FVSBGC: A Dual Resolution Hybrid Model with Physiological and Biometrical Growth Engines

Kelsey S. Milner
Dean W. Coble
Eric L. Smith
Drew J. McMahan

Abstract—This paper describes the physiological model, Stand-BGC, and how it was linked to the Forest Vegetation Simulator (FVS) base code as a system extension. Using a set of Stand-BGC keywords, a user can invoke the extension in an FVS simulation and grow a stand using the physiological growth engine. A daily climate file and information on soil depth and texture must be provided. Understory vegetation can be input via keywords or by running the Cover extension. When the Stand-BGC extension is running, all vegetation is grown so that grass and shrubs directly impact tree growth. Regardless of the growth engine selected, standard FVS formatted output is produced. The Stand-BGC extension also generates various reports containing elements of the water and carbon balance calculations at tree and stand levels at daily and yearly time intervals. The Stand-BGC extension may be roughly calibrated to FVS through user-controlled multipliers on annual precipitation and canopy photosynthesis. After calibrating Stand-BGC so that predicted top height after 30 years matched that from FVS, the two growth engines produced similar tree and stand attributes. The daily and yearly tree and stand level physiological variables produced should be useful in describing ecosystem function and for driving other models requiring higher resolution and climate sensitive inputs. Results suggest that more sophisticated communication between the two types of models is possible.

Ecosystem management, by definition, requires information on ecosystem processes. Generally, the current suite of mensurational models in common use by forest management organizations are not constructed to provide such information. Models such as the Forest Vegetation Simulator (FVS) simulate tree and stand dynamics through statistical correlation of the results of underlying processes that operate at higher temporal and spatial resolutions. These underlying processes are driven by factors not relevant at the resolution of such a biometrical model. Thus, our forest management models are insensitive to climate and other site variables at the resolutions needed to assess ecosystem functions.

In the past decade or so, physiological models, such as Stand-BGC (Milner and Coble 1995), have been developed that explicitly represent some of these underlying ecosystem processes at the higher resolutions needed. There is, of course, still plenty of empiricism; it just exists at a higher level of resolution in the hierarchical system. However, with this higher resolution comes the increased difficulty of simulating reliable system behavior at the resolutions useful to forest management. The underlying processes modeled are still approximations, and the complex linkages within and between scales are not well understood. For many forest management needs, it is perhaps a truism that a physiological model will never be able to achieve the prediction accuracy of a well-defined, biometrical model fit to adequate data. Moreover, physiological models are generally designed neither to process the kinds of data collected in forest inventories nor to simulate the activities that need to be analyzed in forest management.

The challenge then is to combine the two types of models into one system that contains the strengths of both types of models. The work described in this paper is an attempt to achieve such a linkage between FVS and Stand-BGC.

Stand-BGC Description

Stand-BGC (Milner and Coble 1995) is an individual entity, distance independent, version of the whole stand physiological model, Forest-BGC (Running and Coughlan 1988). The term "entity" is used because grasses and shrubs are input and grown, as whole stand entities, right along with individual tree entities. As with Forest-BGC, Stand-BGC is a climate-driven, carbon and water balance model that operates at a daily resolution for basic production processes and at an annual resolution for carbon allocation. Unlike Forest-BGC, Stand-BGC scales the "big leaf" level physiology to individual entity subcanopies rather than to the whole stand. Combined with stand structural information, the resulting interacting subcanopies provide the mechanism for competition for site resources among entities. Details of the basic physiological modeling are contained in papers by Running and Gower (1991) and Running and Hunt (1993) and will not be repeated here.

Like FVS, Stand-BGC was designed to process tree lists from standard forest inventories. In addition to standard tree measurements such as height, diameter, and crown ratio, cover and canopy depth of understory vegetation, by lifeform or species, should be provided. A daily climate file
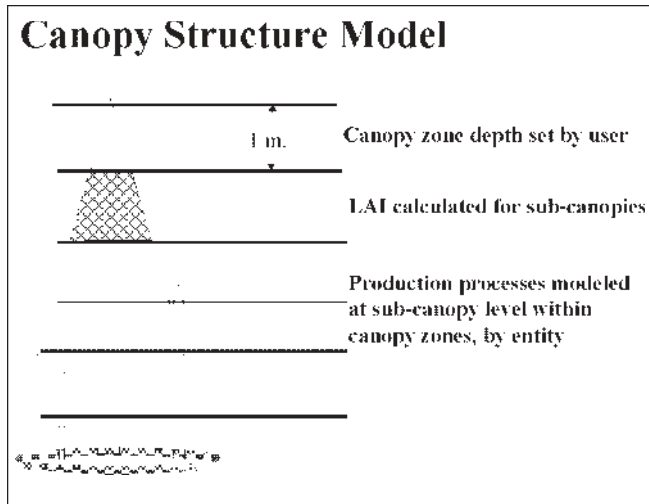
Canopy Structure Model

1 m.   Canopy zone depth set by user

LAI calculated for sub-canopies

Production processes modeled at sub-canopy level within canopy zones, by entity

Figure 1—Schematic showing how stand canopy structure is abstracted. Individual tree crowns are right circular cones. Crowns for per hectare grass and shrub entities are cylinders. Foliar biomass is assumed to be uniformly distributed in the crown volume.
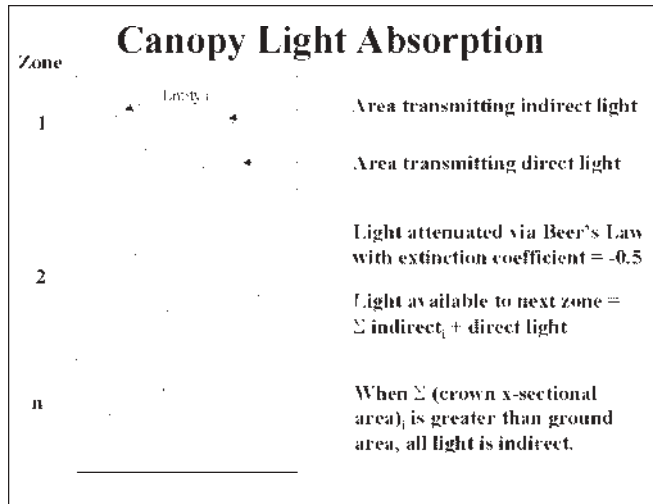
Canopy Light Absorption

Zone	
1	Area transmitting indirect light
	Area transmitting direct light
2	Light attenuated via Beer's Law with extinction coefficient = -0.5
	Light available to next zone = Σ indirect$_i$ + direct light
n	When Σ (crown x-sectional area)$_i$ is greater than ground area, all light is indirect.

Figure 2—The light absorption model in Stand-BGC. A Beer's Law calculation provides the solar radiation that drives photosynthesis and transpiration at the subcanopy level.

containing maximum and minimum temperatures, relative humidity, solar insolation, and atmospheric transmissivity must be supplied. Soil depth and texture must also be supplied. A default set of physiological parameters is provided that may be altered by the user.

Stand dynamics result from competition for site resources (light and water) among entities. The differential access to these resources arises from how water and light are modeled and from assumptions as to how different lifeforms acquire each resource. Based on the input vegetation list, foliar biomass equations, and assumptions about the geometry of entity crowns, leaf area index for any subcanopy of an entity can be calculated. The vertical position of any subcanopy, relative to those of its neighbors is also known (fig. 1). Either a fixed distance (user defined), or one defined by entity tops and crown bases, is used to define the subcanopy layers through which light will pass. Individual entities then absorb light according to a subcanopy's LAI based on a Beer's Law formulation (fig. 2). The presence and amount of leaf area in canopy zones above a particular entity directly affect its access to the light resource. Thus, there is shading within and between canopies.

Entities access water according to their rooting depth and the size of their "water bucket" (fig. 3). The latter is proportional to the amount of leaf area an entity supports. Precipitation events provide water to the topsoil layer first. If and when the top layer's water holding capacity is exceeded, water moves to the lower soil layer. If both layers are filled, the excess leaves the site as overland flow. Entity subcanopies transpire from bottom to top, sequentially removing water from the entity's water bucket. Small trees and understory vegetation are limited to the top soil layer of their water buckets, while large trees tap water in either layer according to which has the least negative water potential. At the end of each day, a site water balance is calculated for each soil

layer, and all water buckets equilibrate to the site water potential. Thus, large trees dominate the site water balance. Small trees compete with understory vegetation for water in the top layer until they become "large," at which time they access water in the lower soil layer. Competition intensifies when droughty conditions exist. Different "leaf-on" and "leaf-off" dates, transpiration rate parameters, and stomatal conductance parameters also influence realized competition.

- Soil water for each entity proportional to LA
- Small trees and grass/brush access top soil layer only.
- Large trees (>4.5') access whichever layer has highest water potential (-Mpa).
- Daily transpiration for each entity proceeds layer by layer from lowest canopy layer to top.
- Water is depleted after each layer transpires.
- All water buckets equilibrate to site water potential at start of day.
- "Tipping bucket" approach used in adding water to soil layers.

Soil Water Model

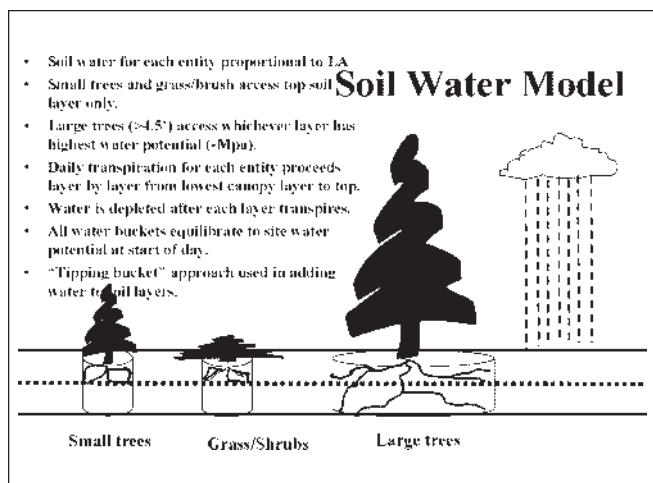Small trees   Grass/Shrubs   Large trees

Figure 3—The water access model in Stand-BGC. Large trees (greater than 2 m in height) can access water in either soil layer. Small trees and herbaceous vegetation are restricted to water in the top layer.

At the end of each year, a carbon balance is calculated for each entity, and carbon in excess of respiration and turnover is allocated to leaf, stem (including branches), and roots using the approach described by Running and Gower (1995). Leaves and roots receive their allocation first, based on accumulated moisture stress during the year and some constraining allometric ratios. Whatever is left over is allocated to stems. In dry years, more carbon is allocated to roots and less to leaves.

Following carbon allocation, entity dimensions are updated. For trees this means converting the stem carbon allocation to diameter and height growth. After converting carbon mass increment to wood volume increment, a volume equation and a height/diameter equation are used to change height and diameter (fig. 4). For understory entities, percent canopy cover and canopy depth are updated by inverting the appropriate biomass equations. When site resources are plentiful, entities have carbon in excess of turnover and maintenance respiration costs and growth occurs. When total stand leaf area approaches site capacity (hydrologic equilibrium), competition for resources intensifies. Those entities of lesser social status cannot access sufficient resources to balance turnover and respiration, and their leaf area declines. Mortality ultimately occurs when leaf area goes to zero. Currently, an entity dies and is removed from the projection when respiration costs exceed net canopy photosynthesis for more than 3 years successive.

Output from Stand-BGC currently includes an updated entity list annually along with attributes of the carbon and water balance calculations at entity and stand levels at daily and annual intervals.

Model Linkage

We linked Stand-BGC to FVS as a system extension to the base FVS code (Milner and others 2002; McMahan and others 2002). Thus, all variants can access the Stand-BGC extension. Users invoke and control the extension through a set of FVS keywords. The linkage is illustrated in figure 5. When a user invokes Stand-BGC as part of an FVS run, FVS initializes Stand-BGC with its tree list at the start of the projection. Each model then grows the tree list forward independently: FVS at about 10-year growth steps, Stand-BGC at daily and yearly time steps. Stand-BGC increments are aggregated to the cycle length specified for the FVS projection. At each FVS cycle boundary, the models can exchange growth increments, mortality, and change in crown ratio. If the user has specified, via keyword, that FVS should use the Stand-BGC increments, the FVS tree list is updated with these increments. Otherwise the tree list is updated with FVS increments. Any scheduled FVS management activities are implemented and the updated tree list, which also contains any new trees from the FVS Regeneration Model, is passed from FVS to Stand-BGC. Each model generates its standard suite of reports and the next cycle begins.

If the user has specified that Stand-BGC increments are to be used in FVS, only the new trees from FVS are processed into the carbon pools needed by Stand-BGC. The end of cycle carbon pools for the trees remaining after any thinnings in FVS are already present in Stand-BGC. Thus, the Stand-
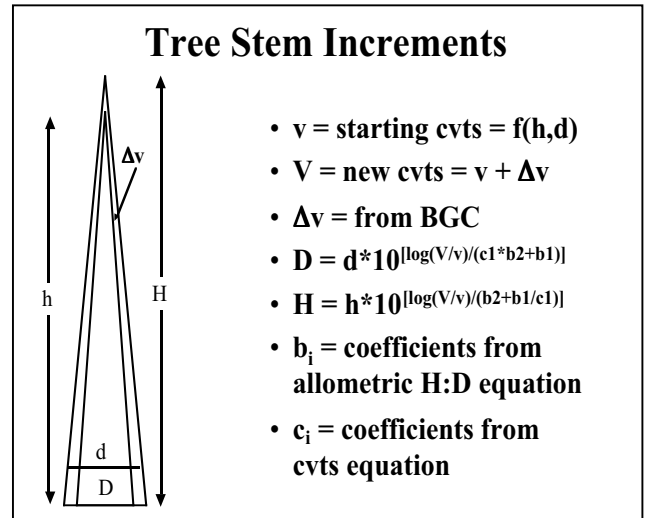

Tree Stem Increments

- v = starting cvts = $f(h,d)$
- V = new cvts = $v + \Delta v$
- Δv = from BGC
- $D = d*10^{[\log(V/v)/(c1*b2+b1)]}$
- $H = h*10^{[\log(V/v)/(b2+b1/c1)]}$
- b_i = coefficients from allometric H:D equation
- c_i = coefficients from cvts equation

Figure 4—Procedure for updating tree height and diameter from the volume increment predicted by Stand-BGC.

BGC output is identical to that from a stand-alone Stand-BGC projection of the initial tree list. The standard FVS reports show stand dynamics and growth and yield information as usual; the trees have just been grown using the climate-driven physiological growth engine.

If the user decides to use the FVS increments, the FVS output is unaffected by Stand-BGC. Stand-BGC is completely reinitialized at the start of each FVS cycle, and the
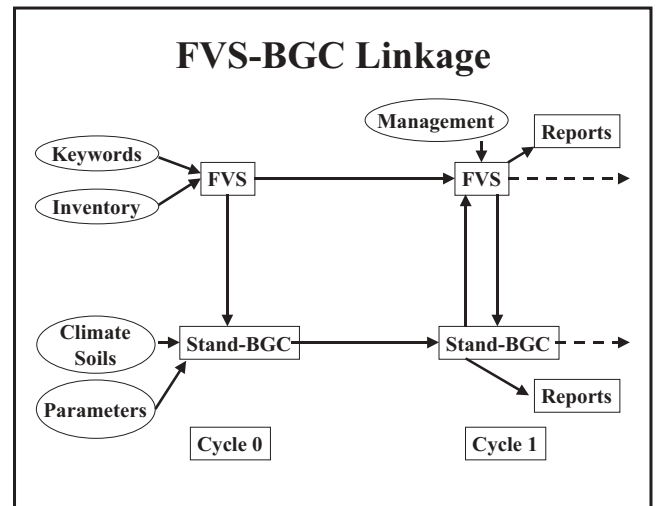

Figure 5—Schematic of the linkage between Stand-BGC and FVS. FVS initializes Stand-BGC at the start of a simulation and at FVS cycle boundaries. The user may choose to have growth and mortality predicted by FVS or Stand-BGC.

end-of-cycle Stand-BGC output just provides a suite of physiological variables for that FVS cycle.

An Example

An FVS tree list was prepared from plot data in an even-aged lodgepole pine stand in western Montana. The stand had the following characteristics:

— QMD = 7.4 inches
— TPA = 302
— BA/acre = 90 square feet
— Top height = 45 feet
— Slope = 15 percent, aspect = NE, elevation = 3800 feet
— Habitat type = PSME/PHMA
— Grass cover = 30 percent
— Soil was a sandy loam, 1 meter deep

A 30-year climate file was prepared from a nearby valley bottom weather station and extrapolated to the site using the MT-CLIM climate model (Nemani 1988). The stand was projected forward for 30 years with and without the Stand-BGC growth increments and mortality so the two models could be compared. All Stand-BGC parameters were the defaults. The model was calibrated to FVS by setting a multiplier on net canopy photosynthesis so that top height from Stand-BGC matched that from FVS after 30 years. For these runs, the multiplier reduced photosynthesis by 10 percent. The Stand-BGC keywords for the simulation were as follows:

Keyword	Explanation
BGCIN	Signals the start of Stand-BGC keywords and invokes the Stand-BGC growth engine. Matched with an END keyword.
BGCGROW	Indicates that Stand-BGC increments are to replace FVS increments when growing trees.
VEGOPT 2	The keyword signals how understory vegetation is to be entered. A '1' means output from the COVER extension will be used. A '2' means vegetation data will be entered in a supplemental record.
UNDERVEG	Signals the start of vegetation data.
G gr 1.0 30	G = grass life form, gr = species label, 1.0 = grass canopy depth, 30 = percent cover of grass.
ENDENT	Signals the end of vegetation data.
END	Signals the end of Stand-BGC keywords.

The summary yield tables from FVS, with and without the Stand-BGC increments, for the 30-year projection of the unthinned stand, are quite similar (table 1). The most noticeable difference is in the amount and pattern of predicted mortality. FVS killed a few more trees, with the mortality occurring in a gradual pattern; Stand-BGC killed fewer trees but all in the same period.

A variety of physiological variables are produced by Stand-BGC so that a user can view the underlying processes. For example, tables 2 and 3 show annual estimates of photosynthesis, respiration, and transpiration at stand and entity levels, respectively. Other tables (not shown) are produced that give these variables at daily resolutions, show light absorption by canopy layer, provide details of the daily stand and tree level water balance calculations, give estimates of mortality, and show updated entity lists.

Discussion

Assuming that FVS provided a reliable forecast over the 30-year period, the fact that Stand-BGC can, with minimal calibration, produce similar results, suggests that the underlying physiological processes may be reliably modeled as

Table 1—Summary statistics from FVSBGC using FVS vs. Stand-BGC growth increments.

Summary statistics when using FVS Increments					
Year	TPA	BA/ac	QMD	Top Ht	CVTS/ac
1984	302	90	7.4	45	1853
1994	285	111	8.5	50	2517
2004	269	132	9.5	57	3272
2014	251	148	10.4	61	3977
Summary statistics when using Stand-BGC Increment					
Year	TPA	BA/ac	QMD	Top Ht	CVTS/ac
1984	302	90	7.4	45	1853
1994	302	119	8.5	52	2807
2004	302	135	9.1	56	3437
2014	267	145	10	61	4051

Table 2—Annual stand level processes from Stand-BGC

Annual stand-level output from Stand-BGC								
FVS Cycle	Year	Psn (KgC/ha)	Trans (m3/ha)	Mresp (KgC/ha)	Gresp (KgC/ha)	Grass LAI	Tree LAI	Total LAI	Stem C (tC/ha)
1	0	0	0	0	0	0.21	6.9	7.1	42.9
1	1	11843	1882	2997	3358	0.19	6.7	6.9	45.0
1	2	11604	1997	3063	3217	0.17	6.8	6.9	48.2
1	3	8318	1378	3055	2325	0.16	6.1	6.2	50.0
1	4	9831	1482	2921	2783	0.14	6.6	6.8	51.6
1	5	10820	1806	2788	3013	0.13	7.1	7.2	53.9
1	6	9088	1463	2780	2486	0.14	6.8	6.9	56.0
1	7	14271	2551	2978	4076	0.17	8.5	8.6	58.9
1	8	10876	1575	3411	3024	0.15	7.8	8.0	61.7
1	9	12628	1745	3454	3553	0.13	8.4	8.6	64.2
1	10	16429	2558	3219	4768	0.13	9.7	9.9	68.5

Table 3—Annual entity level processes from Stand-BGC

Annual Entity level output from Stand-BGC											
FVS Cycle	Year	Entity	SP	Psn (KgC)	Transp (m3)	Mresp (KgC)	Gresp (KgC)	Leaf (KgC)	Stem (KgC)	Root (KgC)	Turnover (KgC)
1	0	1	Lpp	0.0	0.0	0.0	0.0	3.0	43.6	3.0	0.0
1	0	2	Lpp	0.0	0.0	0.0	0.0	1.7	23.2	1.7	0.0
1	0	3	Lpp	0.0	0.0	0.0	0.0	5.2	95.4	5.2	0.0
1	0	53	gr	0.0	0.0	0.0	0.0	85.3	0.0	85.3	0.0
1	1	1	Lpp	12.5	1.8	3.0	3.5	2.9	45.8	3.5	3.3
1	1	2	Lpp	6.9	0.9	1.9	1.9	1.6	24.4	1.9	1.8
1	1	3	Lpp	21.8	3.0	5.1	6.2	5.1	99.2	6.2	5.8
1	1	53	gr	163.9	95.0	315.8	0.0	76.7	0.0	42.6	51.2
1	10	1	Lpp	16.5	2.3	3.5	4.7	4.0	68.3	2.9	3.3
1	10	2	Lpp	6.9	0.8	2.0	1.9	1.7	33.2	1.2	1.4
1	10	3	Lpp	29.0	3.8	5.8	8.4	7.2	139.7	5.2	5.9
1	10	53	gr	94.1	39.7	45.0	28.1	53.6	0.0	11.3	17.2

well. While significant work is needed to establish this reliability for the Stand-BGC model, the possibilities are clear. Such a linked model can provide a means for analyzing impacts of climatic variation on forest growth and yield, provide variables at resolutions perhaps more suitable for driving pest models, and provide insights into the mechanisms of stand responses to thinning treatments.

The way in which FVS and Stand-BGC were linked in this study is quite simple; tree lists and predicted increments are merely passed back and forth. A more exciting approach would be to have each of the two models contribute to one combined forecast. The complete suite of state variables for each model is available to the other at FVS cycle boundaries. Thus, one can envision communication between models ranging from creating weighted averages of some predicted states (such as basal area increment) to alteration of underlying model parameters. For example, the strong dimensional relationships in FVS could be used to calibrate or constrain carbon allocation fractions and leaf turnover rates in Stand-BGC. Alternatively, the climate sensitive rates of photosynthesis, respiration, and water stress could be used to modify FVS mortality parameters.

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