# Working Paper

## Incorporating natural vegetation into the LUC project framework

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WP-96-112
December, 1996

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# ABSTRACT

A detailed description of the incorporation of natural vegetation within the larger LUC model framework is given. The approach focuses on first adapting and then coupling three existing vegetation models; BIOME3 (*Haxeltine et al., 1996*), BIOME1 (*Prentice I.C. et al., 1992* ) and the CBM (*Kurz W.A. et al., 1992*). Section 1 concentrates on a description of the adaptations made to BIOME3 and BIOME1 and a comparison of the results obtained from a present climate run for Russia, Mongolia and China with the existing LUC natural vegetation data set. The three way model coupling methodology and usage within the larger LUC model framework is given in Section 2. The authors wish to thank Mike Apps, Günther Fischer, Colin Prentice and Cynthia Rosenzweig for their valuable contribution and advice at different stages during the project.

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## 1. INTRODUCTION

The recognition of the direct influence of mankind on the global environment has led to a necessary change in the focus of environmental research from a purely natural-science based approach to an interdisciplinary one which includes both natural and socio-economic theory. Many studies have been made on parts of the global climate system, yet few have attempted the ambitious task of coupling the essential components in a consistent manner. One such interdisciplinary study is the *Modeling Land-Use and Land-Cover Changes in Europe and Northern Asia* (LUC) project (*Fischer et al., 1996*).

The objective of the LUC project is to analyze the spatial characteristics, temporal dynamics, and environmental consequences of land-use and land-cover changes that have occurred over the period 1900 - 1990 as a result of a range of socio-economic and biogeophysical driving forces (*Fischer et al., 1996*). A main task of the LUC project is the development of a coupled computer model that can be applied to provide plausible future projections of land-use and land-cover change for the next decades from 1990 to 2050. The chosen study region includes China, Japan, Mongolia and Russia, an area representing diverse social and economic practices. Within the project detailed data with regard to present vegetation, soil, ecosystem degradation and land use have been compiled. Access to this additional information allows fine scale modeling studies to be conducted i.e., one may apply the model on a finer spatial scale and include a more detailed ecosystem description than would otherwise be possible.

The LUC modeling framework is divided into three components; input scenarios (climate variables, policy formulation, future technologies), the core socio-economic module, and the geobiophysical assessment modules. This paper focuses on the biophysical module and in particular on the vegetation model. A full description of the complete model framework is given in *Fischer et al., 1996*. The vegetation model provides information on the structure (vegetation type) and function (productivity, biomass, density) of natural land cover at each geographic location. This information is important within the LUC model framework with respect to possible land exploitation for forestry and other land-use purposes and to simulate the land cover of areas which are currently under 'non-used' land-use type. In order to provide both structural and functional information for natural vegetation three vegetation models were selected. BIOME1 (*Prentice et al., 1992)* and BIOME3 (*Haxeltine et al., 1996),* collectively named BIOME, provide essentially structural and productivity information. And the Carbon Budget Model (CBM), (*Kurz et al., 1992, Samson et al., 1995*) provides information about the vegetation functioning, like biomass, and density and about the occurrence of disturbances. Since each individual model has been designed for a specific purpose and therefore contains different starting assumptions and requires different input data, the task of coupling the three in a scientifically consistent manner is a difficult one. A brief description of each vegetation model including their input requirements is given in Section 1. The first task has been to extend the number of vegetation types of BIOME and to reclassify their combinations. A detailed methodology is given in Section 2. The BIOME model is an equilibrium model, i.e., it assumes vegetation is in equilibrium with the climate. This assumption is considered valid for the present climate, but is not longer valid when making projections about future vegetation functioning. This is because a significant increase in the rate of future environmental change is projected due to anthropogenic activities leading to increasing green house gas emissions perturbing the natural system from its natural state. Further assumptions will be made with regard to how migration, competition and disturbance affect the competitive balance between vegetation types in a changing climate so that the BIOME-CBM-LUC, the collective name of the coupled vegetation model, can be run consistently in a dynamic mode (Section 3).

# SECTION 1

## 2. BASIC MODEL DESCRIPTIONS

### 2.1 BIOME1

BIOME1 (*Prentice et al., 1992*) is a biogeography model which simulates successfully patterns in global vegetation developed from physiological considerations influencing the distribution of different so called *plant functional types* (pfts). Plant functional types are defined as groups of plant species, grouped by using plant morphology (e.g. broad-leaved versus needle-leaved), physiology (e.g. C3 versus C4 photosynthetic pathway) and phenology (e.g. evergreen, summergreen or raingreen). Input variables for BIOME1 include monthly climate, i.e. precipitation, temperature and percentage sunshine. The primary driving variables are mean temperature of the coldest month, annual accumulated temperature over 0 and 5°C (GDD(0) and GDD(5) respectively) and the so-called Priestley-Taylor coefficient of annual moisture availability (defined as the ratio of actual evapotranspiration (AET) / potential evapotranspiration (PET)). Using interpolation routines, regressions and a single layer soil moisture bucket model, values for the primary driving variables are derived from the input variables for each grid-cell. A distinct set of environmental thresholds and constraints is assigned to each pft. Furthermore, each pft belongs to a certain dominance hierarchy to approximate competition between the pfts. Applying the environmental sieve determines which pfts can exist at a site in that none of the ecophysiological constraints are violated. A dominance hierarchy is then applied to predict which of the possible pfts would be dominant. The final step is to group the dominant pft combinations into biomes. The standard version of BIOME1 defines 14 pfts and 17 biomes and is applied on a 0.5° spatial resolution.

### 2.2 BIOME3

BIOME3 (*Haxeltine et al., 1996*) combines biogeography (predicts vegetation distribution) and biogeochemistry (predicts production and simulates the elemental pools in the ecosystem) in a single model framework, still assuming vegetation to be in an equilibrium state. Essentially, BIOME3 predicts the vegetation combinations present at any location using a mechanistic approach, and an improvement of the simple dominance hierarchy of BIOME1, based on fully linked photosynthesis and water balance calculations. These modules are coupled through feedbacks due to allowing a variable canopy conductance. First the model uses a BIOME1 type environmental sieve based on absolute minimum temperature tolerances and then estimates the annual *net primary production* (NPP) of each individual pft. In general, one can regard BIOME3 as incorporating the BIOME1 constraints methodology with competition based on a mechanistic productivity calculation. The Priestly-Taylor index used in BIOME1 is replaced with the NPP estimates of BIOME3 through the coupled photosynthesis and water balance modules. The underlying hypothesis of the model is that a combination of vegetation types which are predicted to have the maximum NPP will represent the equilibrium vegetation, with a few additional rules accounting for light competition and leaf area sustainability. The equilibrium vegetation combination is then taken as the potential natural vegetation assuming once again the equilibrium assumption holds as described earlier in the BIOME1 model description. BIOME3 requires the same climate input data as BIOME1 plus an additional attribute, absolute minimum temperature, and a soil texture data set. Five woody pfts and two grass pfts are described and these are individually parameterized for rooting strategy, phenology and photosynthetic activity. Unique combinations of the 7 pfts describe 18 global biomes. A more detailed description of BIOME3 is given by *Haxeltine et al. (1996)*.

## 2.3 CBM

The *Carbon Budget Model* (CBM) is a biogeochemistry model which was originally created in order to study Canadian forest ecosystems and forestry activities. A detailed description of this model is given in *Kurz et al. (1992) and Samson et al. (1995)*. CBM is used to simulate the spatial and temporal changes in vegetation structure, growth, litterfall, soil and disturbance dynamics. Important features of the model are (i) the inclusion of a detailed disturbance routine (ii) the recognition that the function of the forest (i.e., the age class structure) is very important in the dynamics of the system, including inputs into the various carbon pools. Both these aspects have been ignored in the majority of the presently available biogeochemistry models. However, one can not simply assume that the vegetation at a given location consists of only mature individuals, especially in a study operating at the continental scale. Ignoring disturbances and forest dynamics leads to inaccuracies in the ecosystem carbon pool size estimations and changes the very nature of competition between pfts, especially when one considers changing climate scenarios. The smallest spatial unit within CBM is defined by the intersection of the administrative and ecoclimatic region. Administrative regions are taken into account because of the recognition of the heterogeneity of regional management policies and because administrative information (like forest inventory data) is gathered on this level. Ecoclimatic regions contain forest ecosystems of contrasting types, due fundamentally to different climate and soil conditions. Thus, an ecoclimate region can be defined as an area where the climate forcing variables, e.g. temperature and precipitation, lie within defined ranges. For the present climate model run over Canada 10 ecoclimatic provinces were defined. The smallest and most detailed unit in CBM is the *State Variable Object* (SVO) which is an aggregation of forest stands with uniform attributes: (i) carbon in biomass and soil pools, (ii) growth curves, (iii) maturity status (regeneration, immature, mature, overmature), (iv) age, (v) type of management for each tree species, (vi) land type (forested/unforested), important in the context of the broader LUC project, (vii) forest type (softwood, hardwood, mixed wood), and (viii) site quality. Thus a SVO represents an area with homogeneous characteristics. The model runs at the dominant species level and therefore requires detailed information of growth curve and site class in order to give accurate representations.

Spatial units in CBM are thus composed of a number of SVOs, with their combined area equal to the area of the spatial unit. It is worth noting that the exact geographic location of any SVO, is <u>not</u> known, and it can be located anywhere within a particular spatial unit (since one is necessarily dependent on field data often available only on the aggregated administrative level). Therefore it is important to carefully define the size of the ecoclimatic regions to a suitable spatial scale in order to give scientifically meaningful results, and this depends on the specific aim of the individual study. This model feature and its consequence for the broader model coupling activities is discussed in greater detail in Section 3, with special reference to applying the coupled model for climate change scenarios. Growth, litterfall and soil dynamics occur in each SVO for each time step. Growth is described by biomass increment inferred from age over biomass curves. A change in the maturity state may also occur depending on the new biomass and duration the stand has been in its present state. Variation in climate in the form of temperature and precipitation growth multipliers are implicitly included. Another important feature of the CBM is the inclusion of a disturbance module. The CBM defines 3 groups of disturbance: fire, insects, and logging (clear cut, slash and burn etc.). A disturbance event changes many characteristics, like biomass and maturity status of some proportion of an SVO's area. On one hand, since SVOs no longer have homogeneous properties existing new SVOs can be defined at the beginning of the next time step. On the other hand two original different SVO (split because of differences in age) can be combined into one single SVO if a similar type of disturbance occurs in the same period. The model has been used for past, present and future climate and forestry practice scenario studies. Comprehensive input data at the administrative level are required to construct growth curves, and climate data is needed for the growth and disturbance multipliers.

# SECTION 2

## 3. THE LUC NATURAL LAND COVER CLASSIFICATION

A detailed description of the natural land cover classification used in the LUC project is given by *Van Minnen et al. (1996)*. The number of pfts has been extended to 31 to enable a more detailed vegetation description for the LUC region. Included in Tables 1 and 2 is a list of the pfts used in the LUC project. These can be subdivided into five categories: trees, dwarf trees/arborescents, shrubs/forbs, grammonoids/grasses and desert plants. Each category contains a set of pfts which differ according to climate zone, leaf morphology, phenology and level of drought and salt tolerance. A total of 42 biomes were defined from combinations of these pfts. The biomes were subdivided into 6 land cover classes; forests, woodlands, shrublands, grassland areas/steppes, deserts, and others (arable land, water bodies, ice, swamps etc.). Table 3 shows the biomes used in the LUC project. The pft combinations proposed in *Van Minnen et al. (1996)*, have been revised for incorporation in the BIOME3-LUC study. This was necessary since it is not simply the pfts which are present that defines a biome but also the dominant pft combination. e.g. a tropical raingreen forest has been defined as containing both tropical raingreen and tropical evergreen pfts but it is the raingreen phenology which is the optimal strategy and therefore the raingreen pft is dominant. The NPP calculation of BIOME3 determines the dominant and sub-dominant pfts. Taking the pft combinations of *Van Minnen et al. (1996)*, as a starting point the dominant pfts which are characteristic of each biome have been defined.

## 4. INCORPORATING THE LUC LAND COVER CLASSIFICATION

### 4.1 Introduction

In order to incorporate the LUC vegetation types and classification scheme into the BIOME3 model framework various modules had to be adapted and extended. The intermediate product will thus be referred to as BIOME-LUC. Currently BIOME3 contains an environmental sieve subroutine which is based on the absolute minimum temperature limits of pfts. This is perfectly appropriate for the purposes of BIOME3 where only 7 pfts are defined. Since the number of pfts was increased to 31 it was necessary to reintroduce other environmental limits from the original BIOME1 model in order to differentiate between pfts, especially due to the extension of grass pfts and the explicit inclusion of shrubs, which have previously not been considered as ecophysiologically different from trees. Although shrubland biomes exist in BIOME3 these are defined at the biome selection stage and represent areas with a low woody LAI prediction. New pfts were included into BIOME3 in a two step process. First (see 4.2), environmental constraints for the whole list of pfts are defined for use in a BIOME1-type environmental sieve module. Secondly (see 4.3), a number of parameter values were assigned to each pft for the computation of the water balance, photosynthesis, respiration and phenology. After the two steps, the pfts had to be combined into the 42 biomes (see 4.4), based on productivity and LAI levels.

### 4.2 Description of the PFT constraints in BIOME-LUC

Step one in the selection of environmental limits for the BIOME-LUC pfts was to associate them with the original BIOME3 and BIOME1 pfts. BIOME3 uses only a cold temperature tolerance constraint. This is sufficient to distinguish between its 5 woody and two grass pfts. A measure of the cold tolerance for plants is the absolute minimum temperature below which the pfts are considered non-viable. The original data on minimum temperature tolerances for various woody plant forms is summarized in *Woodward (1987)*. However, using only the cold temperature tolerance is insufficient to differentiate between the grass and shrub pfts. Values for these are not available. Instead a measure of the length of the growing season is required. Therefore five additional environmental constraints were added to the BIOME3 concept: GDD5min, GDD0min, Twmin (similar to BIOME1 approach), soil fertility, and a continentality index. Table 1 summarizes the environmental constraints for each of the 31 pfts. *GDD* represents the accumulated growing season heat requirement for each pft, calculated using a 0°C and 5°C base, respectively. *Twmin* is the mean temperature of the warmest month and is used to select which of the C3 and C4 photosynthetic pathways for grass pfts is dominant. Although this is not strictly a limit on the existence of grasses, in reality it is used here to represent the competitive exclusion of one type by the other based on the greater efficiency of one photosynthetic pathway. The C4 photosynthetic pathway is more efficient above this temperature for present atmospheric $CO_2$ concentrations. For future climate runs this must be adapted using the regression relation approach similar to that used in BIOME3 for the increased competitiveness of C3 grasses under elevated $CO_2$. The variable *fert* is a measure of the soil nutrient requirement of each pft in relation to availability. It is used to differentiate locations which are nutrient poor and thus favor the presence and growth potential of less demanding species, like some coniferous forest types or dwarf and shrub woody pfts. The variable *cont* is an index of climatic continentality. It is used to differentiate continental biomes from sub-continental ones. We define the variable as the temperature difference between the warmest and coldest month. The Priestley-Taylor coefficient of annual moisture availability was excluded in the initial present climate equilibrium run since the fully coupled water balance and photosynthesis modules cover the competition for available water in a mechanistic manner and is thus preferred. Soil fertility was defined in terms of 4 broad classes (poor, medium, rich, and saline soils). Each soil type of the FAO Revised Legend (*FAO-UNESCO, 1988*) was assigned to one of the classes (van Velthuizen and Nachtergaele, pers. comm.). The impact of soil fertility was implemented in a two-step approach. First, in the constraints part it is used as a threshold. For example, temperate deciduous species (pft 8) are practically not found on poor soils. Therefore a threshold was formulated for this pft. Secondly, a reduction factor is applied to reduce the potential growth (see 4.3). The limits for soil fertility of each pft are based on current knowledge from literature, and on analyzing the vegetation distribution in relation to soil types, both datasets being available in the project. The impact of soil fertility is discussed in Section 5 of this report. The critical thresholds of the continentality indices are based on overlay in temperature data and vegetation distribution.

### 4.3 Description of the PFT parameterization

The second step in extending the number of pfts in BIOME-LUC consisted of completing the parameterization of the new pfts. Six pft specific parameters are required for the description of pft properties/physiology: phenology, rooting strategy, photosynthetic pathway, leaf longevity, minimum canopy conductance, and soil fertility (Table 2). The information is used in the model to compute photosynthesis, respiration and growth.

Three phenologies are defined: evergreen, summergreen, and raingreen. The model does not determine a minimum number of days without leaf cover for the deciduous types. Thus, if the environmental conditions are adequate the predicted productivity of the summergreen or raingreen pft will be exactly the same as its evergreen counterpart because all other parameterizations are equal. In this case, a rule in the biome assignment routine selects the evergreen pft as the dominant pft.

Rooting strategy is described in BIOME3 in terms of the percentage of the active roots in the top and bottom soil layer, respectively. This is taken into account to be able to simulate the differences between grasses, shrubs and trees in relation to soil water requirements. The importance of different rooting depths is also indicated by *Prentice et al. (1989)* and *Otto et al. (1995)*. Roots of grass species, for example, are found almost entirely (~90%) in the upper 0.5 m soil layer, while only one third of tree roots are found here.

Each pft is assigned a photosynthetic pathway, either C3 or C4. The CAM photosynthetic pathway is not explicitly modeled. Furthermore, each pft is assigned a minimum canopy conductance which accounts for cuticular transpiration. As in BIOME3 a lower value of the minimum canopy conductance is assigned to conifer plant functional types compared to broad-leaved pfts. Likewise the xerophytic dwarf, sclerophyll, hot desert and saline desert pfts are assigned low values for the minimum canopy conductance due to their thick cuticles adapted to minimize plant water loss.

Finally, growth reduction factors are defined for each pft. The basic idea is that under less optimal nutrient conditions (poor and medium soils) non-woody species are favored over woody ones, and coniferous pfts can grow better than deciduous species. And most of the pfts get negligible growth potentials under saline soil conditions. The parameterization of these reduction factors was based on statistical analysis, using the GIS information available in the LUC project, and was generally in agreement with the literature.

## 4.4 BIOME assignment rules

A divergence from the BIOME3 classification and assignment scheme has been developed to achieve a consistent selection procedure in BIOME-LUC. Our method utilizes, as does BIOME3, the NPP and Leaf Area Index (LAI) predictions of each pft. First, BIOME3 calculates the annual NPP and LAI for each potential pft. For each of the five main vegetation categories (tree, dwarf, shrub, grass, desert) the dominant pft is taken to be the one with the highest NPP estimate. Thus for each vegetation category an optimum pft and its corresponding properties are known. This information is taken forward to the next stage, the selection of the dominating land-cover class, again requiring two steps. First, NPP and LAI of the optimum pft are used to determine one of six major land cover classes: forests, woodlands, shrublands, grassland areas/steppes, deserts, and other (water bodies etc.). Secondly, a sub-division into the biomes is carried out, again using climatic constraints and NPP and LAI of the potential pfts within a selected major land cover category. A comprehensive list of the assignment rules for all 42 biomes is given in Table 3.

The determination of the main vegetation category proceeds as follows: If the GDD0 <175 and/or none of the optimum pfts has an estimated LAI>0.3 a *desert* land cover class is selected. Four desert biomes have been defined and are differentiated using LAI and GDD0 constraints along with the presence/absence of the desert pfts. If the optimum LAI of the tree pft is > 2.5 a *forest* land cover category will be selected, regardless of LAI and NPP estimates of the other optimum non-tree pfts. This threshold is chosen, assuming that an optimum LAI >2.5 represents a closed forest canopy, reflecting the decisive competitive advantage of trees for light over both shrubs and grasses. The forest land cover type is divided into 14 biomes (Table 3). Each biome has been defined as having associated dominant/sub-dominant tree pfts. The temperate, cool and boreal forest biomes are in addition differentiated approximating the competitive balance between the needle-leaved evergreen and the summergreen forest types. This balance is computed by using the ratio of their NPP estimates. For example, in the cool region a NPP ratio > 1.5 between conifers and deciduous species indicates a distinct advantage of the evergreen phenology over the summergreen, and thus a coniferous forest (biome 7) is defined. In the sub-continental boreal area the NPP estimates are used to distinguish middle sub-continental taiga (biome 11) from northern types (biome 13). The difference between the warmest and coldest month was used to distinguish sub-continental boreal forest types (biomes 11 and 13) from continental biomes (biome 12 and 14). The threshold value was set to 40°C, based on an analysis of out climate data set. Although this simple approach used here is different from the continentality index of *Ivanov (1947)*, data analysis has shown similar results for the cool and boreal areas.

Areas are also assigned to northern boreal *forest* (biome 12 and 14) if the wood LAI is > 1.75 and the optimum grass LAI and shrub LAI are both < 3. The area represents a kind of open forest, which can be seen as a transition to woodlands.

*Woodland* biomes (biome 15-18) are selected if the optimum tree LAI is larger than 1 and smaller than 1.75, and the optimum LAI of grass and shrubs are both below 3. We assume that a LAI smaller than 1.75 represents an open canopy, resulting in more light for the understorey. A grid-cell with an estimated grass or shrub LAI greater than 3 and a substantially lower optimum tree LAI estimate indicates a decisive competitive advantage of grass/shrub for water supplies over the deeper rooted trees due to the seasonality of rainfall and/or unfavorable soil percolation attributes. Woodlands are divided into four biomes which are differentiated primarily on the presence /absence of tree pfts in the different climate zones. For example, if the optimum tree LAI is between 1.0 and 1.5 a xerophytic woodland is defined since it is assumed that under such conditions, water is insufficient and limits growth of most biome types.

A *grassland* is selected if the optimum grass NPP is largest and the above conditions are not satisfied. An optimum grass LAI larger than 3 is taken to represent a grassland which can be considered self-perpetuating by inducing a high disturbance frequency which consequently discourages woody pft establishment. Alternatively, when the optimum grass pft produces the highest NPP and the above grass LAI conditions are not met then a forested grassland or shrubland land cover type is selected. If trees are the second most competitive vegetation category then a wooded grassland biome is selected, otherwise one of the shrubland biomes is chosen. The shrubland biome selection procedure is identical to that described earlier.

If the optimum shrub pft is simulated to have the largest NPP, and the above forest or woodland conditions are not met, then a *shrubland/savanna* land cover type is selected. Seven shrubland biomes are distinguished in BIOME-LUC (Table 3). A xerophytic shrubland is chosen if the estimated shrub LAI$\leq$1.5 and either the tropical or cool-temperate shrub pfts are present. Southern and northern tundra has been distinguished from alpine tundra using a measure of continentality (again set to 45$^{o}$C). If the temperature difference is larger than this threshold the more continental tundra biome (alpine tundra) is selected. Otherwise southern or northern tundra are chosen, differentiated on the base of GDD5.

**Table 1.** Environmental constraints: Minimum and maximum temperature of coldest month (Tabs min and max). Growing degree days on a 5°C base (GDD5); growing degree days on a 0°C base (GDD0); mean temperature of the warmest month, (Tw), minimum soil fertility (Fert; 1: Poor, 2: Medium, 3: Rich, 4: Saline), Maximum continentality value (Cont, in °C)

| | | Tabs min | Tabs max | GDD5 min | GDD0 min | Tw min | Fert | Cont |
|---|---|---|---|---|---|---|---|---|
| Trees | | | | | | | | |
| 1 | Tropical broad-leaved evergreen | 15.5 | | | | | 1 | |
| 2 | Tropical narrow/needle-leaved evergreen | 15.5 | | | | | 1 | |
| 3 | Tropical broad-leaved raingreen | 15.5 | | | | | 1 | |
| 4 | Warm broad-leaved evergreen | 5 | 15.5 | | | | 1 | |
| 5 | Warm/temperate needle-leaved evergreen | 0 | 5 | 1200 | | | 1 | |
| 6 | Temperate broad-leaved summergreen | -15 | 5 | 1200 | | | 2 | |
| 7 | Cool/temperate needle-leaved evergreen | -19 | 5 | 900 | | | 1 | 40 |
| 8 | Cool broad-leaved summergreen | -19 | 5 | 900 | | | 2 | 40 |
| 9 | Boreal broad-leaved summergreen | | 5 | 350 | | | 1 | 40 |
| 10 | Boreal needle-leaved evergreen | -35 | -2 | 500 | | | 1 | 40 |
| 11 | Boreal needle-leaved summergreen | | 5 | 500 | | | 1 | |
| 12 | Cold needle-leaved summergreen | | 0 | 350 | | | 1 | |
| Dwarf trees/arborescents | | | | | | | | |
| 13 | Tropical dwarf | 15.5 | | | | | 1 | |
| 14 | Warm temperate/xerophitic dwarf | -19 | 15.5 | 1200 | | | 4 | |
| 15 | Temperate/cool dwarf | -19 | 15.5 | 500 | | | 2 | |
| 16 | Boreal dwarf | | 0 | 250 | | | 1 | |
| Shrubs/forbs | | | | | | | | |
| 17 | Tropical shrubs | 15.5 | | | | 22 | 1 | |
| 18 | Warm temperate/sclerophyll | 5 | 15.5 | | | | 4 | |
| 19 | Temperate shrubs | -19 | 15.5 | 1200 | | | 1 | |
| 20 | Cool/Boreal shrubs | | | 250 | | | 1 | |
| 21 | Cold shrubs | | | | 100 | | 1 | |
| Grammonoids/Grasses | | | | | | | | |
| 22 | Tropical tall grass | 15.5 | | | | | 1 | |
| 23 | Tropical short grass | 15.5 | | | | | 1 | |
| 24 | Warm temperate tall grass | | | | | 22 | 1 | |
| 25 | Warm temperate short grass | | | | | 22 | 1 | |
| 26 | Temperate tall grass | | | 900 | | | 1 | |
| 27 | Temperate short grass | | | 500 | | | 1 | |
| 28 | Boreal/cold short grass | | | | 100 | | 2 | |
| Desert plants | | | | | | | | |
| 29 | Hot/dry desert plants | | | | | 22 | 1 | |
| 30 | Halophytic/saline desert plants | | | | | 22 | 4 | |
| 31 | Cold desert plants | | | | 100 | | 1 | |

**Table 2.** Plant functional type specific parameters and ecophysiological attributes incorporated into BIOME-LUC. P: phenological type where E= evergreen, S= summergreen, R= raingreen. R: fraction of roots in the upper soil layer. C4: indicates whether the pft uses the C4 photosynthetic pathway. F: parameter defining the fractional reduction in photosynthesis in conifers due to leaf age. $g_{min}$: minimum canopy conductance, mm $s^{-1}$; $h_{fert}$: growth reduction factors for the four different soil fertility classes (see text for explanation)

| | P | R | C4 | F | $g_{min}$ | $h_{fert}$ |
|---|---|---|---|---|---|---|
| Trees | | | | | | |
| 1 Tropical broad-leaved evergreen | E | 0.33 | no | 1 | 0.6 | 0.8,1.0,1.0,0.1 |
| 2 Tropical narrow/needle-leaved evergreen | E | 0.33 | no | 1 | 0.4 | 0.8,1.0,1.0,0.1 |
| 3 Tropical broad-leaved raingreen | R | 0.33 | no | 1 | 0.6 | 0.8,1.0,1.0,0.1 |
| 4 Warm broad-leaved evergreen | E | 0.33 | no | 1 | 0.6 | 0.8,1.0,1.0,0.1 |
| 5 Warm/temperate needle-leaved evergreen | E | 0.33 | no | 1 | 0.4 | 0.8,1.0,1.0,0.1 |
| 6 Temperate broad-leaved summergreen | S | 0.33 | no | 1 | 0.6 | 0.2,0.6,1.0,0.1 |
| 7 Cool/temperate needle-leaved evergreen | E | 0.33 | no | 1 | 0.4 | 0.8,0.9,1.0,0.1 |
| 8 Cool broad-leaved summergreen | S | 0.33 | no | 1 | 0.6 | 0.2,0.8,1.0,0.1 |
| 9 Boreal broad-leaved summergreen | S | 0.33 | no | 1 | 0.6 | 0.8,1.0,1.0,0.1 |
| 10 Boreal needle-leaved evergreen | E | 0.33 | no | 1 | 0.4 | 0.8,1.0,1.0,0.1 |
| 11 Boreal needle-leaved summergreen | S | 0.33 | no | 1 | 0.4 | 0.8,0.9,1.0,0.1 |
| 12 Cold needle-leaved summergreen | S | 0.33 | no | 1 | 0.4 | 0.8,0.9,1.0,0.1 |
| Dwarf trees/arborescents | | | | | | |
| 13 Tropical dwarf | E | 0.33 | no | 1 | 0.6 | 0.8,1.0,1.0,0.1 |
| 14 Warm temperate/xerophitic dwarf | R | 0.33 | no | 1 | 0.3 | 0.8,1.0,1.0,1.0 |
| 15 Temperate/cool dwarf | S | 0.33 | no | 1 | 0.4 | 0.8,1.0,1.0,0.1 |
| 16 Boreal dwarf | S | 0.33 | no | 1 | 0.4 | 0.8,1.0,1.0,0.1 |
| Shrubs/forbs | | | | | | |
| 17 Tropical shrubs | R | 0.5 | no | 1 | 0.6 | 1.0,1.0,1.0,0.1 |
| 18 Warm temperate/sclerophyll | R | 0.5 | no | 1 | 0.3 | 1.0,1.0,1.0,1.0 |
| 19 Temperate shrubs | E | 0.5 | no | 1 | 0.6 | 1.0,1.0,1.0,0.1 |
| 20 Cool/Boreal shrubs | S | 0.5 | no | 1 | 0.6 | 1.0,1.0,1.0,0.1 |
| 21 Cold shrubs | S | 0.5 | no | 1 | 0.6 | 1.0,1.0,1.0,0.1 |
| Grammonoids/Grasses | | | | | | |
| 22 Tropical tall grass | R | 0.9 | yes | 1 | 0.8 | 0.9,1.0,1.0,0.1 |
| 23 Tropical short grass | R | 0.9 | yes | 1 | 0.8 | 0.9,1.0,1.0,0.1 |
| 24 Warm temperate tall grass | E | 0.9 | yes | 1 | 0.8 | 0.9,1.0,1.0,0.3 |
| 25 Warm temperate short grass | E | 0.9 | yes | 1 | 0.8 | 0.9,1.0,1.0,0.3 |
| 26 Temperate tall grass | S | 0.9 | no | 1 | 0.5 | 0.9,1.0,1.0,0.1 |
| 27 Temperate short grass | S | 0.9 | no | 1 | 0.5 | 0.9,1.0,1.0,0.1 |
| 28 Boreal/cold short grass | S | 0.9 | no | 1 | 0.5 | 0.9,1.0,1.0,0.1 |
| Desert plants | | | | | | |
| 29 Hot/dry desert plants | R | 0.9 | yes | 1 | 0.3 | 1.0,1.0,1.0,0.1 |
| 30 Halophytic/saline desert plants | R | 0.9 | yes | 1 | 0.3 | 1.0,1.0,1.0,1.0 |
| 31 Cold desert plants | S | 0.9 | no | 1 | 0.5 | 1.0,1.0,1.0,0.4 |

**Table 3**. Biome classification scheme, used for modeling natural land cover within the IIASA-LUC project. (T=tree, S=shrub, G = grass, D = desert, A=all types of vegetation). Where brackets are used, biomes are defined by the presence of characteristic pfts and no division into dominant and sub-dominant pfts is made. TS (= warmest month temperature - coldest month temperature) is used as an indicator of continentality.

| BIOME | | | | | |
|---|---|---|---|---|---|
| FORESTS | | Dominant pft | Sub-dominant pft | LAI | NPP |
| 1 | Tropical evergreen forest | 1,2 | 3 | T>2.5 | |
| 2 | Tropical raingreen forest | 3 | 1,2 | T>2.5 | |
| 3 | Broadl. evergreen/sub-tropical forest | 4 | 5 | T>2.5 | |
| 4 | Warm/temperate coniferous forest | 5 | 4 | T>2.5 | |
| 5 | Temperate deciduous forest | 6 | 7 | T>2.5 | NPP(7)/NPP(6)<1 |
| 6 | Temp. mixed forest | 7 | 6 | T>2.5 | NPP(7)/NPP(6)<2 |
| 7 | Cool-temperate coniferous forest | 7 | 8 | T>2.5 | NPP(7)/NPP(6)<1 |
| | | | | or | NPP(7)/NPP(8)>1.5 |
| 8 | Cool deciduous forest | 8 | 7 | T>2.5 | NPP(7)/NPP(8)≤1 |
| 9 | Cool mixed forest | 7 | 8 | T>2.5 | NPP(7)/NPP(8)>1 |
| 10 | Cool conif. forest/southern taiga | 7 | 8,10 | T>2.5 | NPP(7)/NPP(8)>1.5 |
| 11 | Middle sub-continental taiga | 10 | 9 | T>2.5 | NPP(9)>NPP(10) |
| 12 | Middle continental taiga | 11 | | T>2.5 | |
| 13 | Northern sub-continental taiga | 9 | 10 | T>1.75 | NPP(9)<NPP(10) |
| 14 | Northern continental taiga | 12 | | T>1.75 | |
| WOODLANDS | | | | T<1.75 | |
| 15 | Tropical dry woodland/savanna | (1,2,3) | | T>1.5, G<3.0, S<3.0 | |
| 16 | Xerophitic woods | (1,2,3,14) (4,5,6,15) | | T>1.0, G<3.0, S<3.0 | |
| 17 | Temperate woodland | (4,5,6) | | T>1.5, G<3.0, S<3.0 | |
| 18 | Cool/boreal woodland | (7,8,9,10,11,12) | | T>1.5, G<3.0, S<3.0 | |
| SHRUBLANDS | | | | T<1.0;G>T;S>G | |
| 19 | Tropical shrubs | 17 | | S>2 | |
| 20 | Xerophitic shrubs | 17 or 18,19 | | S≤2 | |
| 21 | Cool-Temperate shrubs | 18,19 | | S>2 | |
| 22 | Wooded tundra | | | 1.0<T≤2, G<3.0 | |
| 23 | Southern tundra | 20 | 21 | TS<45.0 | |
| 24 | Northern tundra | 21 | | TS<45.0 | |
| 25 | Alpine tundra | 21,28 | | TS≥45.0 | |
| GRASSLAND AREAS/STEPPES | | | | G>S | |
| 26 | Tropical steppes, tall | 22 | 23 | G>2.5 | |
| 27 | Tropical steppes, short | 23 | 22 | G>2.5 | |
| 28 | Warm/temperate dry steppes/meadow | 25,27 | 24,26 | G>2.5 | |
| 29 | Warm/temperate steppes | 24,26 | 25,27 | G>2.5 | |
| 30 | Wooded grassland | (22,23,24,25,26,27) | | | NPP(T)≥NPP(S) |
| 31 | Cool grassland | 27,28 | | G>2.5 | |
| DESERTS | | | | | |
| 32 | Hot dry desert | 29 | 30 | LAI<0.3 | |
| 33 | Salt halophytic desert | 29 | 29 | LAI<0.3 | |
| 34 | Cool desert | | | GDD0<175 | |
| 35 | Polar desert | | | GDD0<100 | |
| OTHERS | | | | | |
| 36 | Alluvial sequences | | | | |
| 37 | Reed brakes | | | | |
| 38 | Mires/swamps | | | | |
| 39 | Large water bodies | | | | |
| 40 | Ice | | | | |
| 41 | Arable land | | | | |
| 42 | Barren land | | | | |

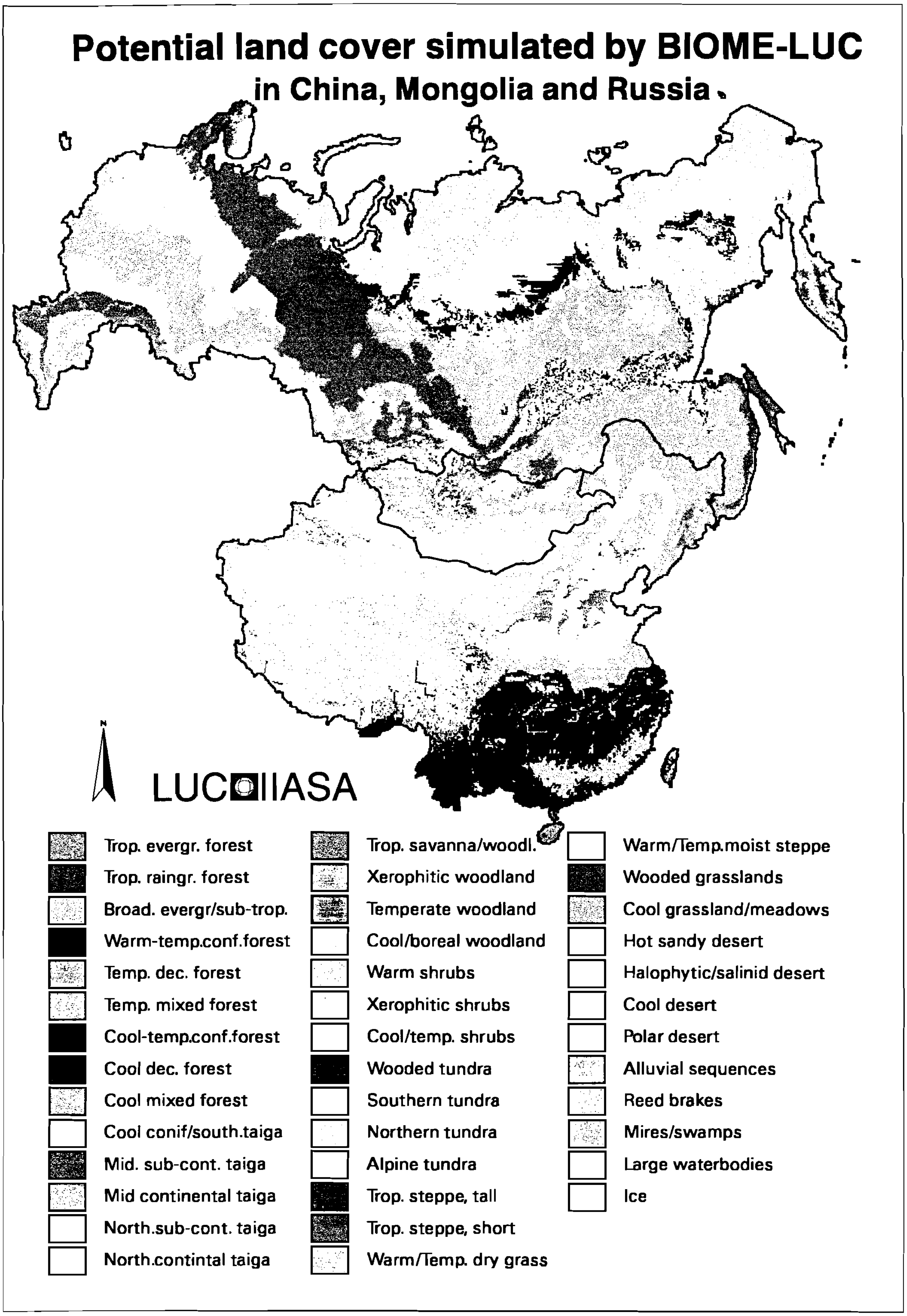
## 5. PRELIMINARY RESULTS

Preliminary applications of the BIOME-LUC model for current climate showed an overall good agreement between the LUC vegetation data set (Fig. 1) and the modeled vegetation cover (Fig. 2). The broad patterns of the vegetation cover are well simulated. Tuning of the different biomes is however still necessary. Some unusual results are found in western-Mongolia, where a mixture of warm/temp. dry grass (biome 28), warm/temp. steppe (biome 29), and wooded grassland (biome 30) are simulated. This mixture is most probably caused by the similarity of the climatic constraints of the underlying pfts. These similarities already cause the appearance/disappearance of the pfts in relatively small changes in climatic conditions, resulting in a different biome type. Therefore the constraints, especially those related to the photosynthetic production, might be too strict and need more investigation. Among the features successfully simulated is the extent of southern, alpine and wooded tundra. Furthermore, the extent of wooded grassland and deserts, and the border between continental and sub-continental biomes are in agreement with the observations. And the broad distribution of temperate, cool and boreal forest biomes is also most often in correspondence with the data set. The division between the individual forest types, however, raises some interesting questions. Continental boreal forests in Russia are almost entirely modeled as middle continental taiga (biome 12) with the absence of northern continental taiga (biome 14) and boreal woodland (biome 18). North of this area the climate is too harsh to allow a modeled wood LAI >1.5. Thus BIOME-LUC simulates tundra vegetation, while northern continental forest and woodland are observed. An assignment mainly based on LAI might be insufficient for the more detailed model exercise. In northern sub-continental regions BIOME-LUC simulates a dominance of the evergreen coniferous tree species over broad-leaved summergreen ones, due to a greater NPP estimate. This sometimes leads to a middle sub-continental taiga (biome 11) being assigned where the data set gives northern sub-continental taiga (biome 13). Also in other areas coniferous and mixed forest types dominate deciduous ones. This is partly caused by the additional environmental constraints, like soil fertility, which is one of the new aspects in BIOME-LUC. The inclusion of these constraints led to changes from high demanding biomes to less demanding ecosystems, which turned out to be correct in many areas. For example, cool coniferous forest (biome 10) replaces cool deciduous forest (biome 8). And different grassland biomes are now simulated around the Caspian sea, while in simulations based on only climate, these areas would be covered by certain woodlands. However, in some other areas the inclusion of soil constraints led to less agreement, like the discrepancy described in northern sub-continental regions. It has been suggested that the implemented growth reductions for deciduous biomes, due to nutrient shortage might be too large. And/or the modeled NPP estimate of the evergreen conifer species is too high relative to the broad-leaved summergreen. This latter effect would be reduced if one takes into account the lower productivity of conifers associated with their longer leaf longevity (younger leaves being more productive) and possibly a greater soil nutrient/fertility requirement. Deserts are successfully simulated in North-west China and South-west Russia. The simulated distribution of hot deserts (biome 32) matches also with land-cover data for Mongolia, which recently became available within the LUC project (Ojima, pers. comm.). There is less agreement where wooded grasslands (biome 30) has been simulated instead of xerophytic shrubland (biome 20). This implies that an optimum tree pft in the simulations is more successful than an optimum shrub pft, even though it is the grass with its shallow rooting strategy that is most successful. This appears to be counter-intuitive as shrubs have an intermediate rooting strategy between that of grass and trees. Therefore, when an optimum grass pft is most successful, then one would expect shrub pfts to be second, all other parameterizations and constraints being equal. Since the direct shrub counterpart of grass does not exist in the modeling framework for tropical/temperate zones this situation can arise. A re-parameterization of the tropical/temperate shrub pfts would therefore be desirable. Also, in other areas shrub types are simulated, while grassland biomes have been observed. Northern tundra (biome 24), for example, is simulated for large parts of the Tibetan Plateau instead of a mixture of cool grassland (biome 31) and (alpine) tundra (biome 25). And in South-west Russia, xerophytic woods (biome 16) and shrubs (biome 20) are modeled, while warm/temperate dry grassland (biome 28) is observed. This too little representation of grassland biomes may be caused by a (too) high leaf-area requirement of an optimum grass pft (LAI>2.5) for grassland biomes. Other parametizations which affect the water balance may also contribute to this difference. Further sensitivity analysis is needed to improve the setting of grassland LAI constraints. Tropical evergreen forest (biome 1), broad-leaved evergreen/sub-tropical forest (biome 3), and warm-temperate coniferous forest (biome 4) are correctly modeled in South-east China, although the area is somewhat overestimated at the expense of warm shrubs/warm temperate dry grass. This discrepancy will be investigated further since other data sets (like *Matthews, 1983)* indicate much less shrubland. This would match much better with the BIOME-LUC results. Finally, a considerable proportion of North-east China is mapped as arable land. Thus comparison of the simulated potential vegetation with these data is not possible. The Matthews vegetation data set (*Matthews, 1983*), one of the most frequently referenced global vegetation data sets, assigns cold-deciduous forest with evergreens and grassland with shrub cover in this region, giving good agreement with the temperate mixed forest (biome 6), and warm/temperate steppe (biome 29), respectively, projected by BIOME-LUC.

**Figure 1:**


VEGETATION DISTRIBUTION
for China, Mongolia and Russia
N
LUC IIASA
Trop. evergr. forest
Trop. raingr. forest
Broad. evergr/sub-trop.
Warm-temp.conf.forest
Temp. dec. forest
Temp. mixed forest
Cool-temp.conf.forest
Cool dec. forest
Cool mixed forest
Cool conif/south.taiga
Mid. sub-cont. taiga
Mid continental taiga
North.sub-cont. taiga
North.contintal taiga
Trop. savanna/woodl.
Xerophitic woodland
Temperate woodland
Cool/boreal woodland
Warm shrubs
Xerophitic shrubs
Cool/temp. shrubs
Wooded tundra
Southern tundra
Northern tundra
Alpine tundra
Trop. steppe, tall
Trop. steppe, short
Warm/Temp. dry grass
Warm/Temp.moist steppe
Wooded grasslands
Cool grassland/meadows
Hot sandy desert
Halophytic/salinid desert
Cool desert
Polar desert
Alluvial sequences
Reed brakes
Mires/swamps
Large waterbodies
Ice
Farming land
Barren land

Figure 2:



Potential land cover simulated by BIOME-LUC
in China, Mongolia and Russia
N
LUC IIASA
Trop. evergr. forest
Trop. raingr. forest
Broad. evergr/sub-trop.
Warm-temp.conf.forest
Temp. dec. forest
Temp. mixed forest
Cool-temp.conf.forest
Cool dec. forest
Cool mixed forest
Cool conif/south.taiga
Mid. sub-cont. taiga
Mid continental taiga
North.sub-cont. taiga
North.contintal taiga
Trop. savanna/woodl.
Xerophitic woodland
Temperate woodland
Cool/boreal woodland
Warm shrubs
Xerophitic shrubs
Cool/temp. shrubs
Wooded tundra
Southern tundra
Northern tundra
Alpine tundra
Trop. steppe, tall
Trop. steppe, short
Warm/Temp. dry grass
Warm/Temp.moist steppe
Wooded grasslands
Cool grassland/meadows
Hot sandy desert
Halophytic/salinid desert
Cool desert
Polar desert
Alluvial sequences
Reed brakes
Mires/swamps
Large waterbodies
Ice

# SECTION 3

## 6. BIOME-LUC AND CBM COUPLING METHODOLOGY

### 6.1 Interface description / scientific consistency

Several difficult conceptual problems must be addressed in order to link BIOME and CBM in a scientifically consistent manner, that will maintain the integrity of the projections. The major challenge in this phase of the study has been to decide on a strategy for coupling models which are run on different spatial scales and operate at different levels of ecological complexity. For instance, a decision on the smallest ecological unit was required.

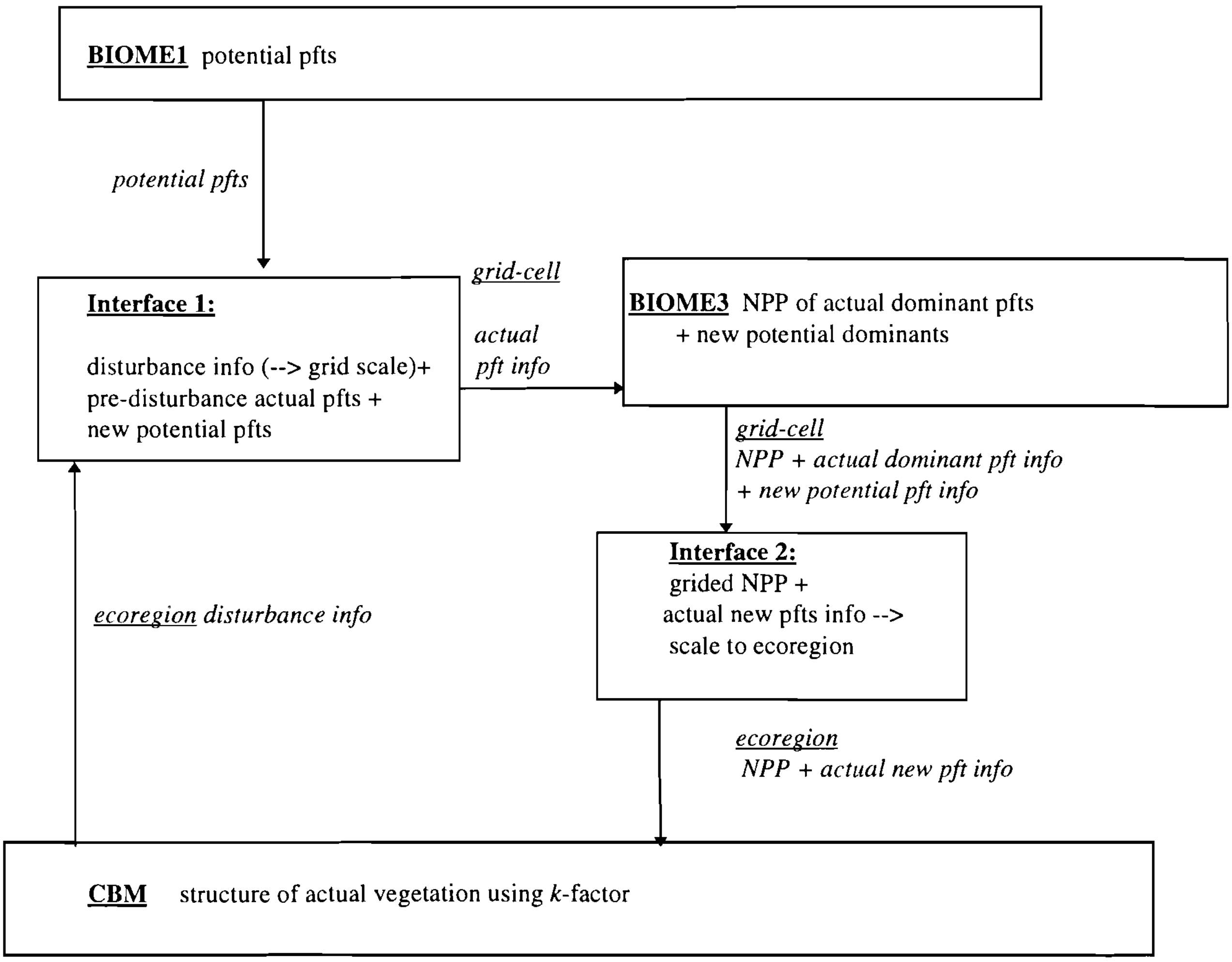
In the context of the LUC project the economic core model scales up from the grid-cell level to larger spatial units which depend, among others, on administrative boundaries. As mentioned earlier, the CBM is not spatially explicit in the sense that although one knows the growth curve (including age-class) information and other stand properties within a region, one cannot infer the exact location of any individual stand. The spatial units within the CBM are based on overlaying ecoregions with administrative regions. In order to maintain consistency, the administrative boundaries should be the same in both the LUC core model and CBM. Thus a model linkage can be achieved where BIOME3 results are scaled up, with the results obtained from the CBM directly compatible with the LUC core model. It is desirable to run the CBM model with ecoregions which are defined to be no larger than approximately 1000 $km^2$ (approximately equivalent to 2.5'' x 2.5'' on a grid system). This is necessary to obtain a realistic spatial heterogeneity of climate change scenarios/projections and thus future carbon balance projections.

BIOME3 calculates potential natural vegetation on the pft level whilst CBM operates at the dominant species level. The BIOME-CBM combined model for the LUC project will be applied over a large spatial area covering different ecosystems and biological diversity and thus it is not feasible to work on the species level. It is therefore necessary to aggregate up to the pft level by characterizing the dominant species using their morphological and phenological properties. Hence, it was decided that the combined BIOME-CBM model will simulate at the pft level. Several important forest biomes, especially those in the boreal zone, contain only a few dominant species which have distinct morphological characteristics and thus assignment of these species to pfts is not difficult and no significant loss of information is expected running CBM at this level of ecological complexity.

It is not only the vegetation structure which changes due to climate change but also the vegetation function. BIOME3 predicts the equilibrium vegetation, i.e. the pfts which are best suited to their environment, assuming long-term steady state environmental conditions. We made the assumption that under an environmental change, forest vegetation will only be replaced once a disturbance event has occurred, although its growth and production will be altered. The LUC project has a time frame of 50-100 years, which is less than the average stand age. It is therefore justifiable to assume that forest stands can only be replaced after a disturbance event and not due to natural stand age mortality, thereby simplifying the modeling methodology. Another decision was to include the multiplier term $k$ ($k=f$ (productivity)) in the stand growth equations, representing forest stand production change. The idea is to relate this $k$-factor to the (equilibrium) NPP predictions of the BIOME3 model (and changes in it between different years) to estimate the change in productivity due to a changing climate. A flow diagram representing the proposed model coupling is shown in Figure 3. Furthermore, the $k$-factor will in the future also be linked to other environmental changes. An example is soil acidification, as proposed by *Gaidarova & van Minnen (1996)*.

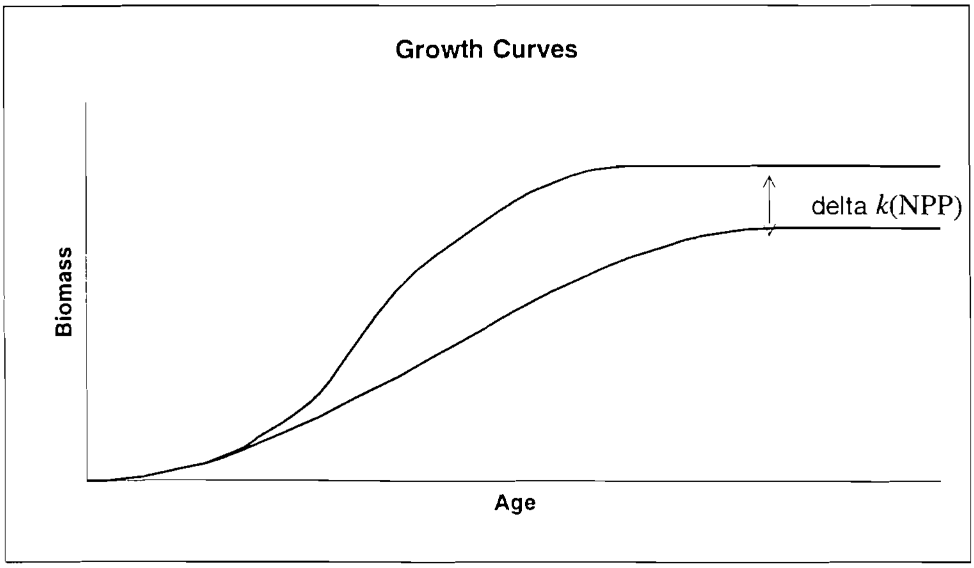
A BIOME1-type environmental sieve module to determine potential pfts is an integral part of BIOME3. For illustrative purposes the two models are shown as separate. To avoid confusion the environmental sieve routine is referred to as BIOME1 due to its origin and the mechanistic water balance and photosynthesis routines as BIOME3. Therefore the linkage study may be viewed as a coupling between two models, a modified BIOME3 and the CBM. At present BIOME3 has been run for equilibrium climate scenarios or for static future climate scenarios where the environmental sieve module is called only once. When applying a dynamic climate scenario it must be called at each iteration. Two interfaces are required to link the outputs of the separate models. For each iteration BIOME1 is run and outputs potential pfts. CBM outputs the area within an ecoregion which has been disturbed. A routine within interface 1 will map this disturbance onto the grid-cell format, using statistical techniques to decide which pixels within the ecoregion will be affected. Again, we made the assumption that forested grid-cells can only be replaced if they have been affected by a disturbance. To be more specific, for each pixel, BIOME3 runs first for the set of actual dominant pfts, and for the new potential pfts. Depending on their NPP predictions (approximating the productivity of vegetation in the mature phase), a set of new potential dominant pfts is selected.

## Figure 3: Proposed model coupling in BIOME-CBM-LUC



If the climatic and soil conditions have not significantly changed, the set of current actual pfts will be the same as the set of new potential dominant pfts. Thus BIOME3 generates information on two separate sets of pfts: the actual, and new potential actual, which flows to the CBM model. The new potential pfts will replace the former pft in a grid-cell if either it has been disturbed or if a forest type is in a over mature phase or if a grass/shrub ecosystem is predicted to be replaced by tree pfts (accounting for the trees decisive competition for light). If none of these conditions is met the vegetation cover within the grid-cell remains the same. This methodology may appear counter-intuitive when one considers that the dominance selection routine in BIOME3 implicitly includes light competition and thus represents a mature ecosystem state, whilst after a disturbance it is the first successional types, i.e. grasses, which dominate. Fortunately, this apparent inconsistency has been avoided since the CBM model needs to know merely that the forest stand, described by the dominant tree pfts, is in the immature phase. The new pft distribution is required on the ecoregion level by the CBM. The first step in interface 2 is to redefine the ecoregion if a climate change run is made. One must regard an ecoregion not only as an area of similar vegetation cover, but as a combination of this and a region with similar climate. Therefore a shift in climatic conditions can also result in a redefinition of the ecoregion. Secondly, interface 2 maps the BIOME3 grid-cell output to the ecoregion format. The ecoregions may also be updated here when previously forested area is simulated to become grasslands/shrublands or agricultural areas (interface with the LUC core model) after disturbance. Third, BIOME3 NPP values are scaled up to the ecoregion (interface 2) and then taken as input into the CBM. This information is used in the pft growth curve equations within the CBM in order to update the vegetation functioning and the carbon pools. A simplified growth curve describing only the immature and mature phases is shown below (Figure 4).

**Figure 4:** **Simplified growth curves for one BIOME type, affected by changes in growth conditions.**




As stated previously, the NPP estimated by BIOME3 for each pft represents the NPP of the vegetation in the mature phase. Thus as the NPP estimation of BIOME3 changes with changing climatic conditions, *k*(NPP) shifts the final peak on the growth curve and possibly the number of years required to reach the mature phase, e.g., a reduction in productivity leads to a reduced mature phase biomass and possibly the stand takes a longer time to reach maturity. This is only true for stands which are in the immature phase, since the mature phase vegetation will not able to take advantage of or be disadvantaged by any changes to more favorable or unfavorable conditions, although litter inputs and consequently soil carbon pool sizes will change.

### 6.2 Equilibrium model application methodology

Before any future climate runs can even be considered the model must first be run to equilibrium for the present day climate and the resulting vegetation projection and carbon pool sizes must be comparable to the current data. The environmental sieve routine is run only once since the climate conditions are set constant, and therefore the potential pfts will not change. BIOME3 is then run to decide which of the potential pfts are dominant. These dominant pfts must be the same as those contained in the inventory data sets used in the CBM. At this stage the forest structure should be consistent. This constitutes the BIOME-CBM combined model initialization step.

### 6.3 Future climate model application methodology

Once the new equilibrium model run has been successfully completed, the model can be applied for dynamic climate change scenarios, with a minor change in the methodology. Each iteration requires a run of BIOME1 to project a new set of potential pfts. Interface 1 then sends BIOME3 information on the actual dominant pfts (from the previous iteration), the new set of potential ones from BIOME1, and grid-cell disturbance information. Each grid-cell (in our case 10 x 10 km) is prescribed as either being changed or not changed, depending on site conditions and disturbance frequencies (see part 6.1). BIOME3 then calculates NPP and LAI values for the selected pfts. This information and the actual land cover type is sent to interface 2. All areas which have been disturbed will have vegetation reset to be in the initial phase. Interface 2, takes in climate data and the grided vegetation cover (and its corresponding estimate of productivity), disaggregates this and then redefines the ecoregions. CBM is now run with this new information and the vegetation function is updated using the $k$(productivity) multiplier in the stand growth equations. This updated vegetation function is stored whilst disturbance information and the grided vegetation cover data set is sent back to interface 1. Using the percentage disturbance within each ecoregion, statistical techniques are used to determine which grid-cells have been disturbed at the end of the current iteration. Note, the vegetation cover is updated during the next iteration.

# SECTION 4

## 7. DISCUSSION

The good results obtained from this modeling exercise, as described in Section 2, validates the approach used in the BIOME-LUC model to project potential natural vegetation. Several short-comings have been identified and require further investigation. In particular an increase in the extent of all grassland biomes is important to achieve. As mentioned above, further sensitivity analysis on the minimum LAI requirement for grassland is required. A reduction would lead to an increase in the projected grassland area. Redefining the boreal forest minimum LAI constraint would also lead to an increase in northern continental taiga, reducing the present predicted extent of cool/boreal woodland. An improvement in the definition and parameterization of the shrub pfts according to sound ecological principles is envisaged. Also reducing the productivity of the evergreen conifer pft relative to the broad-leaved summergreen pft is required. This may in part be due to an absence of a pft soil nutrient/fertility requirement. The inclusion of this factor is intended in the ongoing model development.

Until fully dynamic ecosystem models become available, coupling existing biogeography and biogeochemistry models is a major step forward in ecological research. One such model coupling methodology has been described in detail in Section 3. Successful completion of this study is expected to yield exciting results both in the context of the broader LUC project requirements, and also in obtaining more reliable ecosystem carbon storage, vegetation structure and function projections. Further challenges will be faced when uneven aged stands, covering large areas of boreal Russia, and comprehensive peatland dynamics are included in the model framework.

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