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Strategy for a Fire Module in Dynamic Global Vegetation Models

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Introduction

Disturbance plays a major role in shaping and maintaining many of the Earth's terrestrial ecosystems. In fact, many ecosystems depend on fire for their very existence. Global Change is expected to result in changed distribution of current ecosystems, changed composition of those ecosystems, and in creation of new ecosystems. The International Geosphere Biosphere Program (IGBP), through the Core Projects Biospheric Aspects of the Hydrological Cycle, International Global Atmospheric Chemistry, Global Change and Terrestrial Ecosystems and International Global Atmospheric Chemistry, Biomass Burning Working Group, recognized that disturbances need to be included in the modeling efforts of each project. Disturbance from fire. land use and other factors may be as important as climate change in shaping future landscapes (Weber and Flannigan 1998). Three main themes were recognized: impact of disturbance on carbon pools, vegetation change, and feedbacks to the atmosphere. In June 1998, a workshop was held in Potsdam, Germany to develop a strategy to introduce disturbance into dynamic global vegetation models. This strategy was based on the fact that vegetation burning influences atmospheric chemistry, that feedbacks of energy, water and trace gases to the atmosphere are influenced by vegetation, and that changes in the composition of ecosystems have direct impact on the carbon pool, on biodiversity, and on health and productivity of the land. Disturbance includes fire, insect, disease, drought and flooding, land conversion, land use, air pollution, and introduction of exotic species. While it will be necessary to ultimately include all disturbances, the Potsdam workshop limited itself to fire. This strategy is based on the fact that there are no process driven models for all disturbances, and that fire has a number of reliable models with which to begin the process of introducing disturbance into dynamic global vegetation models. While this workshop limited itself to fire, a great deal of consideration was given to the fact that the model shell must be able to include other disturbances in the future. As a result, the strategy was to focus on a hazard function which would lead to effects of disturbance. The hazard function is basically a probability statement of risk of effects. This approach seems equally valid for all forms of disturbance.

A Conceptual Fire Module

Dynamic Global Vegetation Models (DGVM) contain several common elements or modules. These include: (a) some form of rule base to determine the plant functional types (PFT) that can be supported at a site or pixel, such as evergreen conifer or deciduous broad leaf trees; and in some cases, (b) a module to calculate the biogeochemical cycles and carbon and nutrient pools; and (c) a disturbance module to simulate the impacts of fire and other disturbances on vegetation structure and carbon balance, as well as other modules such as biogeochemical cycles, nutrient status and bi-directional feedbacks between the biosphere and the atmosphere. Global models, of necessity, are simplified expressions of temporal and spatial reality. As a result, many fine scale processes must be parameterized or aggregated to the pixel or model grid cell. Capturing both sub grid processes and texture of data and spatial representation of processes and texture of data in a model is more art than science. Generally, the first rule is to assure that such characteristics as fluxes of energy and matter are aggregated correctly. In a linear system, area weighting is adequate. In a non-linear system, the aggregation becomes far more complex. Suffice it to say, there is no uniform process of aggregation, and that aggregation is highly dependent on model formulation. The fire module can be constructed in a number of different ways ranging from broadly statistical to largely mechanistic. Given that there are constraints based on computational and data limitations, a variety of approaches is desirable in this early stage of fire model development. However, it would also be desirable to be able to test alternative approaches to fire modeling within various alternative DGVMs. Thus, structural modularity and a common set of inputs and expected outputs should be considered when developing alternative approaches to fire modeling in DGVMs. For example, the fire model should be dependent upon, that is accept as inputs, information about climate and fuels. The level of detail required as input could vary depending on whether the fire model is highly mechanistic, or primarily statistical or combined elements of both. The inputs could include information about plant functional type, stand structure and the size classes and moisture characteristics of fuels. Outputs of the fire model should include the impacts of fire on carbon pools, stand structure and emissions of carbon dioxide and other trace gases. These outputs need to be described in a fashion which will lead to a re-initialization for vegetation models, to those parameters needed for energy, water and trace gas feedbacks to the atmosphere, and to emissions of trace gases both during the fire and post fire decomposition.

Mechanistic, or process-based fire models at coarse scales can become quite elaborate and include many of the following types of calculations. Calculations of fuel loading are based on the plant functional types and the amount of carbon in different stand elements, such as leaves, boles, and fine to coarse surface litter. Allometric equations may be required to desegregate coarse descriptions of carbon pools to a larger number of fuel classes needed to predict fire intensity or may be based on simple rules defined by plant functional types. Both live and dead fuel classes, as well as their moisture characteristics must be calculated. Ignition may be based on a combination of fuel characteristics and some source of ignition, either natural (lightning) or of human origin. Given ignition, the ability of the fire to spread is based both on fuel characteristics and weather, mainly wind in the case of stand replacement or crown fires. Given that a fire will ignite and spread, then the impacts of the fire are calculated, again based on fuel characteristics for calculating fire intensity and the impacts on plant mortality and fuel consumption. Trace gas emissions are calculated based on fuel consumption, while some components of live fuel are killed and moved into either black carbon (recalcitrant to decomposition) or to various litter pools. Fuel loadings are, of course, dependent upon the PFTs and the stage of succession, or time since last disturbance. Since ignition is a function of fuels and climate (or humans), fire return interval probability distributions should be an emergent property of the model.

Probability functions can be used to describe disturbance regimes and could be useful for validation of the output from DGVM fire models (Johnson and Gutsell 1994). Effects may include those on emission potential and standing biomass. Three mathematically-linked functions may be used. The first of these is the hazard function, the simplest of which is a constant. The second function is a time-since-fire function and the third is a fire-interval function. The hazard function describes the probability of a point on the landscape being subject to fire; the second function describes the proportion of the landscape having experienced particular times since the previous fire, and the interval function describes the proportion of the landscape having experienced a particular fire interval. Once the fire return interval is known for an area - an output of some DGVMs - the simplest hazard function can be used to show the variation in simulated stand age and in proportions of the landscape having various intervals between fires. Of course, another aspect of the fire regime, like fire intensity (Gill 1975), can also be important in ecosystem behavior.

An ideal hazard function concept or shell would be applicable to all disturbance in dynamic global vegetation models. That is, it should reflect the various elements of the fire regime (areal extent, mortality, intensity) and take spatial distribution into account in order to aggregate these to the pixel or grid scales used in global models (Gill 1998). Intensity of the disturbance and the areal extent of the disturbance, should provide spatial statistics, and should have as input, the appropriate vegetation characteristics and the drivers of the disturbance. Such a shell can be constructed by a linearization of the disturbance models. In the case of fire, spread and intensity, models contain functional representations of the vegetation structure and biomass, and functional representations of weather (humidity, precipitation and wind) which are weighed by vegetation structure. Because for any given fire, the biomass and stand structure are constant, the weather factors can be separated from the stand structure as a first approximation (Fosberg 1978, Fosberg et al. 1993, Roads et al. 1997). In fact, a fire weather index (Fosberg 1978, Roads et al. 1997) can be devised and then weighted by plant functional type (Fosberg et al. 1993) to provide a first order approximation of fire behavior. Since we are interested in both areal extent of the fire as well as intensity, two such functions can be devised, one for fire spread and one for intensity. Fire area is basically governed by fine fuels and wind, while fire intensity is basically governed by heavy fuels. A fast response weather driven function can be constructed based on representing weather by only fine fuels, that is, those fuels which have rapid response to changes in weather, while a slow response weather driven function can be constructed using moisture content of large fuels. Plant functional types then can be used to calibrate the fire spread and fire intensity based on maximum potential spread or intensity for a given plant functional type (Fosberg et al., 1993). By analogy, such a shell could also be developed for other disturbances.

Knowing, or estimating, the variation in proportions of landscapes having experienced various times-since-fire and fire intervals allows for the effects of simulated non-linear interactions to be evaluated. Using the mean interval to examine effects may be misleading. Between-fire intervals are just one aspect of the fire regime which interact with ecosystem states to result in fire effects. Other components are fire type (peat or above-ground fires), fire intensity and seasonality of fires and variability of fire return interval.

DGVMs typically simulate a small number of plant functional types, usually fewer than ten. They are primarily based on characteristics of growth form (tree, shrub, grass), leaf form (broad leaf, needle leaf), leaf phenology (evergreen, deciduous) and leaf physiology (C3, C4). Functional attributes with respect to reproduction (such as vegetative or seed) or fire resistance (such as thick or thin bark) are usually not represented in DGVM plant functional types. An open question is whether these additional attributes need also be considered in the definition of PFTs in order to adequately simulate both the occurrence of and impacts from fire. For example, a more precise description of the fuels that carry fires may become an important consideration in relation to the prediction of some aspect of fire behavior such as fire-intensity range. As fuels for fires are often linked to a particular dominant plant form, it is possible to define fuel characteristic in the plant functional types. To what extent the list of plant functional types needs to be expanded in order to be made comprehensive requires exploration. However, an appropriate addition to the usual lists would be "lichens" (a class which could include mosses), an important fuel type found in some boreal forests. Like other plant functional types this one could be linked to a particular climatic situation.

A consideration of the fire responses of plant functional types needs to be undertaken for the prediction of shifts in the proportions of plant functional types after fires. An example of some importance may be a type called "ephemerals" (in addition to the grasses already simulated by DGVMs). Ephemerals may include those plants that arise temporally as the result of unusual years of rainfall in arid areas. Such ephemerals may then carry fires over areas that are far greater in extent than those usual for the area. There are ephemerals that appear temporarily after fire as well; these may be taxonomically diverse and comprise a significant proportion of the regional plant diversity. At a broad scale the arid and semi-arid distribution of ephemerals may be defined in terms of climate.

Other Disturbances

Besides fire, there are a number of other disturbances which should be considered on their own merits as well as because they may interact with fire (and each other). An immediate need is a rationale for deciding which disturbances to include and which to leave out.

It is also useful to classify disturbance types in terms of their dynamics. For instance, disturbances (e.g., harvesting, some diseases and insects, wind throw) can probably be thought of as analogues to fire and hence the approach proposed for fire (above) has potential for application to these other disturbances as well. However, a considerable amount of fine-tuning may be necessary in some cases.

For instance, taking spruce budworm (*Choristoneura fumiferana*, Clem.) as an example for periodically outbreaks of insects (parameters of insect or disease characteristics in plant functional types), one could consider the outbreak period as a "return interval" for outbreaks. In addition, the concept of fuel load would seem to have an analogue with forest maturity since the spruce budworm seems to require mature forest for outbreak.

However, plant functional types such as "needle leaf evergreen" will need more resolution since spruce budworm prefers spruce and fir over pines. Another difference from fires is that insects act more slowly. Spruce budworm outbreaks may last 5-15 years and it takes about 5 consecutive years of 100 percent defoliation of the current year's foliage to kill a host tree. Growth loss on surviving trees can be substantial even after just a couple of years of severe defoliation. Another complication is that spruce budworm outbreaks seem to collapse for different reasons in different parts of the range. In northern Alberta, late spring frosts are reported to be major causes of collapse, while in Ontario such frosts have made little difference to outbreak progression.

A second group of disturbances could be handled as monotonic changes in plant functional types. Conversion of forest to agriculture, decimation of native plants by exotic pests (weeds, insects, diseases) are two examples.

About 15 percent of the land surface is used for cultivation of crops (arable land). Especially in tropical and subtropical regions, conversion of natural vegetation for agricultural purposes is often associated with burning events. In contrast, arable land is protected from fires, but burning of agricultural wastes may occur. Crops may be represented in a DGVM by separate plant functional types (e.g. different types may be used for irrigated and non irrigated crops). Disturbances through land use changes may then be considered as switches between plant functional types.

Data Initialization and Validation

There are few congruent, consistent, and complete global carbon and nutrient databases that can be used to quantify initial conditions of all plant functional types represented in the DGVMs. This lack of initialization data requires the model to compute levels of carbon pools and nutrient status within the biome, which often results in questionable estimates of initial carbon pools and nutrient status. This is especially true for below ground carbon pools. Validation of these estimates is difficult because of the scarcity of field data. The DGVM disturbance module will be sensitive to initial conditions because these conditions influence many fine scale parameters important to the computation of disturbance effects. What is needed is a comprehensive database of above and below ground pools of carbon pools and nutrient status that accurately reflects natural and managed ecosystems. And, because parameters in the disturbance module are somewhat age dependent, this database should also include a stratification of stand development for these carbon pools. Knowing this global database would be difficult and costly to construct, it would seem a likely starting place would be to consolidate and compile carbon pool and age structure estimates found in the literature into a metadatabase accessible to all.

Also, it might be desirable to construct independent initialization models that empirically compute carbon pool initial conditions from mechanistic algorithms or direct gradient analysis developed from ecosystems studies where field data are extensive. For example, direct gradient analysis could be used to predict below ground carbon pools from independent mechanistic variables such as precipitation, transpiration, and soil depth using statistical approaches. The data collected from the IGBP transect studies would be invaluable for this type of effort. Another method to populate this global carbon database might be to parameterize the global carbon pools from aggregated fine scale model outputs.

Global initialization data base development will also be confounded by the lack of separation in existing data sets between land use and natural disturbances. The main problem is that the disturbance module does not, as yet, include land use activities, such as forestry, agriculture, and settlement. But, nearly all published disturbance data sets from this century include human impacts with natural disturbances along with their complex interaction. Until the DGVM models simulate land use, validation data sets-must be able to separate natural disturbance regimes from those brought about from human impacts. Spatial databases that explicitly integrate long term disturbance dynamics into general or robust statistics like fire return interval and fire severity are desirable because the coarse climatology time step (i.e., monthly) in the DGVM may not allow the accurate simulation of individual events in time and space. Also, other aspects of the fire regime, such as fire severity and size, would be difficult to generate by individual events given the coarse scale of the model spatial grid and the plant functional types.

Since there are no natural disturbance regime maps of the globe, the best validation data sets may be in regional summary efforts and in the current literature. Fire history studies summarized at the regional scale are especially valuable and these include fire regime maps of Australia (Walker 1981) and the Columbia River basin of the USA (Morgan et al. 1995).

Validation of the effects of disturbance on the biota and carbon cycle is also important (e.g. fuel consumption, smoke, and mortality). Key data sets for this effort include global and regional emission production statistics (Hao and Liu 1994) and satellite derived land cover change maps" (Loveland et al. 1991, 1993). Regional burning statistics compiled by various agencies and governments over the last 20 years will undoubtedly be a valuable validation source once human land use is included in the DGVM structure. These summaries include spatial, multi-year compilations of fires in Europe (European Commission 1992), spatial global fire occurrence remotely sensed from AVHRR satellite sensors (IGBP 1994), and 50-year statistics on area burned in the boreal forests by decade (Stocks 1991).

Other possible validation sources might be lightning strike frequency maps, fire occurrence and ignition locations, historical fire danger indices and weather, and spatial maps of fire perimeters. A comprehensive validation should also include an independent accuracy assessment of initial conditions. This may be accomplished by referencing satellite derived land classifications with the initial plant functional types or comparing startup carbon pool values generated from initial runs of the models to values found in the literature or remotely sensed from satellites (e.g. leaf area index, standing biomass).

Challenges and Recommendations

The inclusion of disturbance models within DGVMs creates a number of unique challenges for model development, calibration, and verification. These challenges include:

1. Optimum model formulation for disturbances cannot be currently specified. Therefore, alternative model approaches must be systematically implemented, tested and compared. Criteria for comparison of disturbance modules should be based on the adequacy of their representation of the disturbance regime and subsequent effects of disturbances on vegetation.
2. Model comparison is dependent upon the adequacy of data describing vegetation structure, land use, and reconstruction of historical climate and fire history. Some of these data may never be available at a global scale. Therefore, construction of such data for different regions (e.g., boreal, tropical, savanna, etc.) should be developed as case studies for model comparison.
3. Plant-functional types used in DGVMs are not yet specifically designed to account for responses to disturbance. Detailed consideration must be given to the possible need to expand the definition of PFTs to include disturbance effects.
4. Inclusion of fine grained details of vegetation response to disturbances within coarse grained DGVM's is difficult from both a practical and theoretical stand point. Theory suggests that predictions across temporal and spatial scales is possible for single attributes (i.e., either mean, variance, or extreme disturbance events), but prediction in shifts of disturbance regimes are difficult to characterize by simple models alone.
5. A general disturbance framework for inclusions within DGVM's should account for multiple disturbance agents. The present challenge is to consider both fire and insect disturbance (and the interaction

between fire and insect effects) within different vegetation types.

6. Because fire and insect effects are contagion processes, the simulation of coarse grained dynamics of disturbance effects may benefit from fine grained descriptions of the spatial heterogeneity of vegetation and land use.
7. The spatial scales associated with both data and models for development and testing of prediction of global change are arbitrary. Systematic investigation of aggregation errors and resulting prediction bias associated within consistencies in scales between models and data is a needed to insure the adequacy of current descriptions and future predictions.
8. Plant ecophysiological responses to multiple disturbances are poorly understood, making the interaction between fire, insects and plant physiology difficult to simulate. Response functions that describe changes in DGVM ecophysiological parameters as a consequence of disturbance are needed to accurately simulate vegetation dynamics. This is particularly important as DGVMs are combined with other models in total earth system models which include biogeochemical and hydrological cycles, nutrient status and feedbacks of energy and water to the atmosphere.
9. Identification of disturbances which may act at global scales to affect patterns of growth and productivity of vegetation remains a significant challenge for DGVM models. Specific research tasks need to be designed to address the above issues in order to insure that model projections adequately and reliably reflect changes in vegetation dynamics as a consequence of global climate change, land use change and disturbance.

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