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History and General Description of the Dynamic Global Vegetation Model MC1

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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

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[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

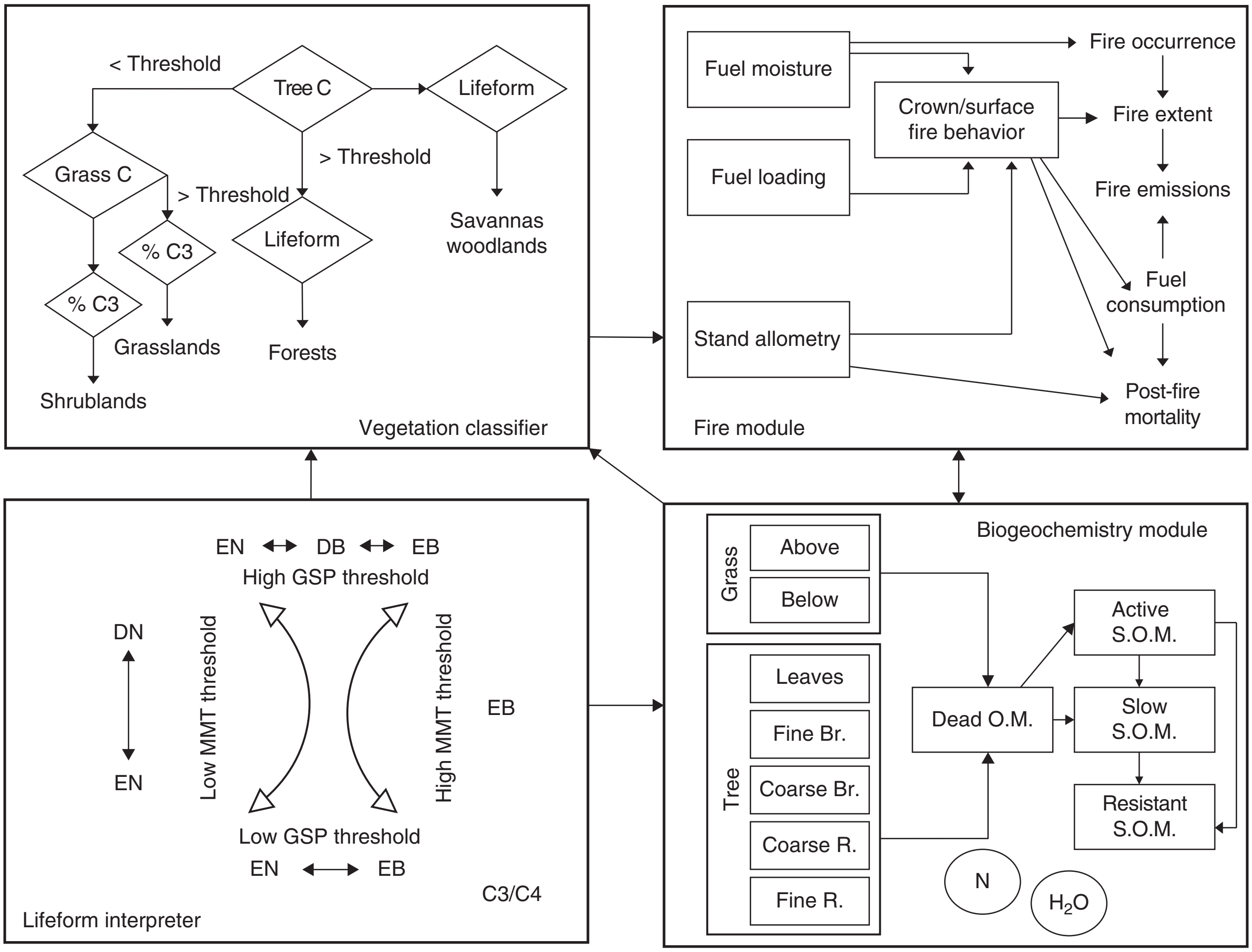

Figure 1.1 Diagram describing the MC1 model; the biogeography model is composed of (1) a lifeform interpreter (lower left) that uses climate rules to determine climate-adapted lifeforms (E = evergreen; D = deciduous; N = needleleaf; B = broadleaf; GSP = growing season precipitation; MMT = minimum monthly 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

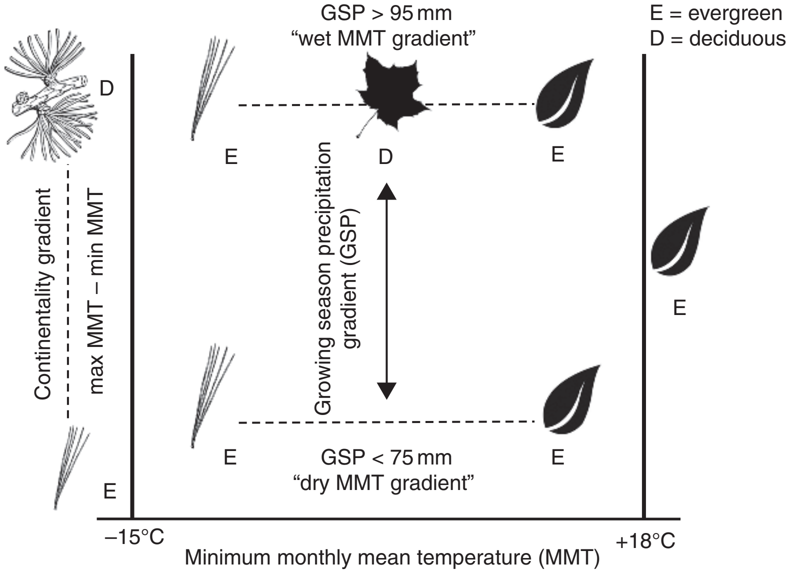

Figure 1.2 Diagram describing the lifeform interpreter. The fraction of evergreen needleleaf versus broadleaf lifeforms in each grid cell is determined annually as a function of the minimum temperature of the coldest month (MMT) and growing season precipitation (GSP), both smoothed over 10 years to avoid overly rapid transitions.

Table 1.2 Climate zone thresholds (temperatures are smoothed by a factor of 10 years) (GDD = sum of growing degree-days above 0°C; T_{min} = minimum monthly temperature).

Zone	Rule (Threshold)	Threshold Definition
ARCTIC–ALPINE	GDD <1000	Upper GDD (above 0°C) limit for arctic/alpine zone
TAIGA–TUNDRA	1000<GDD <1330	Upper GDD (above 0°C) limit for taiga-tundra
SUBALPINE	1330 <GDD <1900	Upper GDD (above 0°C) limit for subalpine zone
BOREAL	T_{min} < –13.0°C	Upper min. temperature limit for boreal zone
TEMPERATE	–13°C < T_{min} =<7.75°C	Upper min. temperature limit for temperate zone
SUBTROPICAL	7.75°C < T_{min} <18°C	Upper min. temperature limit for subtropical zone

rates are influenced by soil texture, soil moisture, and temperature, as well as by the existing soil carbon content and the nutrient content of the dead material.

Production rates are based on maximum monthly rates that are interpolated from lifeform-dependent parameter values, depending on the mixture of woody and herbaceous lifeforms set by the biogeography module. Maximum production rates are then multiplied by temperature-, water-, and atmospheric CO_2-related scalars that differ between lifeforms [*Bachelet et al.*, 2001a]. In the case of woody types, an additional scalar related to leaf area index (LAI, defined as one-sided leaf area per unit ground area) is used to approximate the fraction of incoming light intercepted by trees. For herbaceous types, scalars incorporating the effects of shading by trees and standing dead grass are also included. The temperature scalars are based on mean monthly surface soil temperature, as affected by canopy shading and reduction of outgoing longwave radiation [*Parton et al.*, 1994]. MC1 projects the sizes of all carbon pools in units of C mass per unit ground area (g m^{-2}). Maintenance respiration is calculated as a separate flux, but growth respiration is assumed to be included in the production rate.

This module also simulates actual and potential evapotranspiration (AET and PET) and soil water content in multiple soil layers, the number of which depends on the total soil depth that is input to the model. Woody leaf and herbaceous moisture contents are calculated as functions of the ratio of woody or herbaceous available water to PET. These simulated live fuel moisture contents affect fire behavior, as simulated by the fire module (described in Section 1,2,3, below).

1.2.3. Fire Module

The fire module simulates the occurrence, behavior, and effects of fire and was designed to project large, severe fires that account for the bulk of observed fire impacts in the conterminous US [*Lenihan et al.*, 1998;

Table 1.3 Climate and biomass thresholds defining the possible potential vegetation types that can be used in MC1.

Vegetation Types	Zone	GDD (degree-days above 0°C)	Grass C Threshold (g C m^{-2})	Tree C Threshold (g C m^{-2})	Dominant ss	Tree Type	Continentality (max T_{max} – min T_{min})	Other
Ice	ARCTIC or ALPINE	=< 0.			C3	EN		
Tundra	ARCTIC or ALPINE	> 0.			C3	EN		
Taiga-tundra	BOREAL				C3	EN		
EN forest	BOREAL	=< 1330		>=3000	C3	EN		
Mixed Woodland	BOREAL			<3000	C3	EN		
Cool N forest	TEMPERATE			>=3000	C3	EN	=< 18°C	< 0°C
Maritime EN forest	TEMPERATE			>=3000	C3	EN	=< 18°C	> 0°C
Temperate EN forest	TEMPERATE			>=3000	C3	EN		
Temperate DB forest	TEMPERATE			>=3000	C3	DB		
Temperate cool mixed forest	TEMPERATE			>=3000	C3	EN-DB		
Temperate warm mixed forest	TEMPERATE			>=3000	C3	EB		
Subalpine forest	TEMPERATE	=< 1900			C3	EN		
Temperate EN woodland	TEMPERATE			>=1150	C3	EN		
Temperate DB woodland	TEMPERATE			>=1150	C3	DB		
Temperate cool mixed woodland	TEMPERATE			>=1150	C3	EN-DB		
Temperate warm mixed woodland	TEMPERATE			>=1150	C3	EB		
Temperate (C3) shrubland	TEMPERATE			>=1	C3	EN-DB		
Temperate desert	TEMPERATE			< 1	C3	EN-DB		
Temperate (C3) grassland	TEMPERATE BOREAL		>= 200	< 200	C3	EN-DB		
Subtropical (C4) grassland	SUBTROPICAL or TEMPERATE		>= 200	< 200	C4	EN-DB		
Subtropical EN forest	SUBTROPICAL			>=3000	C4	EN		
Subtropical DB forest	SUBTROPICAL			>=3000	C4	DB		
Subtropical cool mixed forest	SUBTROPICAL			>=3000	C4	EN- DB (EB)		

(*Continued*)

Table 1.3 (*Continued*)

Subtropical EB forest	SUBTROPICAL		>=3000	C4	EB	
Subtropical EN woodland	SUBTROPICAL		>=1150	C4	EN	
Subtropical DB woodland	SUBTROPICAL		>=1150	C4	DB	
Subtropical mixed woodland	SUBTROPICAL		>=1150	C4	EN-DB (EB)	
Subtropical EB woodland	SUBTROPICAL		>=1150	C4	EB	
Subtropical shrubland	SUBTROPICAL		>=1	C4	EN-DB (EB)	
Subtropical desert	SUBTROPICAL		< 1	C4	EN-DB (EB)	
Tropical grassland	TROPICAL	>= 200	< 200	C4	EB-DB	
Tropical EB forest	TROPICAL		>=3000	C4	EB	
Tropical D woodland	TROPICAL		>=1150	C4	DB	=< 0.45
Tropical savanna	TROPICAL		>=1150	C4	EB-DB	> 0.45
Tropical shrubland	TROPICAL		>=1	C4	EB-DB	
Tropical desert	TROPICAL		< 1	C4	EB-DB	
Barren						No soil or NPP=<0.

Note: "Tree" refers to woody lifeforms in general, including shrubs and trees; "grass" refers to herbaceous lifeforms including sedges and forbs (E = evergreen, D = deciduous, N = needleleaf, B = broadleaf; NPP = net primary production). Temperatures used to calculate growing degree-days (GDD) are smoothed over 10 years.

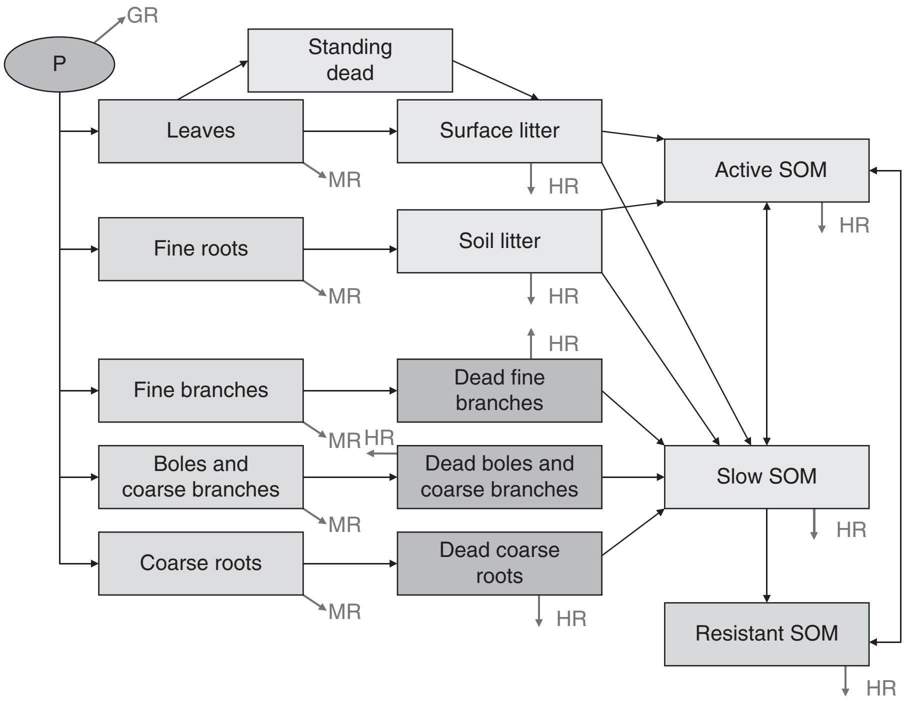

Figure 1.3 Diagram describing the various carbon pools in the MC1 model (P = production; GR = growth respiration; MR = maintenance respiration; HR = heterotrophic respiration; SOM = soil organic matter).

Table 1.4 List of annual variables used in MC1.

Variable Name	Description	Units
adeadcx	Maximum aboveground dead carbon	g C m^{-2}
aetx	Actual evapotranspiration	mm H_2O yr^{-1}
afcaccx	Aboveground tree NPP	g C m^{-2} y^{-1}
AFLIVCmy1	Aboveground live forest carbon, decadal average of annual maximum values	g C m^{-2}
AFLIVCmy2	Aboveground live forest carbon, average of annual maximum values for a user-defined interval	g C m^{-2}
aflivcx	Maximum aboveground live tree carbon	g C m^{-2}
agcaccx	Aboveground grass NPP	g C m^{-2} y^{-1}
agg_vclass	Aggregated vegetation class (VEMAP)	none
aglivcx	Maximum aboveground live grass carbon	g C m^{-2}
bdeadcx	Maximum belowground dead carbon	g C m^{-2}
bflivcx	Maximum belowground live tree carbon	g C m^{-2}
bgcaccx	Belowground grass NPP	g C m^{-2}
bglivcx	Maximum belowground live grass carbon	g C m^{-2}
bio_blkc	Total black carbon produced by fire	g C m^{-2}
bio_consume	Biomass consumed by fire (fire module)	g C m^{-2}
bio_consume_century	Biomass consumed by fire (biogeochemistry module)	g C m^{-2}
bio_consume_dead	Dead biomass consumed by fire	g C m^{-2}
bio_consume_live	Live biomass consumed by fire	g C m^{-2}
bio_death	Live biomass killed (not consumed) by fire	g C m^{-2}
broadleaf_ppt	Min. monthly precipitation during growing season (threshold)	mm H_2O
bui_max	Max. fuel buildup index	none
burn_count	Years since fire	years
burn_year	Flag indicating fire occurred this year	true or false
BURN_YEARmy1	Number of fire years per decade	fire years per decade
BURN_YEARmy2	Number of fire years per decade for a user defined interval	fire years per decade
c3	C3 (photosynthetic pathway) grass presence/absence	true or false
c3c4	C3/C4 index, varies from 0 = C4 dominance to 1 = C3 dominance	none
c4	C4 (photosynthetic pathway) grass presence/absence	true or false
class	MAPSS vegetation class id number	MAPSS class
clsf	Annual carbon loss to fire	g C m^{-2} y^{-1}
clsl	Annual carbon loss to leaching through the soil	g C m^{-2} y^{-1}
db	Deciduous broadleaf tree presence/absence	true or false
dn	Deciduous needleleaf tree presence/absence	true or false
eb	Evergreen broadleaf tree presence/absence	true or false
eidx	Evergreen index, varies from 0=deciduous to 100 = evergreen	none
em_ch4	Fraction of Methane produced by fire	g C m^{-2}
em_co	Fraction of Carbon monoxide produced by fire	g C m^{-2}
em_co2	Fraction of Carbon dioxide produced by fire	g C m^{-2}
em_nmhc	Fraction of Nonmethane hydrocarbons produced by fire	g C m^{-2}
em_pm	Fraction of Particulate matter produced by fire	g C m^{-2}
en	Evergreen needleleaf tree presence/absence	true or false
event_month	Month of fire occurrence, Jan = 0, Dec = 11	none
fcaccx	Tree net primary production	g C m^{-2} yr^{-1}
ffmc_max	Fine-fuel moisture content index	none
fire_cat	Fire zone	none
fri	Fire return interval	years
frstcx	Maximum live tree carbon	g C m^{-2}
gcaccx	Grass NPP	g C m^{-2}
gdd_frost	Growing degree days during the growing season	°C.day
gdd_zero	Growing degree days (base zero)	°C day
grass_frac	Grass as a fraction of fuel	fraction of fuel

(*Continued*)

Table 1.4 (*Continued*)

Variable Name	Description	Units
grass_typ	Grass lifeform type: C3=1, C4=2, mixed C3/C4=3	none
grassc	Maximum total grass carbon	g C m^{-2}
INITIAL_CLASSrun	MAPSS initial class id number	none
INITIAL_VCLASSrun	VEMAP initial class id number	none
litfx	Litterfall	g C m^{-2} yr^{-1}
mar_index	Maritime index	none
max_fine_frac	Maximum fine-fuel fraction of total fuel	none
max_grass	Efolded maximum grass LAI	m^2 leaf area m^{-2} ground
max_rleavc	Maximum monthly tree leaf carbon	g C m^{-2}
max_tree	Efolded maximum tree LAI	m^2 leaf area m^{-2} ground
min_tmp	Minimum monthly mean temperature for the year	°C
minx	Net nitrogen mineralization	g N m^{-2} yr^{-1}
nb_ddecid	Maximum fraction of drought deciduous tropical tree	none
nb_tree_typ	Tree type	none
nb_zone	Climate Zone	none
nbpx	Net biome production	g C m^{-2} yr^{-1}
nepx	Net ecosystem production	g C m^{-2} yr^{-1}
nidx	Needleleaf index, varies from 0 = broadleaf dominance to 100 = needleleaf dominance	none
nlayer	Number of soil layers	none
NLAYPGyr	Number of rooted soil layers	# soil layers
nppx	Net primary production	g C m^{-2} yr^{-1}
part_burn	Fraction of grid cell burned	fraction of cell burned yr^{-1}
PART_BURNmy1	Decadal average of grid cell fraction burned each year	fraction of cell burned yr^{-1}
PART_BURNmy2	Average grid cell fraction burned each year for a user-defined interval	fraction of cell burned yr^{-1}
ppt_index	Precipitation index for lifeform	none
prev_class	MAPSS previous year class id number	none
prev_vclass	VEMAP previous class id number	none
rnfx	Runoff	mm H_2O yr^{-1}
ros_max	Maximum fire rate of spread	none
rspx	Soil respiration	g C m^{-2} yr^{-1}
snow_max	Maximum monthly snowpack	mm H_2O
SOIL_DEPTHrun	Depth of mineral soil	cm
tmp_index	Temperature index for defining lifeform	none
totc_dec	Total ecosystem carbon in December	g C m^{-2}
TOTDEADCmy1	Decadal average of minimum annual total dead C	g C m^{-2}
TOTDEADCmy2	Average of minimum annual total dead C for a user-defined interval	g C m^{-2}
tree_typ	Tree lifeform type: 1–8 = EN, EN-DB, DB, DB-EB, EN-EB, EB, DN, DN-EN	none
treec	Maximum tree carbon	g C m^{-2}
tslcx	Mean soil carbon	g C m^{-2}
vclass	VEMAP class id number	none
vegc	Maximum annual vegetation carbon	g C m^{-2}
VEGCmy1	Decadal average Live biomass carbon	g C m^{-2}
VEGCmy2	Average Live biomass carbon for a user-defined interval	g C m^{-2}
whc	Water holding capacity	cm H_2O
YEARS_TO_RUNrun	Number of years to run model	years
zone	Climate zone	none

Note: "Grass" indicates all herbaceous vegetation including forbs and sedges; "tree" indicates all woody vegetation including shrubs (NPP = net primary production). "Class" refers to vegetation class. Efolded refers to a smoothing algorithm described in *Daly et al*. 2000.

2008]. The module includes a set of mechanistic fire behavior and effects functions [*Rothermel*, 1972; *Peterson and Ryan*, 1986; *van Wagner,* 1993] embedded in a structure that enables two-way interactions with the biogeochemistry and biogeography modules. Live and dead fuel loads in 1-, 10-, 100-, and 1000-h fuel classes are estimated from the carbon pool sizes produced by the biogeochemistry module. Allometric functions relate tree carbon pool sizes to height, crown base height, and bark thickness for an average-sized tree. These are the required inputs for determining when crown fires occur (as opposed to surface fires) and for projecting fire effects on vegetation (mortality and/or consumption).

Daily moisture contents of the different fuel classes and potential fire behavior are calculated each day, based on pseudodaily data generated from monthly climate inputs. For temperature and relative humidity, a linear interpolation between monthly values is used to generate daily values. For precipitation, monthly values are divided by the number of precipitation events per month, and resulting values are randomly assigned to days within each month. The number of precipitation events is estimated with a regression function derived from weather station data archived by the National Climate Data Center [*WeatherDisc Associates*, 1995; *Lenihan et al.*, 1998]. Moisture contents of plant parts passed from the biogeochemistry module determine live fuel moisture contents. A combination of the Canadian Fine Fuel Moisture Code [*Van Wagner and Pickett*, 1985] and the National Fire Danger Rating System [*Bradshaw et al.*, 1983] is used to estimate dead fuel moisture contents.

Potential fire behavior (including rate of spread) is calculated each day, based on daily interpolated fuel loads, moisture contents, and weather. Potential fire behavior is modulated by vegetation type, which affects fuel properties and realized wind speeds (fixed values assumed to be higher for grasslands than forest). Actual fire is projected whenever the calculated rate of spread is greater than zero and user-specified thresholds are exceeded for the fine-fuel moisture code (FFMC) and the buildup index (BUI) of the Canadian fire weather index system. These two indices are inverse functions of fine-fuel and coarser-fuel moisture contents, respectively, as specified by *Van Wagner and Pickett* [1985]. Only one fire is simulated per year per cell on the first day when all thresholds are exceeded. Note that the day and year of the fire may vary from cell to cell, given the independent simulation of each cell.

1.3. INPUT DATA

The MC1 model requires inputs of soil depth, texture, and bulk density (Table 1.5). The model has been run in the past with soils data from the Digital General Soil Map of the United States developed by the National Cooperative Soil Survey (STATSGO) gridded to match the project scale of interest and generated by *Kern* [1994, 1995, 2000]. Global runs have used the Food and Agriculture Organization gridded soil maps formatted to provide the required variables for the MC1 model.

Climate inputs to the model include monthly precipitation, mean vapor pressure or dewpoint temperature, and mean daily maximum and minimum temperatures averaged over each month. The MC1 model also requires annual ambient CO_2 associated with both historical and each of the future emission scenarios. Data on 20th-century climate have historically been provided by the PRISM group at Oregon State University. Climate futures and associated annual atmospheric CO_2 concentrations have been provided by the various climate modeling teams most often through the Intergovernmental Panel for Climate Change website.

1.4. MC1 RUN PROTOCOL

The model is run in four sequential phases: equilibrium, spinup, historical, and future. During the *equilibrium* or initialization phase vegetation types and associated carbon pools are first initialized for fixed, vegetation-type-dependent fire return intervals (FRIs) using long-term average monthly climate inputs. The standard version of the static biogeography model MAPSS model [*Neilson*, 1995] is run using one year's worth of average climate (12 monthly values, usually 30-year means) iteratively (until all the soil water during the driest month of the year is used by the vegetation) to obtain a potential vegetation cover that corresponds to these average climate conditions. The MAPSS model (see chapter 4) does not simulate carbon pools (e.g., leaf biomass) but simulates

Table 1.5 Soil input to the vegetation model.

Input Level	% Sand	% Clay	% Rockiness	Bulk Density	Mineral Depth
Surface (0–50 cm)	x	x	x		
Intermediate (50–150 cm)	x	x	x		
Deep (>150 cm)	x	x	x		
Entire profile				x	x

hydrological flows to come up with an LAI value driving an evapotranspiration term that uses all the water available in the soil profile during the driest of the 12 months. Once that vegetation map has been obtained, a crosswalk table between MAPSS vegetation classes and MC1 vegetation types is used to initialize the vegetation cover [*Bachelet et al.*, 2001b, Table 1] and pass the information to the MC1 biogeochemistry module. This module, based on CENTURY, is called to initialize the carbon pools that correspond to this potential vegetation cover using the same average monthly climate (12 monthly values). It is an iterative process until the most resistant soil carbon pool changes by less than 1% between 2 consecutive years. The code stops the run when that threshold is attained. Note that the number of years that each grid cell is run before reaching the threshold is independent of other cells, and that number varies greatly (e.g., 50−100 years for grasslands, ≤3000 years for Pacific Northwest forests). During the equilibrium phase, and only during this first phase, fire is prescribed for each vegetation type using the CENTURY model scheduling process. Because the climate drivers do not provide any year-to-year variability (only 12 months of average climate), woody vegetation could, after several iterations, invade what have historically been grass-dominated areas. Such a phenomenon does not occur with the CENTURY standalone version because it only prescribes grass growth (with a prescribed frequent fire return interval) where grasslands currently exist. However, in MC1, CENTURY has been modified to use its "savanna" mode in every grid cell, always allowing woody lifeforms to compete with grasses. The MAPSS model also prescribes fire frequency for each of its vegetation classes to preserve grass dominance in areas where it is maintained by natural climate variability (see Chapter 4).

During the *spinup phase* a climate time series is used iteratively to allow for adjustments of vegetation type and carbon pools in response to dynamic fire. Fire affects the size of the carbon pools (reducing live pools and increasing dead pools) that are used in the biogeography model (Table 1.3) to determine the vegetation class. For example, it allows forests to transition to open woodlands and to grow back (or not, if grasses can provide enough fine fuel to promote frequent fires) through a "pseudosuccessional" process. To allow these dynamics to run their course, the MC1 code is run iteratively using ~100 years of climate data (monthly time series) corresponding to detrended historical climate (from 1895 to 2009, not averaged) between 5 and 15 times. The model uses its own set of biogeography rules (Table 1.3) during this phase, independent of, though derived from, the standard MAPSS rules. The dynamic fire model is turned on (standard MC1 run) during this spinup phase, and a dynamic equilibrium occurs after several hundreds of years. Unlike in the equilibrium phase, there is no set criterion in the code to make the spinup period stop in each cell. All the grid cells are run for the same number of years until the net ecosystem production/net biome production (NEP/NBP) trace becomes stable (NBP oscillating near zero).

The *historical phase* is then run using historical climate data from 1895 until current, followed by the *future phase* until 2100, using downscaled future climate data from GCMs. In past projects, GCM climate fields have been downscaled to the scale grid relevant to the project objectives using the delta, or perturbation, method [*Fowler et al.*, 2007]. Further details on this method are given by *Rogers et al.* [2011]. In general, any downscaling method that can provide futures for climate variables needed to run the model can be used by MC1 modelers. The MC1 model is scale-independent but does not include the fine scale processes and species information that become critical at the local scale.

1.5. THE FIRE FORECAST MODEL

During the 1990s, the number of fires in the western US increased and firefighting costs exponentially increased [*Calkin et al.*, 2005]. Agencies concerned with rising fire danger and costs decided to fund fire research to prepare and forecast future risk through the Joint Fire Science Program. In 2004, Drs. Neilson and Lenihan (USFS) received funding from the National Fire Plan (NFP) to apply the MC1 dynamic global vegetation model to the problem of seasonal-length fire forecasting for the conterminous US with a forecast range of 7 months, updated each month with new climate observations. An MC1 fire forecasting system [*Conklin et al.*, 2015] was designed in which observed monthly climate data were interpolated by the PRISM model [*Daly et al.*, 2000] to a relatively fine resolution (initially 50-km but later 4-km resolution) modeling grid. With funding from NFP, these observed monthly data grids were continuously updated to incorporate newly available observations. Future climate forecasts were available through cooperation with the International Research Institute for Climate Prediction of Columbia University and Lamont-Doherty, which provided monthly updates of 7-month future climate forecasts from up to five different general circulation models (GCMs) of the global atmosphere. These GCMs came from the University of Maryland (COLA), the University of Hamburg (ECHAM4.5), the National Weather Service's Climate Prediction Center (NCEP), NASA's Goddard Institute of Space Studies (NSIPP), and the Scripps Oceanographic Institute (ECPC). These relatively coarse-scaled forecast data were downscaled to the finer-scale modeling grid using a statistical anomaly or delta downscaling approach and a 30-year observed climatology.

MC1 was run with the climatic data up to the last observed month. The results were then used to initiate MC1 runs for the 7-month period of each of the available weather forecasts. Consensus forecasts for fire-related variables were constructed from the combined results of individual forecast runs. Specific products included in a dedicated data basin gallery (http://bit.ly/1AeMCuj) include the following:

1. *Fire potential*: an overall estimate of fire risk as defined by the National Interagency Coordination Center (http://www.predictiveservices.nifc.gov/outlooks/outlooks.htm).
2. *Standardized Precipitation Index* (SPI): probability index that considers only precipitation, while Palmer's indices are water balance indices that consider water supply (precipitation), demand (evapotranspiration), and loss (runoff).
3. *Palmer Drought Severity Index* (PDSI): measurement of dryness based on recent precipitation and temperature [*Palmer*, 1965].
4. *1000-hour fuel moisture*: moisture content of organic fuels (of 3–8 in. diameter), expressed as a percentage of the oven dry weight of the sample, that is controlled entirely by exposure to environmental conditions.
5. *Energy release component G* (ERC-G): National Fire Danger Rating System index related to how hot a fire could burn. It is directly related to the 24-h, potentially worst-case, total available energy (BTUs) per unit area (in square feet) within the flaming front at the head of a fire. The National Fuel Model G corresponds to dense conifer forests.

Most of the results (including PDSI maps) have been posted on databasin.org and are publically available (http://bit.ly/1yHHq32).

At the beginning of each fire season, the MC1 fire forecasts were presented to fire managers from all nine western Geographic Area Coordination Centers (GACCs) attending the Western National Seasonal Assessment Workshop (NSAW) sponsored by the Predictive Services Group of the National Interagency Coordination Center (NICC), and were routinely incorporated into NICC's seasonal weather/climate/fuels outlooks for the western GACCs. Over 160 land managers from various resource agencies were alerted each month to new fire forecasts posted on the MAPSS website via an email list. Funding for this effort was terminated and Dr Lenihan retired in 2010.

1.6. THE NEXT GENERATION; MC2, C++ IMPLEMENTATION

In the summer of 2012, Dr. D. Conklin (Common Futures) translated the MC1 biogeography and fire submodel code, originally written in C language, into C++, producing more efficient code while retaining the algorithms used in MC1. The resulting code (now referenced as MC2) is also available on the repository for Biological and Ecological Engineering Department at Oregon State University along with a technical documentation: https://envision.bee.oregonstate.edu/svn/MC2/.

A number of major changes were made in the transition from MC1 to MC2: (1) reimplementation of the code previously implemented in the C programming language (e.g., I/O, run control, biogeography, and fire modules) in the C++ language in order to make the code easier to modify; (2) improvement of performance in both I/O and in computation performance by code restructuring; and (3) a new option for the code to run by either completely running each cell in order (cell first) or each cell for each timestep (time first). While the code underwent significant changes, the underlying algorithms remained essentially the same as those in MC1.

The MC2 model is now being used in various projects by various teams, and improvements are regularly added to the code. A list of published documents using MC1 results has been compiled as a working document and is made available in Appendix 1 as a resource for future and current users.

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