Global Vegetation Dynamics

Concepts and Applications in the MC1 Model

Dominique Bachelet and David Turner
Editors

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Buffalo grazing in Yellowstone National Park (Wyoming): grazers are important ecosystem drivers that affect the fire regime and tree seedling establishment.
Olympics National Park (Washington), lake surrounded by temperate rainforest with lush lichen growth: complex surficial and groundwater interactions between terrestrial ecosystems and water features are difficult to simulate accurately.
Mountain ridges and valleys in the Sawtooth Wilderness (Idaho)
Old growth forests are diverse, heterogeneous, and often occur in complex terrain where decoupling from regional climate often occurs.

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PREFACE

The first name for this model was "MCHammer," and I even drew a square peg being hammered into a round hole on the first MC1 poster that I presented at a national meeting in the mid-1990s. The model was conceived and the code written by a small team. We worked well together and had complementary skill sets: Lenihan for the biogeography (and later the fire model), Bachelet for the carbon cycle, Daly for the climate impacts; we were in the trenches. Neilson supervised the project by bringing the 10,000-foot overview and commentaries about what made sense and what did not, sending us back to the drawing board from time to time. Parton was the CENTURY model guru to whom I could always ask questions related to the biogeochemistry part of the model. The USDA Forest Service funded most of the early enterprise. The Joint Fire Science Program funded the fire model development and fire suppression work.

The first results of the model surprised us by their "accuracy," and our confidence in the tool that we had built increased, despite Neilson's constant reminder that a better tool (BIOMAP) would soon be built by other team members. A variety of events marked the model's evolution. Daly moved on to fame and fortune by further developing his PRISM model, the only source of historical climate data for MC1 to this day. The day Lenihan's fire model showed a large fire in Yellowstone without any particular calibration was a happy day for the team that was using the first dynamic global vegetation model (DGVM) in the world to include dynamic fire (instead of prescribed fire events or carbon removals). We readily shared our approach with the LPJ (Lund-Potsdam-Jena) team that quickly thereafter wrote its twin called SPITFIRE. The sad day was when our model disagreed with other DGVMs, MC1 was simulating a decline in global carbon capture by the end of the 21st century. Unlike in other DGVMs, the CO_2 fertilization effect was deemphasized (following Parton's lead with CENTURY). It cost us a place in a much-cited group publication, but our model was still young and only summarily tested, and it did not agree with better-published models. A missed opportunity. Since then, field experiments (free-air CO_2 experiments) have shown that the CO_2 fertilization effect boosting production had been in fact overestimated.

We were a small team with much to do: find and fix model bugs, revise and improve the code, run the model for a variety of domains and scales, deliver the results, and write reports and papers. Formatting and QA/QC of the input climate data became the major responsibility of a new team member, Drapek, who also mapped model results using GIS. If that was not enough, training new users (students) soon became part and parcel of running the model. Much later, when Neilson and Lenihan both retired and funding to further develop the model became nonexistent, it was touch and go for MC1. But Conklin and I kept it going, and the USGS soon provided funding to develop a newer version with land use, MC2, which we are continuing to refine. Even Neilson's replacement, who was supposed to complete BIOMAP to supersede MC1, now also uses MC1 or rather its successor MC2 in his research projects. The model definitely has been a workhorse, and despite the many bugs that were (and may still be) discovered during its long career, it has served us all well.

The purpose of this book *MC1 Dynamic Global Vegetation Model: Concepts and Applications*, is to document the MCI DGVM and provide peer-reviewed documentation that can be cited in future journal publications. Hopefully this will help satisfy unconvinced reviewers of manuscripts reporting MC1 results, making the model a better-known entity. Since 2000, the model has been used in various research projects nationally and internationally and was featured in a number of publications and reports (88 as of April 2015), many of them written by our small research team. Hopefully, this book will entice others to further develop the model and explore our changing future by facilitating the training of new users.

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General Description of the Model MC1

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History and General Description of the Dynamic Global Vegetation Model MC1

Dominique Bachelet

ABSTRACT

The model MC1 was designed during the second phase of the Vegetation Ecosystem Modeling and Analysis Project (VEMAP), a collaborative multiagency project designed to simulate and understand ecosystem dynamics for the continental United States [*VEMAP members*, 1995]. The goal was to focus on transient vegetation dynamics and to link biogeography and biogeochemistry models so that the trajectory of ecosystems between historical and future time periods could be simulated. The model was designed to simulate the potential vegetation that would occur without direct intervention by industrialized societies. Since then, applications of MC1 have included effects of humans on vegetation through cattle grazing and fire suppression as well as direct (CO_2) and indirect (climate) effects of increasing greenhouse gas concentrations. The MC1 model has been used in many projects, at various spatial scales (50 m−50 km) and for different spatial domains (national parks to global) as illustrated by over 80 reports and publications using its projections of vegetation response to climate change. This chapter briefly describes its history and its design.

1.1. MODEL HISTORY

To prepare for the effects of climate change on terrestrial ecosystems, it is essential to understand how climate has driven vegetation distribution and the carbon cycle in the past and how it may affect them in the future. It is well recognized that land use may have transformed some landscapes more than climate, but future land use changes will depend on social and political decisions that are impossible to forecast while climate models can provide robust projections of climate futures. Moreover, anthropogenic influences do not affect all ecosystems equally. Many ecosystems still strongly reflect direct climatic influences, and their response to climate change is likely to influence the ecosystem services they provide. While farmers have access to management alternatives (irrigation, fertilizers, pesticides, genetically modified annual crops) that can alleviate some of the more negative effects of weather, foresters and pastoralists have adapted their management practices to account for climatic influences and will continue to do so, benefiting from projections of natural vegetation responses to change. Therefore many climate change research projects have focused on understanding the effects of future climate on natural vegetation.

The Vegetation Ecosystem Modeling and Analysis Project (VEMAP) was a collaborative multiagency project designed to simulate and understand ecosystem dynamics in the conterminous United States [*VEMAP members*, 1995]. During the first phase of VEMAP, potential vegetation maps for historical and for future conditions were generated by the static biogeography models MAPSS (Mapped Atmosphere Plant Soil System) [*Neilson*, 1995], BIOME2 [*Prentice et al.*, 1992], and DOLY (Dynamic glObaL phytogeographY) [*Woodward et al.*, 1995] using 30-year average observed as well as projected climate data, providing instantaneous

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snapshots of what was (historical starting point) and what might become (future endpoint) the vegetation distribution over the country without describing the path it might follow to get there. The gridded vegetation maps produced by the static models were then provided to three biogeochemistry models, CENTURY [*Parton et al.*, 1987, 1988, 1993], BIOME-BGC (Biome BioGeochemical Cycle) [*Hunt and Running*, 1992; *Running and Hunt*, 1993], and TEM (Terrestrial Ecosystem Model) [*McGuire et al.*, 1992; *Melillo et al.*, 1993; *Tian et al.*, 2000], to calculate the carbon stocks that matched the simulated vegetation type for these two time periods. Phenology and fire disturbance were prescribed in all cases. The underlying assumption was that chronic change was happening and that ecosystem trajectories between 2000 and 2100 were linear. However, scientists believed this assumption might be wrong and wanted to create a model that could explore transient ecosystem dynamics during the 21st century. One of the hypotheses was that land could first "greenup" with warmer temperatures but instead of increasing its productivity continuously until 2100 could be affected by the exceedence of a particular climatic threshold causing a "browndown" driven by increasing evaporative demand and drought stress associated with vegetation shifts, declines in productivity, and carbon losses.

During the second phase of VEMAP, instead of focusing on instantaneous snapshots of what might happen in terms of vegetation type change and concurrent shifts in the location of carbon sources and sinks, the goal was to focus on year-to-year variations and link biogeography and biogeochemistry models so that the trajectory of the ecosystems between historical and future time periods was simulated. At the time there were only a couple of research groups addressing this issue. A team composed of Oregon State University scientists including Chris Daly, Jim Lenihan, and Dominique Bachelet, under the leadership of USFS Ron Neilson and with financial support from the USDA Forest Service, started to link the biogeography rules adapted from the MAPSS biogeography model [*Neilson*, 1995] to a modified version of the CENTURY biogeochemistry model [*Metherell et al.*, 1993] in order to create what was to become the model MC1 [*Bachelet et al.*, 2001a, 2003]. Two other VEMAP-related projects emerged to link biogeochemistry models and biography models, MAPSS with BIOME-BGC (the BIOMAP model, originally started by Ron Neilson, now retired, remains under construction by John Kim, USFS), MAPSS with TEM (project lead by Jeff Borchers terminated before the new model was finished). Neither of the two latter projects provided usable DGVMs to this date. Other combinations of models were never explored by other group members despite the original project objectives.

For MC1, climate-based rules were extracted from the MAPSS biogeography model while the species-specific set of parameters in the CENTURY biogeochemistry model were replaced by globally relevant lifeform parameters. These parameters were defined so as to vary continuously with the fraction of each lifeform under different climate conditions. On the basis of climate zones and a few climatic indices (growing season precipitation, mean monthly minimum temperature), lifeform combinations were used to specify general vegetation types (e.g. maritime evergreen needleleaf forest) defined further by biomass thresholds [unlike the MAPSS model approach of using leaf area index (LAI)–based on an optimized hydrological budget–and ignoring the carbon budget]. The CENTURY code was modified, and only the "savanna" mode was implemented whereby grasses and trees competed for resources at all time.[1] Moreover, deep water was made accessible only to tree roots and surface nitrogen was preferentially accessible to grasses. The first area where the model was tested (at 50-m resolution) and competition between trees and grasses simulated at an existing ecotone, was Wind Cave National Park in South Dakota [*Daly et al.*, 2000; *Bachelet et al.*, 2000].

Since then, the MC1 model has been used in many projects, at various spatial scales and for different domains. After *Lenihan et al.* [2003] started producing results for the state of California, *Galbraith et al.* [2006] considered MC1 projections as "an essential first step" for an integrated assessment of the potential overall effects of climate change on the status and distribution of California's major vegetation communities. *Gucinski* [2005] was one of the first to use it for natural resource management purposes. It was later used at the Nature Conservancy to anticipate and plan for potential biome shifts under warming climates [*Aldous et al.*, 2007] and to design sustainable strategies for prairie chicken conservation [*McLachlan et al.*, 2011]. Projections of changes in fire regimes [*Bachelet et al.*, 2008] have been used for regional climate change assessments [e.g., *Kueppers et al.*, 2009; *Halofsky et al.*, 2014]. They and other model results were included in climate change adaptation reports [e.g., *Doppelt et al.*, 2008, 2009; *Halofsky et al.*, 2011] and used in various workshops [e.g., *Barr et al.*, 2010, 2011; *Koopman et al.*, 2010, 2011] where stakeholders had an opportunity to learn to interpret model results and discuss implications. An up-to-date list of publications that have included MC1 results as an important part of the work published is available in Appendix 1.

To expand the visibility and use of the model, the MC1 code has been made available under version control and is

[1] *Standard Century also includes a grassland and a forest modes whereby only grasses or only trees can grow, respectively.*

currently provided through an Oregon State University website (https://sites.google.com/site/mc1dgvmusers/home/mc1-source-repository-at-the-osu-biological-ecological-engineering-dept). A webpage was designed specifically for MC1 users interested in learning about the latest code revisions (https://sites.google.com/site/mc1dgvmusers/). In 2010, a users' network was created to share MC1 code updates and simulation-related issues between users (http://groups.google.com/group/mc1-dgvm-users). An MC1 developers group (http://groups.google.com/group/mc1-developers) was also created and met monthly until 2012. The USDA Forest Service provided training (with Drs. J. Lenihan and R. Drapek, as well as B. Pitts) for graduate students (B. Rogers, M. McGlinchy, both M.S. students with Dr. B. Law at Oregon State University) in 2010 and funding from the OSU Institute of Natural Resource was used in 2012 (with Dr. D. Conklin) at the Conservation Biology Institute to train a few more scientists. The first MC1 users conference took place in January 2011, and videos of the various presentations are available on the web (http://www.fsl.orst.edu/dgvm/agenda.htm).

1.2. MC1 MODEL DESCRIPTION

MC1 is a dynamic global vegetation model (DGVM) that simulates vegetation distribution, biogeochemical cycling, and wildfire in a highly interactive manner (Figure 1.1). The model always simulates competition between trees and grasses, where the former term refers to all woody lifeforms, including shrubs, and the latter term refers to all nonwoody lifeforms, including forbs and sedges. Shrubs are not explicitly simulated with their own physiological characteristics but are defined as short-stature woody lifeforms. The model does not simulate individual species. The model was designed to simulate the potential vegetation that would occur without direct intervention by humans. However, indirect effects such as grazing, fire suppression, and increasing greenhouse gas concentrations can and have been included.

The model is a gridpoint model that operates on a monthly time step across an input-defined spatial grid. Each grid cell is simulated independently, with no cell-to-cell communication. However, drought conditions that trigger simulated fires often occur regionwide, resulting in similar fire effects across contiguous cells.

1.2.1. Biogeography Module

This module simulates transient changes in biogeography through time, depending on climate-based rules as well as biomass thresholds. It is composed of two distinct components. The *lifeform interpreter* uses temperature- and precipitation-based rules to simulate leaf morphology and phenology for woody lifeforms (Table 1.1). Woody lifeforms include evergreen needleleaf, deciduous needleleaf, evergreen broadleaf, and deciduous broadleaf categories. The mixture of woody lifeforms is determined annually as a function of the minimum temperature of the coldest month and the growing season precipitation smoothed by an "efolding" function (Figure 1.2). This function progressively diminishes the influence of each year's climate on the smoothed climate variables. Using smoothed climate reduces overly rapid transitions between tree types and was implemented to better represent the inertia of vegetation to short-term climate variability [*Daly et al.*, 2000]. The lifeform interpreter separates grasses by their photosynthetic pathway. The C3/C4 mixture is determined by the ratio of C3/C4 grass productivity, calculated using temperature of the three consecutive warmest months, subject to the above "efolding" function. High warm-season temperatures favor C4 grasses. Woody and herbaceous lifeforms are always simulated together and compete for resources (water, nutrient, light), which results in variable biomass values simulated in the biogeochemistry module described below. Relative dominance varies as a function of climatic conditions that limit the availability of the resources as mediated by fire disturbance.

The *vegetation classifier* uses climate zone definitions (Table 1.2) and biomass thresholds to combine lifeforms into vegetation types (Table 1.3), each defined by the association of a climate-defined tree functional type as defined above and either a C3 or a C4 grass. High-latitude vegetation types are simply defined by the growing degree-days that define their climate zone. There are 38 possibilities of potential vegetation types in MC1 that span all the climatic zones, with 14 vegetation types within the temperate zone alone (Table 1.3).

1.2.2. Biogeochemistry Module

The biogeochemistry model is a modified version of the CENTURY model [*Metherell et al.*, 1993] that simulates the cycling of carbon and nitrogen among ecosystem compartments, including plant parts and multiple classes of litter and soil organic matter (Figure 1.3). A list and definitions of the standard variables commonly generated for most research projects with MC1 are provided in Table 1.4. Live and dead plant components include leaves, fine and coarse branches, fine and coarse roots. Dead herbaceous material composes the standing dead compartment. Dead plant material is transferred to aboveground or belowground litter compartments that decompose into three soil carbon pools of increasingly slower turnover rates, releasing CO_2 fluxes defined as heterotrophic respiration as described in the CENTURY model [*Metherell et al.*, 1993]. Decomposition

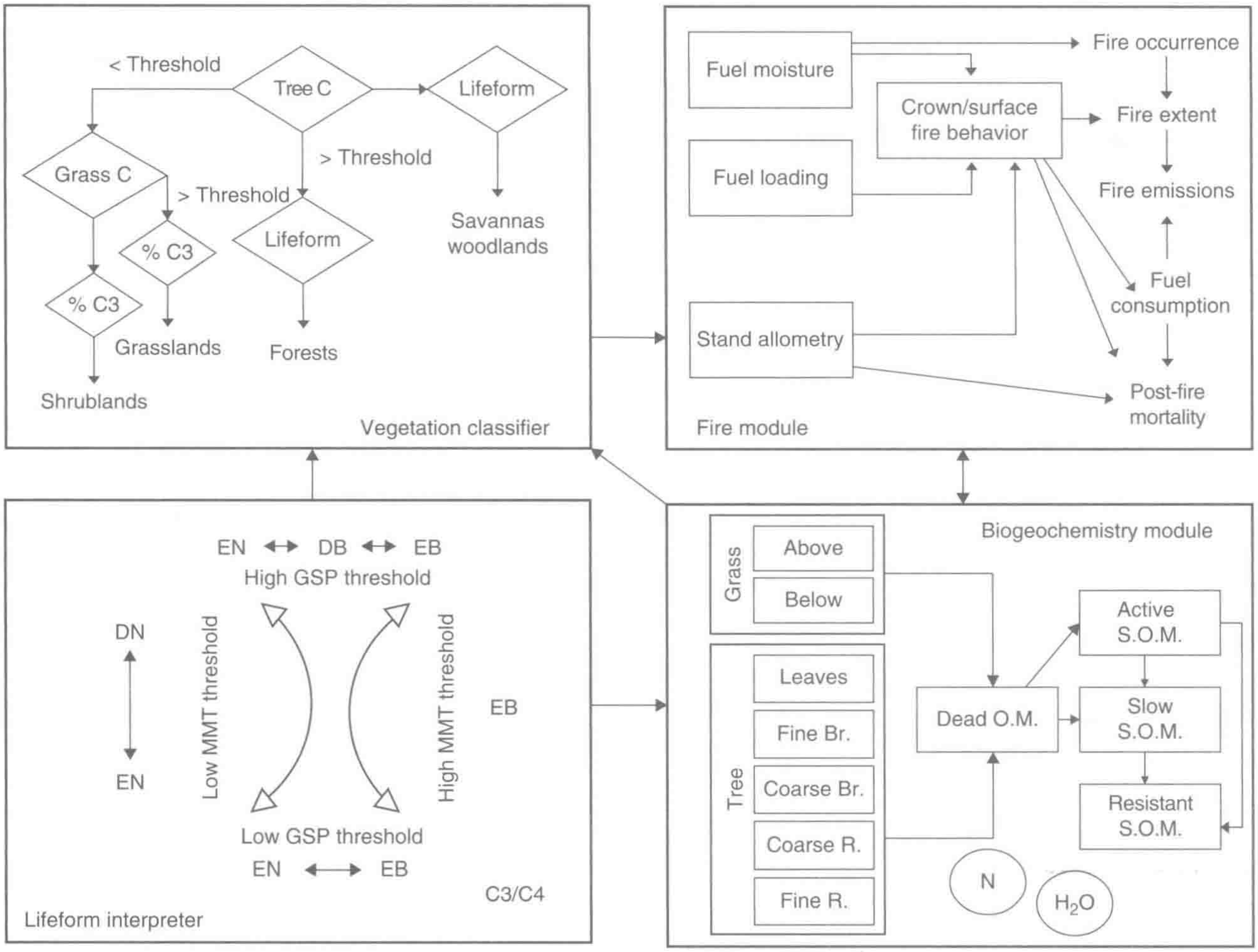

Figure 1.1 Diagram describing the MC1 model; the biogeography model is composed of (1) a lifeform interpreter (lower left) that uses climate rules to determine climate-adapted lifeforms (E = evergreen; D = deciduous; N = needleleaf; B = broadleaf; GSP = growing season precipitation; MMT = minimum monthly temperature), (2) the vegetation classifier (upper left) that uses climate rules and biomass thresholds (see Table 1.3) for the two competing lifeforms (tree and grass) to determine vegetation types (C3 = cool grasses with C3 photosynthetic pathway; C4 = warm grasses with C4 photosynthetic pathway; C = carbon). This information is shared with the fire module (upper right) to inform allometric relationships that are used to determine the type of fire (surface or crown). The biogeochemistry model (lower right) calculates the biomass for each lifeform and passes this information to the vegetation classifier that uses it to determine the vegetation type. Live (Br = branches; R = roots; S.O.M. = soil organic matter; N = nitrogen) and dead biomass pools are also passed to the fire module that translates them into fuel classes. Biomass killed by fire or consumed by fire is passed back to the biogeochemistry module.

Table 1.1 Thresholds used in the lifeform interpreter as woody lifeform determination rules (D = deciduous; N = needleleaf; E = evergreen; B = broadleaf). Temperatures and precipitation are smoothed by an efolding factor of 10 years (T_{min} = minimum monthly temperature, T_{max} = maximum monthly temperature).

Leaf Form	Phenology	Growing Season Precipitation	Minimum T_{min}	Continentality (max T_{max} − min T_{min})	Tree Type
N	D		=< −15°C	>=60°C	DN
N	E		=< −15°C	=< 55°C	EN
	E	< 55 mm	>−15°C and <18°C		EN-EB
		> 55 mm	>−15°C and < 1.5°C		EN-DB
B		> 55 mm	1.5°C		DB
B		> 55 mm	>1.5°C and <18°C		DB-EB
B	E		>= 18°C		EB