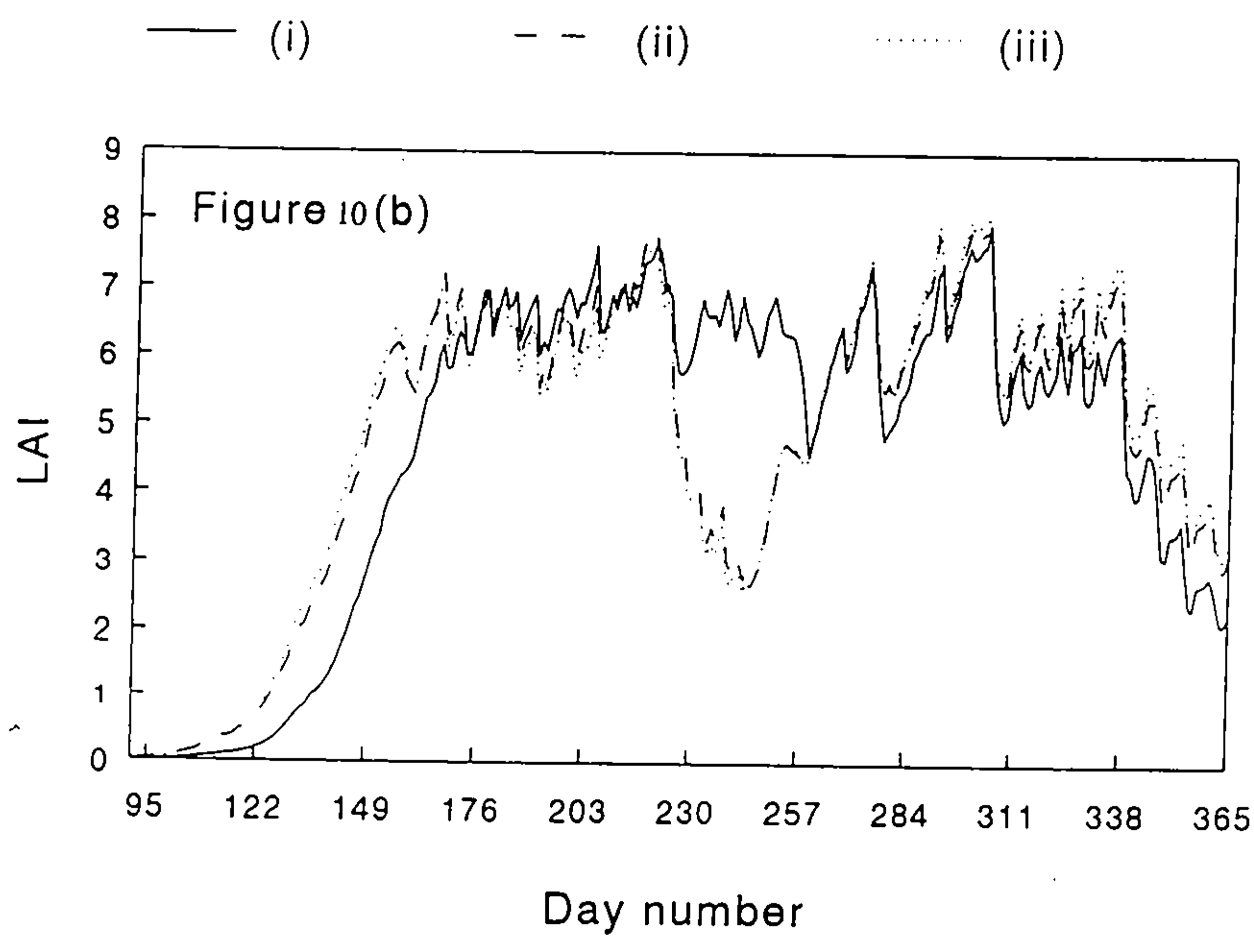
Compared to normal conditions, the increased temperature and CO_2 level regimes dramatically increase the rate of canopy formation (Figure 10), the duration of the spring exponential phase of growth being shortened by about 20 days at both sites for regimes (ii) and (iii). These differential rates of canopy formation are also reflected in the graphs of dry matter production (Figure 11). The fertilization effect of elevated CO_2 levels on dry matter production is also evident. For example, at Morpeth when LAI is about 7 (day 200) for regimes (ii, 360ppm) and (iii, 560ppm) the dry masses are about 550 and 600 g m^{-2}, respectively. Under normal conditions canopy closure at Newton Abbot is achieved about 20 days before that at Morpeth. However, when the 1.5°C temperature increase is applied to the conditions at Morpeth, similar to the seasonal temperature difference between the two sites, canopy closure at Morpeth occurs at a similar time to that at Newton Abbot under normal conditions (about day 170). This demonstrates the general applicability of the grassland model to climatic changes in the order of those projected for future climatic change.

The mid season depressions of LAI and dry matter for regimes (ii) and (iii) for both sites compared with regime (i) coincided with periods of low rainfall, between 250 and 290 days at Morpeth and 220 and 250 days at Newton Abbot. These differences probably reflect the higher evaporative demands and hence earlier onset of drought experienced by the swards in the elevated temperature regimes compared to those under normal conditions.

Figure 12 demonstrates grassland predictions of responses to climatic change extended to

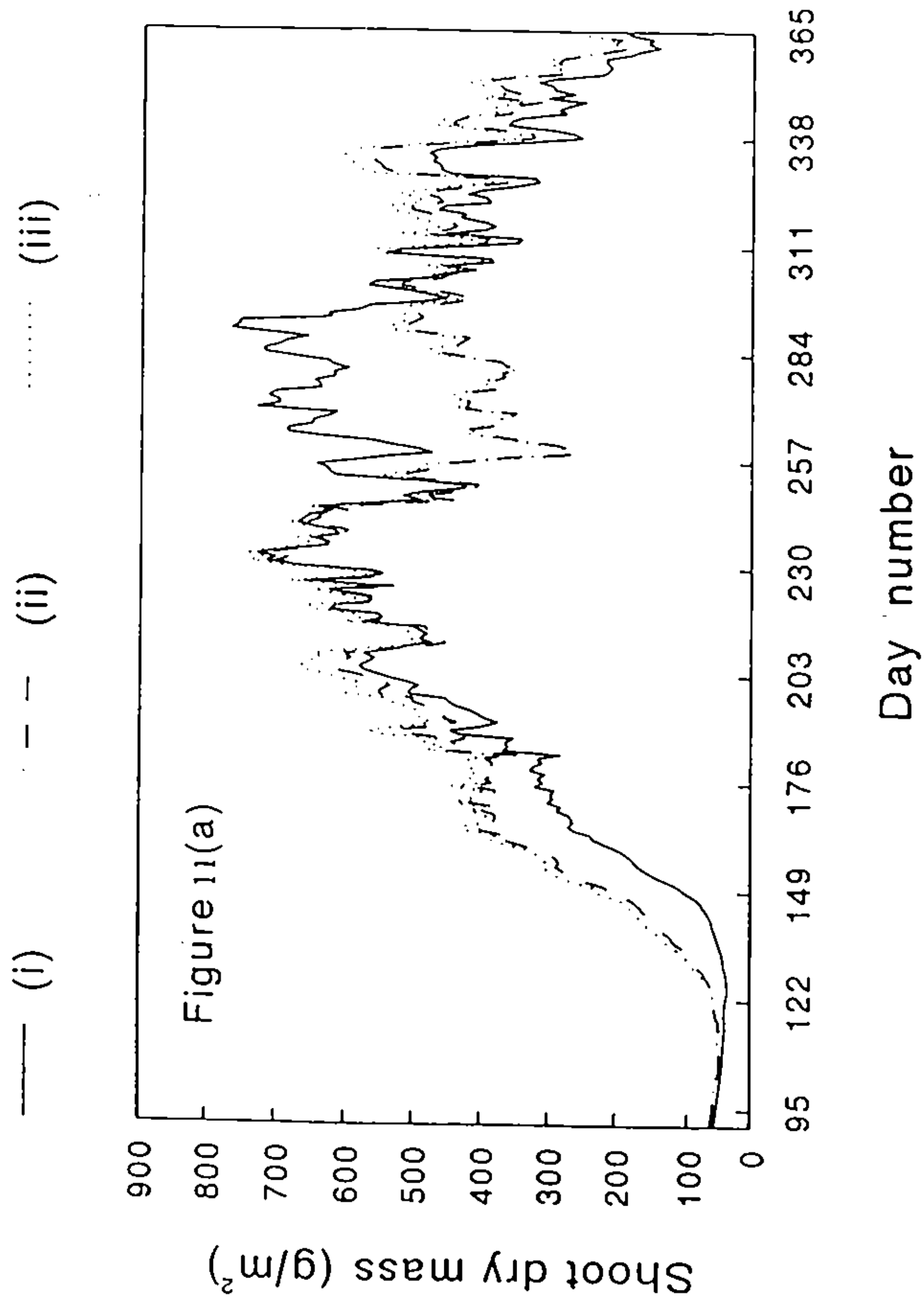
Figure 10 Model simulations of the effects of a 1.5°C warming and a 200ppm increase in CO_2 concentration on leaf area index (LAI) of grass swards at (a) Morpeth and (b) Newton Abbot (1973). See text for description of regimes (i), (ii) and (iii). Model run start date: 1 April (Day = 91).





(i)
(ii)
(iii)
Figure 10(b)
LAI
0
1
2
3
4
5
6
7
8
9
95
122
149
176
203
230
257
284
311
338
365
Day number

Figure 11 Model simulations of the effects of a 1.5°C warming and a 200ppm increase in CO_2 concentration on dry matter production of grass swards at (a) Morpeth and (b) Newton Abbot (1973). See text for description of regimes (i), (ii) and (iii). Model run start date: 1 April (Day = 91).



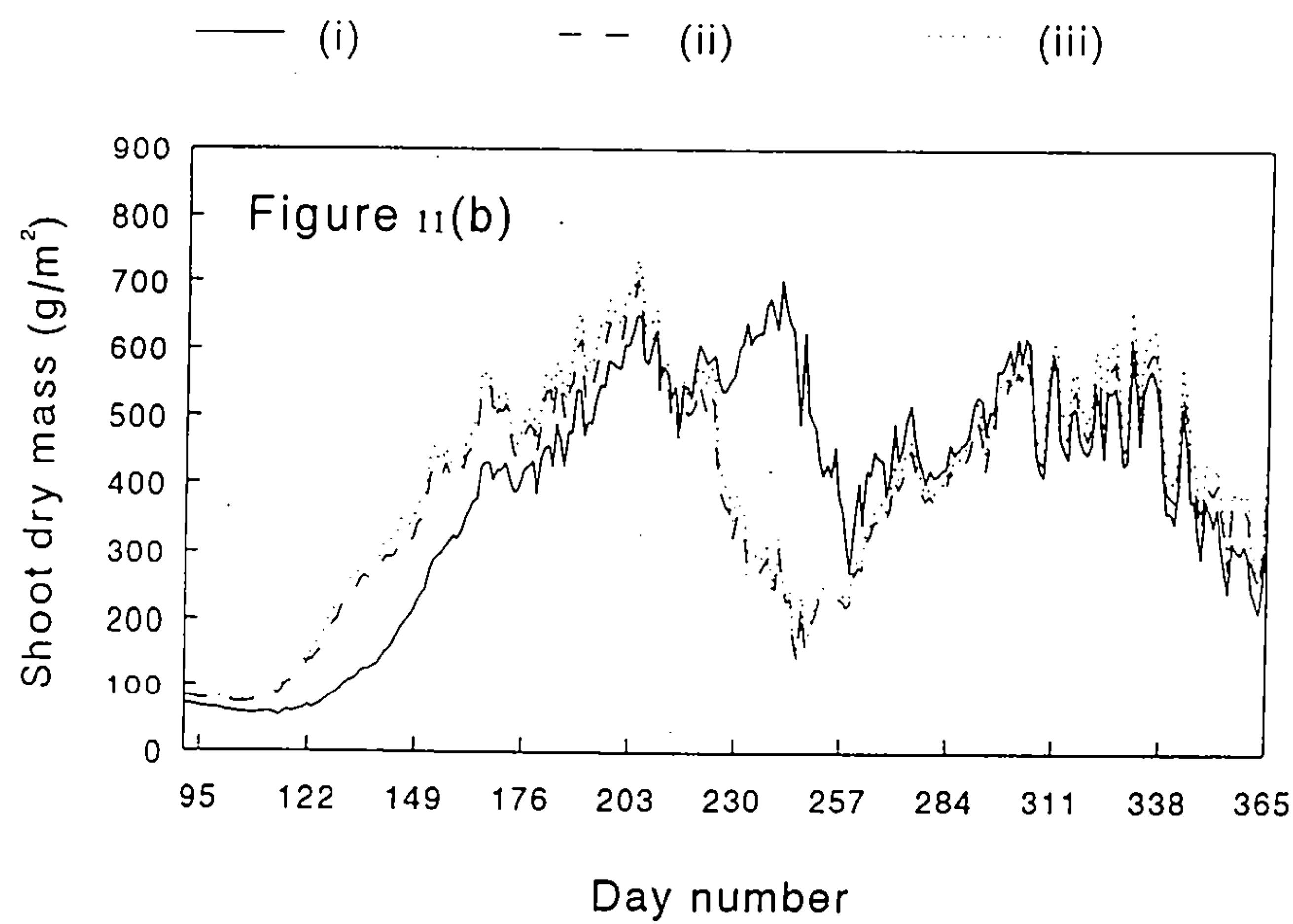
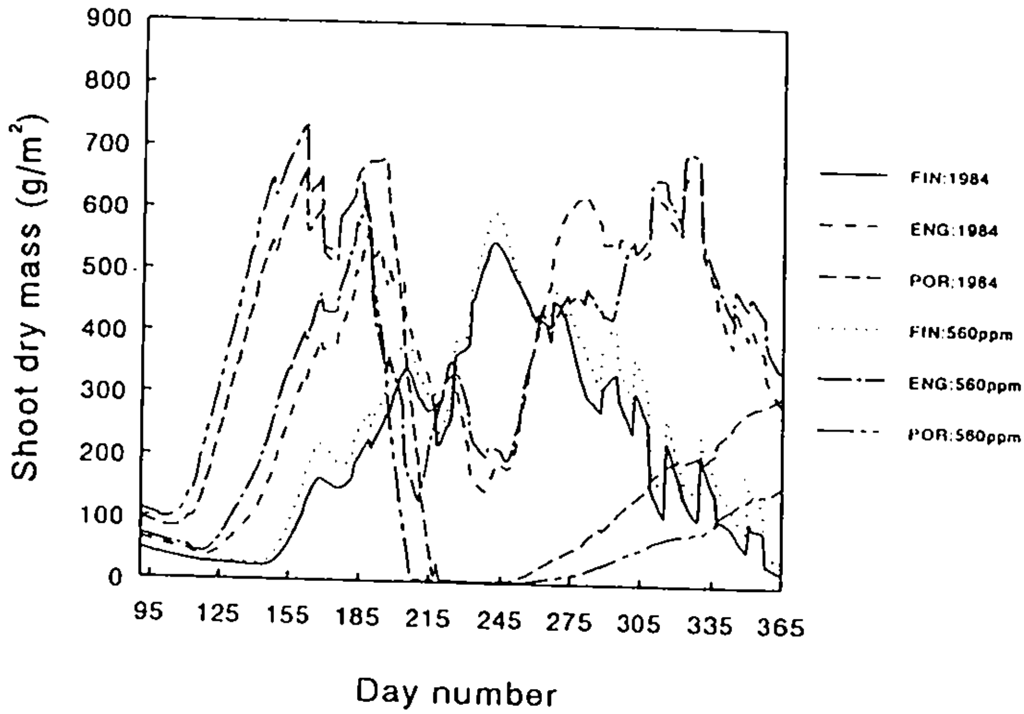

(i)
(ii)
(iii)
Figure 11(b)
Shoot dry mass (g/m²)
900
800
700
600
500
400
300
200
100
0
95
122
149
176
203
230
257
284
311
338
365
Day number

Figure 12 Model simulations of the effects of a 1.5°C warming and a 200ppm increase in CO_2 concentration on dry matter production of grass swards for three sites of contrasting latitudes across Europe (1984) (Finland, England and Portugal - see text). Model run start date: 1 April (Day = 91).



three sites of contrasting latitudes across Europe. The 1984 meteorological data for the three sites in Finland (South Sava; 61.7°), England (North Wyke; 50.7°) and Portugal (Vila Real; 41.3°) are from the Food and Agricultural Organization (FAO) trial L1 dataset [10]. The climate change scenario applied to each site is for a 1.5°C temperature increase together with an increase in CO_2 concentration from 360 to 560 ppm. For all three sites it is apparent that the combined effects of elevated temperature and CO_2 stimulate dry matter production, peak production values being about 50 g m^{-2} higher than under normal conditions. The contrasting climate regimes for the three sites are clearly reflected in the seasonal patterns of dry matter production.

2.6.5) Discussion

The core structure of a grassland vegetation model for investigations of climate change impacts on grassland ecosystems has been described. The model is physiologically based and responds to data inputs of solar radiation, air and soil temperatures, daylength, relative humidity and rainfall.

The model provides adequate simulations of grassland growth and productivity patterns. The seasonal distribution of dry matter production for the model simulations in the UK (Figures 10 and 11) is similar to that reported for pure swards of grasses by Anslow and Green [6]. Two distinct peaks of production are evident, the first in early summer generally being higher than the second during late summer. The midsummer depression of dry matter production is generally the result of lower leaf area indices and low photosynthetic potential of older shaded leaves and can be intensified by high temperatures and water stress and nutrient deficiency [42].

The results show that the grassland model can predict dry matter production to at worst within ±25%, generally within ±10% of the observed values. Although there is good agreement between actual growth data and that simulated by the model more validation data are required to test the model exhaustively. In particular there is a general lack of field data to validate the model's simulated responses to elevated CO_2 levels. However the model's response to CO_2 fertilization reflected by increased peak production of dry matter of upto 10% compared to normal conditions is in general agreement with data compiled by Kimball [20].

2.7) Linking the nitrate and grass-land modules

The first step in linking the modules together was to couple the nitrate module and the grass-land module. The two modules are interconnected in that the plant has a requirement for nitrate which depletes the soil-water nitrate pool, but also returns nitrate back to the soil-water via dead matter from decayed leaves.

The nitrate module runs on a weekly time scale while the grass-land module runs on a daily time scale, with hourly subroutines for photosynthesis. Both modules were written in FORTRAN. The nitrate module was embedded within the grass-land module so that once every seven days the nitrate module was run using the previous seven days of nitrate uptake and deposition from the grass-land module. The grass-land module then uses the new soil water nitrate concentration for the next seven days. For details see annual report 1992 [14].

2.8) Running linked grass-land and nitrate modules on each grid square

The linked grass-land and nitrate modules were run on each grid square. This was achieved by running the modules from within the GIS, which facilitated the manipulation of the spatial data and eased the handling of the large quantities of data involved. In order to do this two steps had to be fulfilled. The first is to have a separate linked module running on each grid square and the second is to have a module which can be run for a single day only for a given grid square. This is because the FORTRAN module would be called from the Arc/Info AML once for each grid square and each day. In order to run the module for a single day only it was necessary to add code which allowed the module to load the data, saved to disk on the previous day, into the module for each specific grid square and day number. This meant that for every grid square the module was run on there was a corresponding file with all of the variables for that days run. The FORTRAN code added to the module allows the correct variable to be loaded for the given day and grid square. After the module has been run for a given grid square, for a given day, control would be returned back to the AML from the FORTRAN code.

2.9) Running the sub-programs together.

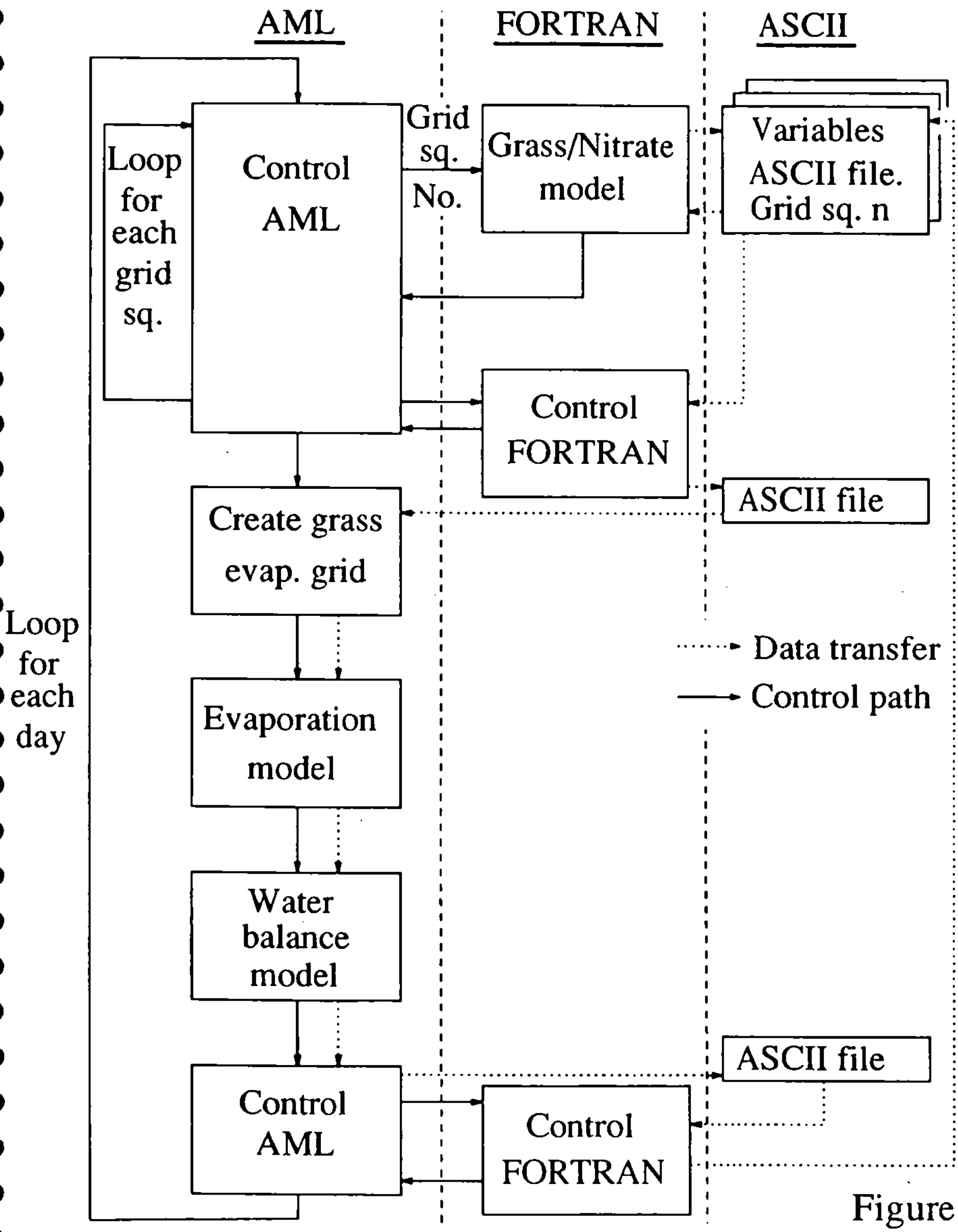
The main linked model was run from a single Arc/Info AML. The order of events is shown in Figure 13 The linked grass and nitrate modules were first run on each grid square for one day. A FORTRAN program was then called which takes the transpiration results from the first days run and puts then into a format that the AML can then read in. Control was then returned to the AML where a grid was created of the transpiration results. The total evaporation was then calculated for each grid square for that day and was followed by the water balance calculations, again for each grid square. Once the new water content has been calculated, the data for each grid square was exported to a file and then a FORTRAN program was called which placed the new water content within the file that holds the variables of the grass and nitrate models, to be used on the next time step. The whole process is then repeated for each day of the simulation.

A problem that has come apparent with the completion of the linked model is the availability of computing power. The linked model is currently being run on a SPARC 10-30, a reasonably quick machine (SPECfp 52.9). It has been estimated that to apply the linked model to each 1 Km^2 grid square of GB, to produce a map of grass-land productivity, will take at least 17 days processing power with no other software running on the machine.

3.0) The GIS framework

Over the last year the GIS framework in which the models are run has continued to be developed. The version of Arc/Info being used has bee upgraded to version 6.1.1. This has facilitated the linking of models with the GIS. As described above (section 2) the coupled modules are now fully integrated within the GIS framework to the extent that two of the modules of the linked model are encoded completely within the AML and the rest of the modules are under the control of the AML.

The GIS menu system has been improved so that data can be accessed from a relational



AML
FORTRAN
ASCII
Control AML
Loop for each grid sq.
Grid sq. No.
Grass/Nitrate model
Variables ASCII file. Grid sq. n
Control FORTRAN
ASCII file
Create grass evap. grid
Loop for each day
Evaporation model
Water balance model
Data transfer
Control path
ASCII file
Control AML
Control FORTRAN

Figure 13

database. In this case data was retrieved when required from an Oracle database across the network. This was used to access data such as the 1961-88 MORECS dataset and the data of the component parts of the land-use data set.

The facility to extract and display data for a particular GB catchment has been added to the GIS menu system. The user provides the menu system with the catchment identity number *e.g.* 039065 (Ewelme Brook river, gauging station Ewelme [17]) and the catchment will be displayed on screen with any upstream catchments and any other data set requested. This facility is of particular use to hydrologists whom frequently require to look at a data layer, *e.g.* land-use that lies within a particular catchment.

4.0) Datasets

New datsets are now accessable from within the GIS menu system, in addition to the existing ones (HOST, Land-use, DTM, Hydrometric areas, Gauged catchment areas and Welsh and English rivers). The new data sets include the results from previous SMD models (see progress report to 1991[13]) along with the data available across the network from the Oracle database. At present this is the MORECS 1961 to 1988 mean monthly values for the variables; Potential evaporation, Actual evaporation, Soil moisture deficit, Effective precipitation, Rainfall, Sun, Temperature, Vapour pressure and Wind speed. Another dataset that is now accessed across the network is the key which links the land-use class and the actual vegetation type. Each of the land-use types can be divided into the percentage coverage, of each 1 Km^2 grid square, for each of the vegetation types. The vegetation types include; Built up, Coniferous woodland, Broadleaf woodland, Miscellaneous natural, Moorland, Bog, Heath/Shrub, Upland grass, permanent grass, Leys and Cultivated land. Figure 2 shows how the Coniferous woodland and Broadleaf woodland vegetation types are used to calculate evaporation for the evaporation module of the linked model (section 2).

4.1) Climate data

Baseline climate is now available from the DoE Climate Change LINK project and it is hoped the transient GCM experiment data will be made available shortly. The baseline climate dataset consists of observed mean monthly values for the 1961-90 period for a range of climate variables gridded at a 10 Km^2 resolution. Although this dataset is a welcome addition to the existing datasets, to utilise the data many obstacles need to be overcome.

The linked model along with many other hydrologically based models runs on a daily time step *i.e.* climate data is a requirement for the model each day. In order to use the baseline climate data from the LINK project it would be necessary to interpolate the monthly data down into daily data. There are many problems involved in this task and a great deal of time and effort would be required in order to arrive at a dataset which would be usable for this project. One method of producing daily rainfall is to use a Markov model. This complex methodology is described in an IH internal document [Arnell,1992] and the 1991 DoE progress report [13]. If this methodology was used in this case it would only solve the problem for rainfall and would not provide the other parameters required such as radiation, humidity and temperature. There is a possibility that daily data may be available for a number of sites across the UK. This data is not yet available and would still require a large amount of processing so that it could be interpolated to a useable grid scale.

5.0 Work for the coming year

This year will be the final year of the project. This will necessitate the consolidation of the work carried out during the course of the project. A report will be written for the end of year seminar and handed out to attendees, which will outline the work of the DoE core model project over the four years

The linked model (section 2) will be applied to the sites to which the grass-land model has been validated. This will compare the grass-land model within and external to the linked model *i.e.* with and without ecosystem feedbacks. It will be interesting to see how the water balance, evaporation and nitrate models feed back onto the linked grass-land model and constrain it. It is hope that the linked model will also be applied to a regional application. Unfortunately this is dependant upon the availability of good daily climate parameters (section 5) and computing time.

The grass-land model will be further developed over the coming year. At present there is no carbon sink in the model for reproduction. The model will include routines allowing for seed production. This will increase the demand on the plant and may have implications under a changed climate.

6.0) Summary of project outputs

6.1) Outline of December 1994 seminar.

The "products" from the research *i.e.* the methodologies, models and knowledge developed will be presented to the climate change community at a seminar at the end of 1994. The meeting in December 1994 is to discuss and present the results from the Core Model Project on Climate Change. The seminar will be designed for members of the climate change impacts and modelling community as well as a range of users in policy fields. Initial discussions have taken place between the DoE, ITE and IH about the form and content of the meeting. The format of the seminar is given below, subject to change, given the early stage of the discussion.

The seminar will be over two days and will start in the evening of the first day where there will be a keynote presentation, dinner and possible computer demonstrations. The main body of the work carried out by the Core Model Project will be presented on day two. The IH and the University of Sheffield presentation will consist of four talks and will be chaired by IH. The session will be titled, "The application and development of a frame work for impacts of climate on hydrochemistry and grasslands". The four talks will be;

1) Modelling hydro-chemical responses under a changed climate.
2) Estimating the hydrological implications of climate change: the regional scale and transient impacts.

3) Linking models and GIS: a practical system for climate change impact assessment.
4) A mechanistic model of grassland vegetation driven by climate parameters.

The afternoon session will be chaired by ITE and again will consist of five presentations by ITE and the sub-contractors.

Through out the day there will be computer demonstrations of the software systems that have been developed and poster presentations of some of the work carried out during the course of the project.

6.2) Final project outputs

As a result of the four year DoE core model project, besides the acquired knowledge and experience there will be a number of tangible products. These are listed below;

1) Three annual progress reports and a final report that will be presented to participants of the seminar in December 1994.

2) A computer package based on a Sun SPARC workstation that can be used to display data, run models, access data from Oracle and present results to the user. (Note: this is for use in-house only)

3) The results from various application studies undertaken during the course of the project.

7.0) References

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