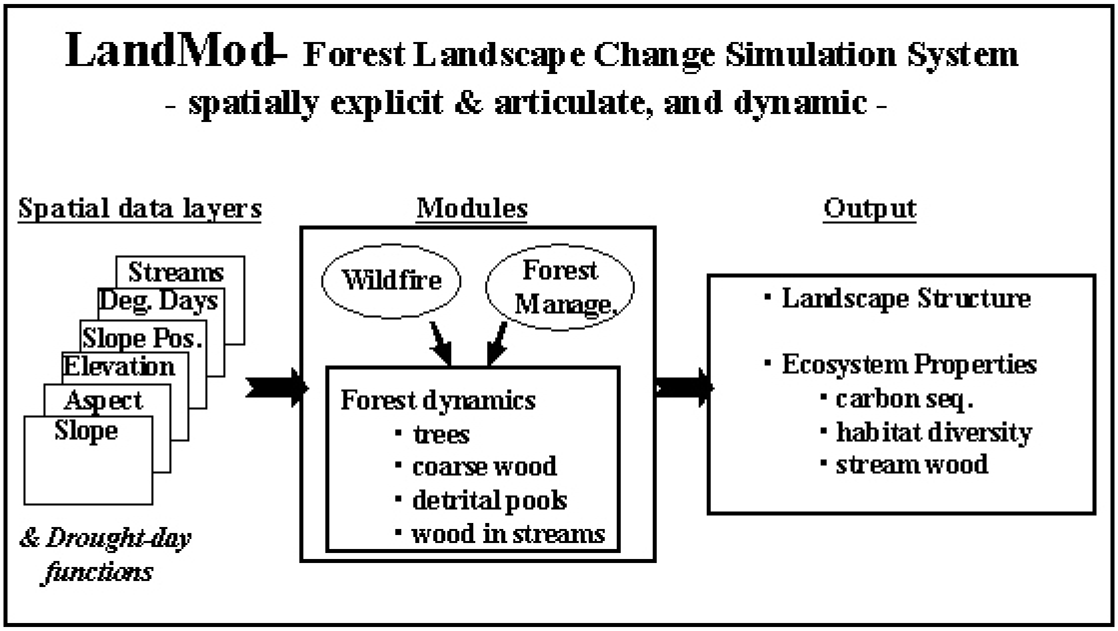
LandMod 2.0 - Documentation



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INTRODUCTION

LandMod is a grid-based forest landscape change simulator developed for western Oregon. LandMod simulates the dynamics of live trees and dead wood over large spatial extents (18,000+ ha) and temporal periods (500+ yrs) at relatively fine spatial scales ($\geq$0.04-ha) in an efficient manner. At the core of the simulator is a unique forest projection model that tracks individual tree species by 5-cm size classes on a 5-yr time step. Enveloped around this core are modules that simulate anthropogenic and natural disturbance processes. All processes are spatially integrated to accommodate dynamic feedbacks over time and space.

The intended use of LandMod is to aid in the assessment of land-management strategies and in landscape-scale research. Alternative land-use strategies can be simulated and compared in terms of timber production and landscape structure. Assumptions related to the long-term responses of key ecosystem properties (carbon sequestration, habitat diversity, wood delivery to streams) to landscape change can be investigated with modeled experiments. Like most landscape simulators, LandMod is best used to explore the relative differences among land-use strategies, and as a heuristic tool for pattern-process research studies.

Numerous forest landscape change simulators have been developed over the past decade (q.v., Mladenoff and Baker, 1999). LandMod differs from other landscape simulators with the integration of three important features: 1) The forest dynamics module of LandMod is based on a forest gap model and thus, has the ability to model trees of any size over long-time frames (500+ yrs). Forest projections are not constrained to previously measured trends as is the case in simulators that rely on empirical growth and yield models. The vital-attributes basis of LandMod's forest projection model, however, trades prediction accuracy for the ability to simulate novel stand conditions over long-time frames. 2) LandMod is designed to operate at a relatively fine spatial scale over a large spatial extent. This fine-scale approach allows reasonable predictions at scales of proposed regional, forest management options (e.g., 0.25-ha leave islands), of relevant natural disturbance processes (e.g., wildfire effects), and of processes influencing key ecosystem properties (e.g., tree fall into streams). Additionally, higher-order processes (e.g., wildfire spread, seed dispersal) are directly integrated in the simulation of fine-scale processes. 3) LandMod simulates processes dynamically. Landscape trajectories are not based on look-up tables or pre-conceived pathways, but instead develop in response to feedbacks among climatic conditions, landscape pattern, and disturbances. The dynamic structure of LandMod provides more realistic projections and greater opportunity to explore pattern-process interactions than approaches using static, pre-determined pathways.

This document describes the salient features of the LandMod system, version 2.0. Version 2.0 is the first fully integrated version of LandMod (Fig. 1), and includes enhancements to rectify deficiencies uncovered in version 1.0 (Garman, accepted). An overview of the system is presented first, followed by descriptions of the underlying spatial structure, of the three primary modules (forest dynamics, disturbance, forest management), and of system inputs and outputs. Additionally, a summary of performance assessments and an overview of computer-hardware requirements and processing speed are provided. Equations, parameter values, and data sources are documented in the appendices.

SYSTEM OVERVIEW

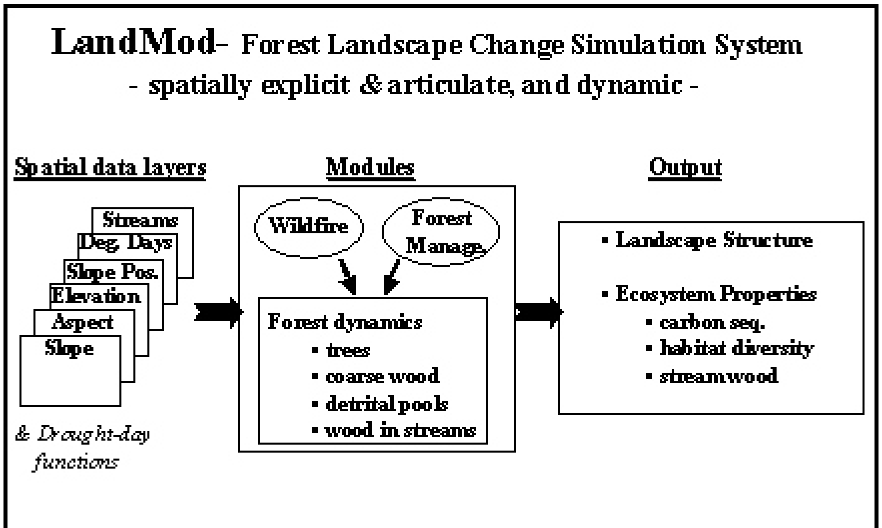


Fig. 1. Conceptual overview of the LandMod system.

LandMod is a spatially-explicit simulator comprised of three integrated modules - forest dynamics, natural disturbance (wildfire), and forest management (Fig. 1). Processes are modeled at the level of the primary landscape element (i.e., the cell), but also incorporate the influence of the spatial neighborhood. Thus, LandMod is both spatially explicit and articulate. Because most processes include a random component, LandMod is considered a stochastic simulator. Simulation applications thus require replication to derive an average trajectory of landscape change. Spatial information used by the three modules are supplied in the form of spatially-registered data layers (i.e., maps). Trends in key ecosystem properties are output as summaries or derived from the standard model output (Appendix E). Components of the LandMod system (Fig. 1) are outlined below.

- Grid-based data layers are used to define landscape attributes. Most data layers define the initial, static conditions of the landscape. Static attributes are those that do not change during a simulation, such as slope, aspect, elevation, stream width, stream order. Spatial data layers also are used to define the initial forest conditions of the landscape and to indicate forest-management strategies over time. The eleven types of spatial data layers used in LandMod are described under SYSTEM I/O.

- The forest dynamics module is a meta-model variant of the PNWGap gap model. The PNWGap model is an enhanced variant of the ZELIG model (Urban, 1993). Underlying equations and algorithms of the two models are similar, but PNWGap additionally simulates dead-wood dynamics and forest-management events, and contains an option for simulating seed dispersal. The latter distinguishes PNWGap from the previous variants of ZELIG developed at Oregon State University (e.g., ZELIG.PNW (3.0)). Detailed description of the ZELIG model, and examples of ecological and forest-management applications with Pacific Northwest (PNW) variants of the gap model are provided in Garman et al. (2003), Busing and Garman (2002) (also see Appendix F). Statistical abstractions of gap-model behavior and simplified procedures of the PNWGap model form the basis of LandMod's forest dynamics module. Similar to the gap model, LandMod simulates diameter growth, resource-limited and non-resource limited mortality, and natural regeneration. Instead of simulating individual trees on an annual time step, LandMod tracks trees by 5-cm size classes at a 5-yr time step. Forest dynamics in LandMod also incorporate spatial properties of the landscape. For example, tree regeneration is influenced by the density of sexually-mature stems within a spatial neighborhood. Snag and log dynamics are modeled using simplified variants of the algorithms from the PNWGap model. In addition, LandMod simulates needle/leaf and branch detrital pools, primarily for use in the wildfire module. As part of the mortality function, LandMod also simulates wood delivery to streams due to tree fall. To enhance the realism of wood delivery, estimates of stream width are portrayed at a finer resolution that what is used to represent a forest stand. Through a spatial approximation procedure and using tree allometries, LandMod estimates the volume of a fallen tree overlapping a stream. The forest dynamics module of LandMod currently is parameterized with the eight most common tree species in the western hemlock, true-fir, and mountain hemlock zones in the west-central Oregon Cascades.

- The natural disturbance module currently is limited to wildfire. A grid-based wildfire module is used to simulate the surface spread of fire, crowning, and spotting. The fire behavior component of this module is based on similar equations and algorithms as FARSITE (Finney, 1998), but employs a variety of simplifications. Fire effects include consumption of fine fuels and coarse wood, and tree mortality, and are modeled using published equations. A windthrow module will be included in future versions.

- Forest management prescriptions are specified as coded, spatial data layers that indicate the year and type of silvicultural prescriptions. Management options include a range of thinning methods and densities, artificial regeneration, and artificial creation of snags and logs. Thinning methods include; from the top, from the bottom, and proportional. Thinning levels can be based on density, basal area, or percent canopy cover. Thinning levels between rotation harvests can be deterministic or dynamic based on specified target levels. For the latter, the user specifies a minimum and maximum Relative Density. LandMod dynamically determines and implements the thinning density required to achieve the minimum target level whenever the maximum is exceeded. Extracted merchantable volume is calculated using specified utilization standards, and is output for further processing.

- Model output includes summaries of wood volume entering streams by stream order, total extracted merchantable volume, and cell-level information used in classifying forest structure, in estimating carbon sequestration, and in estimating animal-habitat diversity with the habitat-association models developed by Garman and Cole (1999). Maps showing the cells that burned during wildfire events are output for each time step with wildfire.

STRUCTURE, DYNAMICS, AND PARAMETERIZATION

SPATIAL STRUCTURE

LandMod is a grid-based model. A simulated landscape is represented by a lattice of similarly-sized cells. The cell size of this lattice is referred to as the primary grain. Each cell has a suite of attributes that define the underlying environmental conditions as well as forest conditions. Most of the static attributes (e.g., topography) are input as spatially-registered data layers (i.e., numerically-coded maps). Initial forest types are codified in a spatial data layer and used in conjunction with tree and dead-wood lists to determine the initial stand structure and composition, and dead-wood levels on each cell. Forest conditions on a cell are updated at the end of a simulation time step. The static and dynamic information comprise what is essentially a spatially explicit database, although a formal database system is not used in LandMod. This database is accessible by all system processes.

Not all cells have to contain forests. Non-forest features, such as rock, can be included in the underlying landscape grid. For the purposes of this document, a landscape cell containing forest is referred to as a forest cell.

There is one map that can be input at a higher resolution than the primary grain. To enhance calculations of wood delivery to streams, stream width can be portrayed at any finer resolution as long as the grain size is an integer division of the primary grain.

The maximum number of landscape cells is not limited by software design. LandMod lacks hard-coded limits. Instead, LandMod uses user-provided parameters to allocate the memory required to store cellular information. The memory load can be extensive for especially large landscapes, however. For all practical purposes, the amount of physical and virtual memory of the computer used to run LandMod is what limits the number of landscape cells that can be simulated (see Hardware Requirements & Processing Speed section below).

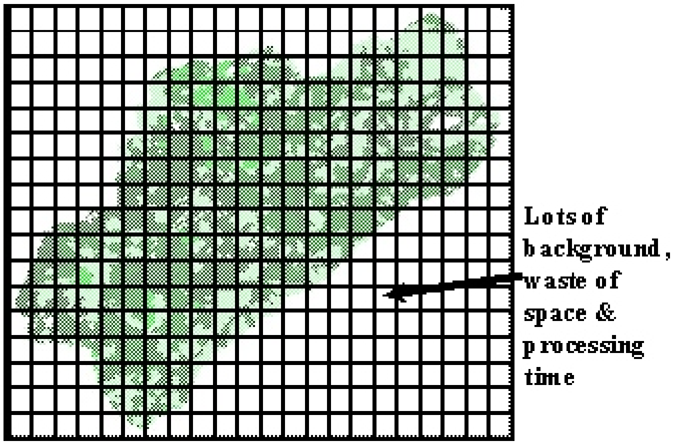
Cell size is not pre-defined, but must be $\geq$0.04-ha. This is imposed due to the design of the forest-dynamics module. There is no upper limit to cell size; however, the prediction accuracy as well as the spatial complexity of simulated forest conditions decreases with increasing cell size. Cell sizes from 0.25- to 1.0 -hectare provide the most reliable predictions.

Grid Processing Enhancements

LandMod contains two features to enhance the processing of large gridded landscapes. The first is a “boundary-fitted” grid design. This design increases processing efficiency by eliminating the background from the landscape - i.e., the portion of a landscape map that is outside the area of interest. The second feature is a virtual aggregation that selectively decreases the spatial resolution of cells.

<u>*'Boundary-Fitted Grid'*</u>. Standard grid-creation methods result in a rectangular grid large enough to encompass the entire landscape (e.g., Fig. 2A). For irregularly-shaped landscapes, this can result in numerous grid cells that are non-landscape (i.e., background). Background area can impact processing time in grid-based models. This is due to the standard procedure of looping through each row and column of an input grid and validating a cell as a landscape element before performing the specified operations. In grids with large amounts of background, the looping and validation procedures noticeably add to processing load. LandMod avoids this unnecessary processing by internally generating and using a grid that just overlaps the landscape (Fig. 2B). This grid is not a true boundary-fitted grid, but it offers many of the same advantages. For the purposes of this document, this internally fitted grid is referred to as the BFG. The BFG cells are sequentially numbered from left to right, top to bottom. The processing loop in LandMod sequentially processes BFG cells based on their newly assigned order. A down side of the BFG grid is that the implicit spatial referencing afforded by the Cartesian coordinate system of the full rectangular grid is lost. In other words, the re-coded numbers of the BFG cells indicate nothing about their spatial location. Spatial referencing, however, is essential for the numerous spatial processes in LandMod. This problem is easily rectified by recording the row and column position of each BFG cell. The BFG and associated Cartesian coordinates are automatically generated at program initiation and stored in internally allocated data structures. It is important to remember that LandMod requires input spatial data layers to be a full rectangular grid (e.g., Fig. 2A). This is because of the implicit spatial coordinate system used in LandMod.

A. Gridded map encompasses study area and background



B. Grid distributed just over the study area

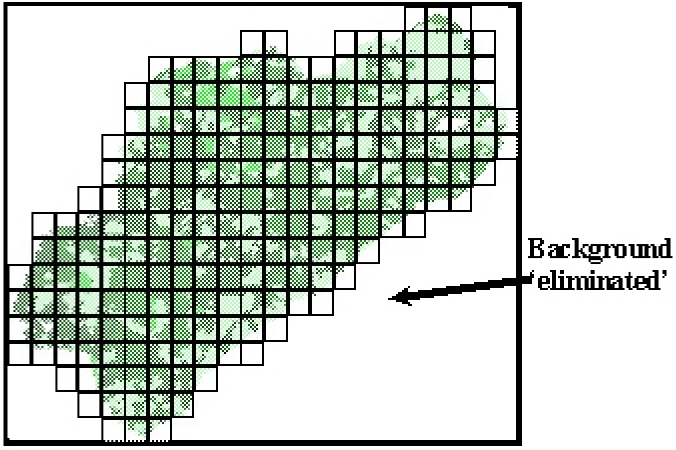


Fig. 2 Two grid-overlay methods. A) Full rectangular method. B) "Boundary-fitted" method used in LandMod.

Virtual Aggregation. This procedure reduces the spatial resolution of a landscape by aggregating adjacent cells. Using a fine-scale grid to represent forest stands on a landscape is an important feature of LandMod. However, there are instances where this level of resolution is not necessary throughout a landscape or for the entire duration of a simulation run. For instance, in applications emphasizing riparian zone dynamics, upland areas may be satisfactorily simulated with a 1-ha resolution while using a 0.25-ha grain for riparian forests. Using different resolutions for forest cells can save time, which can be critical when performing numerous simulation replications and experiments. There are a variety of methods for representing a data layer at variable resolutions. In LandMod, a structure analogous to a quad-tree structure is employed. This structure is fairly simple and efficient, but admittedly, not very flexible. This is how it works.

> A 2 x 2 cell window is sequentially overlaid (from left to right, top to bottom) on the BFG grid described above. Cells within this window are treated as an aggregate. For each aggregate, the cell in the upper left-most corner (the focal cell) is used to represent the other cells. That is, during a time step, the forest dynamics module only processes the focal cell. All other cells in an aggregate are assigned the same updated forest conditions as the focal cell after each time step. It is important to note that the underlying static information of each cell (e.g, topographic conditions) and the layout and information associated with the BFG grid are never altered. The aggregation process is essentially a virtual procedure. The windowing and aggregation steps occur automatically at program initiation. After this initial aggregation, specific cells on the landscape are re-assigned to user-specified aggregates. This re-assignment step allows the user to designate the cells that should be processed at the inherent spatial grain. A user-supplied coded data layer is used to determine aggregation levels. To return to the riparian-upslope example above, if a user wanted to impose a 1-ha grain for upland areas and to simulate every riparian cell at the primary grain size they would supply a coded spatial layer containing the same code for all upland cells and unique values for every riparian cell. If a user-generated aggregation layer is not provided, LandMod uses the automatically generated aggregates. All aggregation procedures occur during program initiation.
>
> Aggregations are maintained until disturbances affect a cell. Disturbances operate on a cell-by cell basis, not on cell aggregates. Thus, any one cell within an existing aggregate can experience a unique disturbance. When a disturbance affects a cell, the cell is disassociated from an aggregate and effectively reverts back to the original spatial grain. Aggregation of cells can not occur after the automatic and user-defined assignment steps at program initiation. The enforced dis-aggregation of cells after disturbance ensures and maintains the spatial variability resulting from disturbances.

This aggregation feature is only cost effective if cell aggregates are employed during most of a simulation. There is a certain amount of processing overhead associated with the tracking and processing of cell-aggregate memberships. This overhead is outweighed by savings in processing time when at least 50% of the possible aggregates contain at least two cells over one-half of the simulation period. Otherwise, the overhead adds to processing load and results in slower performance relative to model versions that lack the cell-aggregation code. Currently, there is no way to turn-off the aggregation feature and to circumvent the associated overhead. This is largely due to the amount of code associated with this feature and the current architecture of the computer code. A version of LandMod that lacks the virtual aggregation feature (LandMod vers. 2.0-Interim) offers more efficient processing whenever all cells are to be simulated at the primary grain. Maintaining two versions of the simulator is only a short-term solution, however. Future enhancements are required to efficiently accommodate the activation and deactivation of the cell-aggregate feature.

FOREST DYNAMICS - LIVE STEMS

Computational Structure and Dynamics

LandMod's forest dynamics module is based on statistical abstractions and other simplifications of the PNWGap model (Garman, accepted). Book keeping and dynamics are simplified in LandMod to balance computational efficiency and prediction accuracy. LandMod is made up of a stage-structured framework, statistical representation of growth and mortality, and simplified regeneration and weather calculations. The stage-structure framework is the basis for tracking stems. The frequency of stems is tracked in 5-cm diameter growth stages (hereafter referred to as size classes) separately for each species. Associated with each size class is a single value for tree height and for crown ratio. Height is derived from the mid-point diameter of a size class using species-specific height-diameter equations (Garman et al., 1995). Procedures for deriving leaf area and adjusting crown lengths are fundamentally similar to those of the gap model. Leaf area is derived from tree-diameter allometries and distributed in 1-m intervals along the crown in determining the vertical light profile on a stand; height-to-base of crown is then adjusted upward to the light compensation point of a species. LandMod derives leaf-area measures only once for each size class with stems and expands these measures to the cell level based on stem frequency.

Diameter Growth

Methods for stem transfer among size classes are designed to accommodate a wide range of tree sizes over long time periods. Previous scaling efforts with the gap model successfully parameterized a transition-matrix model for Douglas-fir (*Pseudotsuga menziesii*) forests <160-years old (see ZelStage in Urban et al., 1999). However, to simulate older forests, the matrix-model required variable size-class intervals and time steps to adequately model the transition of large boles with limited diameter growth. Also, partial-stem transfer was problematic when simulating infrequent, large stems (Urban et al., 1999). Unlike analytical applications, spatially explicit modeling of landscape pattern requires whole trees. These problems were remedied in LandMod by using a calculated and an accrued diameter increment to model growth transition at a time step of five years. For each size class, diameter increment is derived from the mid-point of a size class, crown ratio, and overall growth reduction factor. If the diameter increment is less than the size-class interval, stems remain in the size class and the diameter increment is stored as the accrued increment. In successive time steps the sum of the accrued and the computed increment determines growth transfer among size classes. The accrued diameter increment is updated each time step stems fail to transfer out of a size class. When the sum of the accrued and computed diameter increment exceeds the size-class interval, the new size class is determined, stems are transferred to the new size class, and the diameter increment in excess of the amount required to advance to the new size class is treated as the accrued increment of transferred stems. When stems enter a new size class, the crown ratio and accrued diameter increment of transferred stems are combined with values of the receiving size class by frequency-weighted averaging. The low end of size-class intervals is used to determine the receiving size class and the transferred accrued increment. When a size class is vacated, stored information is cleared.

In version 1.0, one diameter increment was calculated and applied to all stems in a size class. Also, all stems were transferred together among stages. A resulting deficiency with this approach was the lack of differentiation in diameter sizes, especially over long time periods (Garman, accepted). In version 2.0, variability is added to the calculations of diameter growth with the use of statistical variants of diameter-increment coefficients. For each stem in a size class, a set of diameter-increment coefficients is randomly selected and applied to determine growth transfer of the stem. The added variability to growth transfer and allowing stems to transfer at different rates provide more reasonable projections of especially older forest (see Performance Assessment section).

Mortality

LandMod implements the same two forms of mortality as the gap model. Stress mortality occurs due to resource limitations. A 5-year probability of stress-related mortality for each species is predicted from the mid-point of a size class, crown ratio, and overall growth reduction factor. Ambient mortality accounts for small-scale disturbances, such as bark-beetle infestations, root-rot, etc, and is based on the assumption that only 1% of stems will reach maximum age. Because ambient mortality is a totally random process, statistical representation of this mortality source is not possible. Similar to the gap model, LandMod derives the probability of ambient mortality from expected species' longevity, but scaled to a 5-year interval. In each time step, a uniform random variate is generated for each stem in a size class and compared to the maximum of the two mortality probabilities to determine if the stem dies. The application of mortality estimates on an individual stems basis ensures removal of whole stems.

Regeneration/Seed dispersal

Regeneration of saplings is based on estimates of seed production and seed dispersal, available growing space and environmental conditions on a cell, and a random selection procedure.

To avoid estimating actual seed production and the tracking of seed numbers, an index of seed production for each species is used in the dispersal and regeneration calculations. The index of seed production is derived from stem diameter and maximum diameter, and a relative, maximum seed production value. For each sexually mature stem on a cell, the ratio of stem diameter and maximum diameter times a maximum seed production value yields an index of seed production. A species-specific minimum diameter at breast height (dbh) defines sexual maturity. The index of seed production is summed across all sexually mature stems of a species to derive a total seed-production index that is used in the seed-dispersal procedures. Maximum seed production can be any integer value, but values from 0 to 20 are typically used. The maximum seed production value for a species is relative to values for other species with more prolific seed-producing species having higher maximum values. Species' maximum seed production values are typically assigned from calibration procedures.

Seeds are dispersed from each cell on the landscape using species-specific dispersal curves. Dispersal curves of a negative-exponential form are first derived from estimates of maximum dispersal. Deriving these curves requires estimates of the maximum distance reached by a small proportion of seeds. In practice, curves are estimated assuming 1% of seeds reach the maximum distance. The current version of LandMod relies on dispersal distance estimates reported in Burns and Honkala (1990). Through integration, LandMod derives an area-based dispersal curve. This final dispersal curve essentially determines the proportion of the seed-production index that is deposited in a cell as a function of the distance from the source cell. Seeds are dispersed from each cell on the landscape at the beginning of each time step. The sum of dispersed seeds (i.e., sum of the seed-production index) for each species on a cell is used in the calculation of regeneration. Details of the seed dispersal calculations are provided in Appendix C (Seed Dispersal).

The density and composition of ingrowth is determined from the available space and environmental conditions on a cell, and relativized seed-production indices. The latter is simply a species seed-production index divided by the sum of all species' seed-production indices on a cell. Available space is derived by dividing the cell area by a minimum spacing assumption of one stem per seven square-meters, then subtracting the current density and basal area of stems on the cell. This result is essentially the maximum inseeding density. To avoid tracking seedlings, LandMod assumes that 85% of seedlings die before reaching the sapling stage (i.e., attain a dbh of at least 2.54-cm). Thus, maximum ingrowth density is 15% of the maximum inseeding density. Both the seedling mortality rate and the minimum spacing constraint were calibrated to give realistic regeneration densities. The maximum number of regeneration stems by species is derived from the product of the maximum ingrowth density, and a species' relativized seed-production index and growth reduction factors. The latter is based on species tolerance to available light, temperature, and moisture conditions on a cell. The sum of species' maximum regeneration densities is the total number of stems to establish in the time step. The composition of ingrowth is determined using a random selection procedure. This procedure scales the maximum regeneration densities of species to a uniform distribution (scaled from 0 to 1), and randomly samples this distribution n number of times, where n is the number of stems to establish. Each random sample determines the species of an ingrowth stem. All ingrowth is placed in the smallest size class. Overall, the regeneration procedure heavily weights ingrowth composition by seed-source availability, but with the random selection procedure, allows infrequent species to sometime establish. The latter is essential to avoid the loss of uncommon species on a landscape.

Growth Reduction Factors

LandMod uses the same growth reduction factors as the gap model. Response curves are used to derive growth reduction factors based on species' tolerances to growing degree days, the proportion of drought days, soil-fertility (i.e., biomass production), and available light. LandMod employs averages or statistical estimates of weather attributes in deriving some of these factors. Mean annual growing degree days is generated for each cell of a landscape in a pre-processing procedure and input to LandMod as a spatial data layer. The gap model determines the proportion of drought days in a growing season from measures of solar radiation, elevation, soil conditions, stochastic estimates of precipitation and temperature, and calculated evapotranspiration. LandMod simplifies these calculations by using statistical functions to predict mean proportion of drought days from elevation and LAI for aspect classes. Because edaphic attributes influence evapotranspiration and thus the relationship between drought-days and LAI, separate equations are required for each soil type on a landscape. During a simulation, aspect and soil-type data layers are accessed to determine the appropriate drought-day equation for a cell. Similar to the gap model, LandMod derives a soil-fertility growth reduction factor whenever biomass production exceeds a maximum amount (i.e, 10 Mg ha^{-1} yr^{-1}). Available light is dynamically derived from LAI (see below).

Leaf Area Profile

LandMod derives a leaf-area profile using gap model procedures. The gap model determines leaf area from allometries, and distributes leaf area from the top of the crown to the light compensation point (i.e., base of the crown) for every stem in a stand. In LandMod, leaf area is calculated and vertically distributed in a similar manner. However, only one leaf area profile is generated for a size class because all stems in a size class have the same diameter and the same crown ratio. Leaf area measures are expanded to the cell level in LandMod by the frequency of a size class.

Available Light

The amount of available light on a cell determines growth reduction due to shading, and crown ratios of stems. The first version of LandMod assumed a light source directly above the canopy and attenuated impinging light based solely on the vertical leaf-area profile on a cell. This simplification was motivated for efficiency reasons, but tended to under-estimate available light levels and thus tree growth under complex canopies (Garman, accepted). Calculations of available light were upgraded in LandMod (V2.0). Similar to the gap model, LandMod 2.0 derives available light from estimates of direct-beam and indirect light sources. Direct-beam light is assumed to be 60% of total available light, and is based on the stature of tree crowns on cells to the south of the focal cell. The remaining proportion of available light is from indirect sources, and is based on the stature of tree crowns on cells in the four major cardinal directions. Calculations of available light on a cell are described below.

> A diagonal leaf-area profile is developed by aggregating LAI across a sequence of vertical steps starting at a specified height on the focal cell and extending across neighboring cells up to the maximum tree height. Light impinging through the diagonal profile determines amount of available light on the focal cell at the specified height. For both direct and indirect light-source calculations, the height of the vertical swath (i.e., shadow height) is equal to the tangent of the sun angle times the length of a cell. The height of the bottom and top of the vertical step (i.e., bottom and top of the shadow) increases with increasing distance from the focal cell. Specifically, the height of the bottom and top of the shadow is equal to the shadow height times the number of cells away from the focal cell. The bottom and top height of a shadow is first derived for flat ground, then adjusted by elevation difference between the focal and 'shading' cell to account for slope effects. The difference in elevation (in meters) is either added to (shading cell is lower in elevation) or subtracted from (shading cell is higher in elevation) the flat-ground values. On very steep slopes, the shadow may include ground area (i.e., bottom height is negative). The proportion of a diagonal leaf-area profile that includes ground area is recorded and used to adjust available light levels.
>
> The gap model distributes leaf area in 1-m intervals along a bole, and derives available light estimates at a corresponding 1-m resolution. The processing requirements for this level of resolution is prohibitive in LandMod. As an alternative, LandMod distributes leaf area in 5-m intervals along a bole. The lower and upper heights of a shadow are derived in terms of the 5-m intervals that are intersected. LAI of a vertical step is the sum of LAI in the 5-m intervals within the shadow height. Available light is estimated from LAI using a regressed relationship. This relationship was developed from gap-model experiments that essentially examined the relationship between available light levels and leaf area distributed in 1-m and 5-m intervals. Experiments calculated available light for 1-m height intervals using the 1-m leaf-area profiles, but also output LAI values based on a 5-m aggregation. Available light levels derived using the 1-m leaf-area profile were regressed on LAI from the 5-m leaf-area profile by:
>
> $$\ln(\text{AvailLight}) = 0.721961 - 0.296311 \ln(\text{LAI}+1), \qquad (1)$$
>
> where LAI is the leaf area index based on the 5-m aggregation, and AvailLight is the amount of available light scaled from 0.0 to 1.0. If LAI is zero, available light is set to 1.0. LandMod reduces AvailLight by the proportion of a diagonal leaf-area profile that included ground area. The 5-m leaf-area profiles are updated and stored for all cells on the landscape at the beginning of each time step.

Estimates of available light are derived for a given height. In determining the available light growth-reduction factor for a size class, the mid-point of the crown is used. To adjust the crown ratio (i.e., pruning) of a size class, available light is derived starting at the base of the crown and continues until the light compensation point of the species is exceeded. Available light is derived at ground-level to determine regeneration potential.

The diagonal leaf-area profile for direct-beam light begins on the focal cell and extends to cells directly to the south. Diffuse-sky radiation is derived by sampling the four Cardinal directions and the focal cell, and thus, is based on a sample of five leaf-area profiles. Each of the five leaf-area profiles has equal weighting, but all five samples collectively account for 40% of the total available light.

Parameterization

Diameter Growth and Mortality

Diameter growth and mortality are derived from statistical estimators developed from gap-model simulations. To generate sample data, replicated simulations are performed using a modified version of PNWGap, called MetaGap. For each tree in a simulation, MetaGap records the species, the diameter and crown ratio at the beginning of each 5-yr period, 5-yr diameter increment or cause of mortality (stress or ambient) if the stem died, and averaged available light over a 5-yr period. Additionally, stand-level averages for growing degree days, proportion of drought days, and biomass production are recorded for each 5-yr period. Averages of growth-reduction attributes (i.e., available light, growing degree-days, proportion of drought days, and soil productivity) are converted to growth-reduction factors, then to an overall growth-reduction factor for each 5-yr period for each species. MetaGap simulations are performed on a representative sample of the environmental gradient of a landscape. For each sample location, initial stand configurations are generated by varying the density of a focal tree species with all other species equally represented. Simulations are extended over a 500-yr period and replicated 30 times to sample the stochastic variation in gap-model predictions.

Predictive functions of diameter growth and mortality are based on equation forms commonly used in forest-growth models (e.g., Hann and Wang, 1990; Hann and Larsen, 1991), but use measures simulated by the gap model as independent variables. Five-yr diameter increment for each species is regressed on diameter, crown ratio, and overall growth reduction factor by:

$$Dinc = \mathbf{exp}(b_0 + b_1\mathbf{ln}(DBH + 1) + b_2 DBH^2 + b_3\mathbf{ln}(CR + 1) + b_4\mathbf{ln}(GRF + 1)), \tag{2}$$

where, GRF is the overall growth reduction factor, CR is crown ratio, DBH is diameter at breast height (cm), b_0-b_4 are species-specific regression coefficients, and Dinc is the 5-year diameter increment (cm). Dinc is set to 0 if CR or GRF = 0. LandMod derives diameter increment using the mid-point diameter of a size-class, the crown ratio of a size class, and the product of the individual growth reduction factors (i.e., available light, growing degree day, and the minimum of drought-days and soil-productivity reduction factors). Variability in diameter growth is achieved by randomly selecting a set of regression coefficients for eq. 2 and calculating growth on an individual stem basis. For each species, sets of regression coefficients are derived from the mean coefficients (e.g., Appendix A, Table A1) and the variance-covariance matrix (e.g., Appendix A, Table A2) produced in the Least-Squares estimation procedure. Each regression coefficient mean is adjusted by $\pm$ 1 and 2 standard deviations, with all other coefficients adjusted according to the underlying covariance structure. Given that there are five coefficients in eq. 2 and four alternative parameter estimates per coefficient, a total of 20 equations are possible in addition to the set of mean coefficients. For each stem in a size class, one of the 21 sets of coefficients is randomly selected and applied to determine growth transfer.

For each species, the proportion of stems succumbing to stress-related mortality in a 5-year time step is derived for diameter, crown ratio, and growth reduction intervals. The probability of stress-related mortality for each species is predicted by:

$$Smort = \frac{1}{1 + \exp(-1(b_0 + b_1 DBH + b_1 CR + b_1 GRF))}\ , \tag{3}$$

where b_0-b_3 are species-specific regression coefficients and Smort is the 5-year stress-mortality probability. Smort is set to 1 if CR or GRF =0.

Growth and mortality functions are parameterized for the eight most common tree species in western Oregon. Parameterization procedures were performed using the 18,000-ha Blue River Watershed located in the west-central Oregon Cascades, Willamette National Forest. The 500-1600 meter elevation gradient of this watershed encompasses the three major vegetative zones of the western Oregon Cascades - the western hemlock (*Tsuga heterophylla*) zone (<1100 m), the true-fir zone (1100-1500 m), and the mountain hemlock (*Tsuga mertensiana*) zone (> 1500-1550 meters). Environmental data for the watershed were derived at a 100-m resolution from a Digital Elevation Model, and from predictive models of temperature (Urban et al., 1993), precipitation (Daly et al., 1994), and solar radiation (Bonan, 1989). Due to limited information, a single soil type was assumed for the whole landscape. Cells of the watershed were characterized by combinations of slope, aspect, and elevation classes. Replicated MetaGap simulations were performed for a 10% random sample of cells in each combination using a 1-ha stand. Diameter growth and stress-mortality parameters are listed in Appendix A (Tables A1-A3). Ambient mortality is derived from maximum tree age (Appendix C - see Maximum Tree Age).

Drought-day Proportion

Statistical functions for calculating drought-day proportion also are derived from gap-model results. Data used to generate these functions are produced with another variant of PNWGap, called MetaDry. MetaDry produces samples of drought-day proportions by exercising the stochastic weather calculations over a prescribed gradient of LAI values (e.g., 0-9). Similar to the procedures for generating growth and mortality data, MetaDry simulations are replicated over a representative sample of the environmental field of a study area. To minimize the number of equations, predictive functions are derived for aspect classes. A response surface for drought-day proportions for each aspect class by soil type is derived by:

$$DrDays = b_0 + b_1 ELEV + b_2 LAI + b_3 ELEV^2 + b_4 LAI^2 + b_5 ELEV^3 + b_6 LAI^3 , \qquad (4)$$

where LAI is stand-level leaf-area index, ELEV is elevation (meters), b_0-b_6 are regression coefficients for an aspect class and specific soil type, and DrDays is the 5-year average proportion of drought days during a growing season.

Drought-day estimates in the current version of LandMod are derived from replicated MetaDry simulations over a 5% sample of the Blue River landscape (see above). Samples were equally distributed among combinations of eight aspect by six 200-m elevation classes. Because only one soil type was employed for the whole landscape (1-m deep silty-loam), only one set of drought-day functions was generated (Appendix A, Table A4).

Growth Reduction Functions

Species' growth reduction functions and the sundry of allometries used in these and other functions in LandMod are taken directly from the gap model. Equations forms and species' parameters are documented in Appendix C.

FOREST DYNAMICS - COARSE WOOD AND DETRITAL POOLS

Computational Structure, Dynamics, and Parameterization

Coarse Wood

LandMod simulates recruitment and decay of snags and logs. Coarse-wood dynamics are similar to those of the gap model, and are based on empirical measures by Graham (1982). Natural recruitment of snags and logs occurs from tree death. When a tree dies, it has a 30% chance of falling and becoming a log, otherwise it remains standing as a snag. Snags and logs are stored by decay group and decay class. Decay group is based on decay resistance and size (Table 1). Douglas-fir, incence-cedar, and western redcedar are assigned to the slow-decay group and other species are assigned to the fast decay group.

Table 1. Decay group and corresponding size classes for snags and logs.

Decay rate	Decay group	Dbh for snags, large-end diameter for logs
fast	0	<25 cm
	1	25-49 cm
	2	≥50 cm
slow	3	<40 cm
	4	40-64 cm
	5	≥65 cm

Each decay group has unique decay rates which are represented by maximum residence times in a decay class (Table 2). Deadwood pieces transfer among decay classes after exceeding the maximum residence time. Pieces are removed after the last decay class. This simplified approach does not fragment pieces. However, breakage of snags occurs for large boles as they enter decay class 2 and 3. The proportion of volume that breaks off and the number of times a snag breaks is dependent on decay group and decay class. For decay group 5, 20% of the volume breaks off in the transition from decay class 2 to 3. For decay class 3 snags, breakage volumes for decay groups 0-5 are 64, 72, 72, 69, 59, 67 percent, respectively. The volume breaking off a snag enters the log pool.

The number of decay classes differ among snags and logs and among log decay groups. Graham (1982) assigned snags to only three decay classes. These decay classes overlap the five classes more commonly used today. Transferring snag breakage to the log pool requires adjusting the decay class by 1. An exception is when a decay class 3 snag piece transfers to the log pool. The assigned log decay class is set to the maximum decay class of the decay group. Only four decay classes are used for fast-decaying logs.

To minimize computer-memory needs, LandMod stores coarse wood as cohorts. A cohort is defined as all snags or all logs of the same decay group that originate in the same time step. The number of individual pieces, the average diameter and height or length of pieces, and the total volume of pieces in a cohort are recorded. All pieces in a cohort are transferred among decay classes at the same time, and all snags in a cohort break at the same time. Decay-class bulk density coefficients (Harmon et al., 1996) are used to derive coarse-wood mass.

Table 2. Maximum decay-class residence times (yrs) for coarse wood.

Maximum residence times (yrs) for snags

	Decay Class		
Decay group	1	2	3
0	15	20	25
1	15	23	32
2	15	23	32
3	18	20	32
4	25	35	50
5	30	50	70

Maximum residence times (yrs) for logs

	Decay Class				
Decay group	1	2	3	4	5
0	5	8	6	20	
1	7	8	6	20	
2	7	8	6	20	
3	5	12	22	63	72
4	10	16	26	63	78
5	15	20	57	73	89

Detrital Pools

LandMod tracks four detrital pools. These pools are primarily used in the calculation of wildfire behavior and thus, are defined by piece size following the time-lag standards for fuel modeling. Leaf/needle litter and small branches (<0.7 cm) are treated as separate detrital pools even though they collectively constitute the 1-hr time lag fuels (hereafter 1-hr pool). The 10-hr pool is comprised of branches 0.7-2.54-cm in diameter. The 100-hr pool is comprised of branches 2.54-

7.71-cm in diameter. Leaf and needle inputs are derived from leaf area estimates and converted to mass assuming 0.0556 kg/m^2. Leaf and needle litter is decomposed using an annual decay rate of -0.5 (Edmonds, 1980). Fine-wood input is based on estimates of dead and live branch mass derived from empirical allometries (Means et al. 1994 - see biomass coefficients in Appendix C). Estimates of fine-wood mass are adjusted by the crown ratio of a stem since the empirical allometries tended to be derived from stems with high crown ratios. Fine wood is decomposed using an annual decay rate of -0.3 (Harmon et al., 1996).

Litter and fine-wood are added to the detrital pools due to turnover and when a bole dies. Turnover rates for hardwood leaves is annual and for conifer needles it is every five years (i.e., 20% of needle mass falls annually). The annual turnover rate for fine-wood is 10% (Miller and Urban, 1999). Because the branch biomass equations estimate total mass without regard to piece size, assumptions must be made regarding the fine-wood fractions of estimated branch mass (Table 3). For boles ≤30-cm in diameter, all branch mass is distributed among the detrital pools. For boles >30-cm dbh, the proportion of fine-wood mass decreases with increasing diameter. When a bole dies, all leaf, needle, and fine-wood mass enters the detrital pools. Detrital input from all sources, and decomposition are numerically integrated on an annual basis over a 5-yr time step.

Table 3. Fine-wood fractions by tree diameter.

	Fine-wood fractions by detrital pool			
dbh (cm)	1-hr	10-hr	100-hr	
≤5	0.7	0.3	0.0	
5-10	0.3	0.3	0.4	
>10-30	0.2	0.3	0.5	
>30	0.2x	0.3x	0.5x	where x = (1- dbh/400)

FOREST DYNAMICS - WOOD DELIVERY TO STREAMS

Computational Structure, Dynamics, and Parameterization

LandMod estimates wood delivery to streams due to tree fall. Transport of wood to streams due to mass movement or debris flows currently is not considered. The stream-width spatial data layer is used to indicate the location of streams as well as stream width. To enhance the realism of wood delivery, this stream layer typically has a finer grain size than the primary grain of the landscape. For instance, current applications of LandMod use a 50 x 50-meter primary grain. The stream-width layer in these applications, however, has a 5 x 5 meter grain size. When a tree dies and is selected to fall, the spatial location of the stem in the finer-resolution grid is randomly determined. Then a randomly derived fall direction (see below), stem height, stem-volume allometries, and stream width are used to determine if the stem falls into a stream, and the proportion of the stem volume that overlaps a stream (Fig. 3). Boles falling onto first-order streams likely are suspended over the stream due to contact with the opposing bank. LandMod does not evaluate for overhangs, but simply tallies the amount of bole volume overlapping stream cells. The total amount of wood delivery to streams by stream order is recorded and output each time step. Post-processing decisions can be made to exclude the wood-volume estimates of specific stream orders when reporting simulation results.

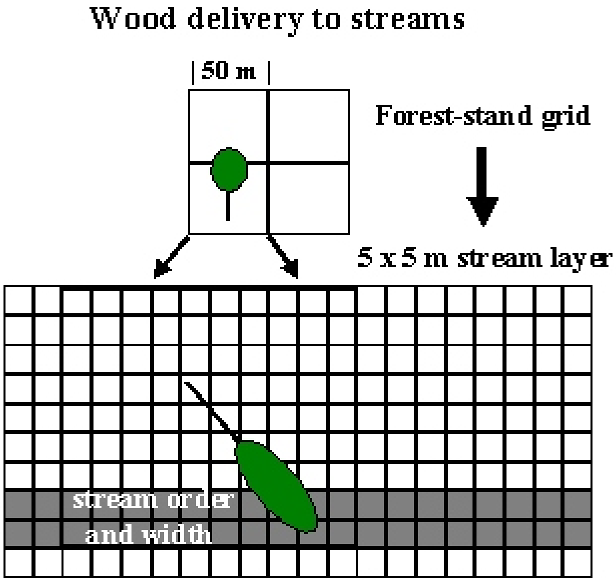


Fig. 3. Schematic of the variable resolution approach used to determine tree fall into streams.

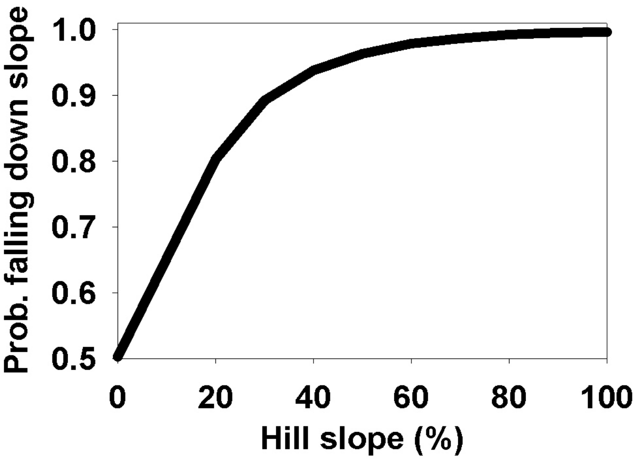


Fig. 4. Probability of a stem falling down slope vs. slope steepness (eq. 4).

The direction a tree falls is conditioned on slope steepness, and is estimated by;

$$Fd = \text{aspect} +(b_0 + (b_1 b_2 / (b_2 + \text{slope}))) 180.0 \ \text{u.r.v.}, \qquad (4)$$

where u.r.v. is a uniform random variate, slope is fractional slope and is assumed to be perpendicular to the stream, b_0 - b_2 are coefficients of a hyperbolic decay function (b_0=0.0892 b_1=0.9055, b_2=0.0981), aspect is the slope aspect (degrees), and Fd is the fall direction (degrees). Results with this function are similar to the empirical observations of down-slope tree fall reported in Minor (1997). On near-level ground, there is a 50-50 chance that a bole will fall down slope (i.e., equal probability of falling in any direction). As slope increases, the probability of a stem falling down slope increases exponentially (Fig. 4).

WILDFIRE

Computational Structure, Dynamics, and Parameterization

Wildfire is simulated in response to user-defined frequency and size parameters. Frequency (return interval) and size (percentage of the landscape) parameters can vary within the simulation period to emulate changing fire regimes. At program initiation, LandMod uses these parameters to randomly derive the number of wildfire events, and the simulation year and size of each event. Wildfire is implemented on a landscape using standard wildfire behavior and effects models, and wildfire propagation procedures. Inputs to these models are generated at different levels of detail. LandMod simulates the dynamics of fine-woody fuels. Ambient fuel moisture during a wildfire event is estimated from user-specified limits and adjusted by topographic position. Weather is not simulated explicitly in LandMod. For this reason, the randomly selected size of a wildfire event is used to terminate a spreading wildfire. There are pros and cons to this approach, but it was deemed suitable for the initial applications with LandMod.

The description of the wildfire module is divided into three sections - wildfire initiation, wildfire behavior, and wildfire effects.

Initiation of Wildfire Events

The ignition point of a wildfire is randomly determined, but constrained by trends in historical wildfires. Based on fire-history reconstruction studies in the Blue River Watershed (Weisberg, 1998), the point of ignition is weighted toward valley bottoms and low-slope positions. When a wildfire event occurs, a 1 x 1 km section of the landscape is randomly selected, and the average elevation of cells within this section is determined. A probability of ignition is generated for each cell, with cells of less-than average elevation assigned a higher probability. Additionally, cells with stems less than 40-m tall or that already burned in the current time step can not be selected as the ignition point. The height constraint assumes that lightening is the primary ignition source and that short-stature stands have an unlikely chance of being struck. Essentially, the 40-m limit prevents fires from starting in young forests (ca. <50-yrs old). This limit was imposed for an ongoing LandMod application, but may not be appropriate for other applications.

The fire frequency constraint assumes that a wildfire has a nominal chance of starting in a cell that already burned within the current time step (multiple fire events can occur within a time step). Based on the ignition probabilities, a cell is randomly selected as the origin of a wildfire.

Wildfire Behavior

LandMod uses grid-based variants of standard fire-behavior models and fire-spread methods. Surface-fire calculations are from the BEHAVE model (Andrews, 1986). Calculations for crowning and spotting were initially derived from FARSITE (Finney, 1998) and pertinent literature, but simplified for efficiency reasons. The objective of the wildfire module in LandMod is to implement wildfire on a landscape, not to make precise predictions of fire behavior and spread. The latter is best achieved with the vector-based FARSITE fire simulator. Given the simplifications of fire processes, LandMod should not be used for operational or real-time assessments of wildfire.

<u>Fire Behavior.</u> A collection of published fire-behavior equations are used to model the attributes of a fire in a cell. These equations are essentially the BEHAVE model (Andrews, 1986). Inputs to these equations include: 1) slope and aspect of a cell, 2) wind speed and direction, 3) an NFFL fuel model, and 4) moisture content of fuels and live crowns. Inputs are derived as follows:

1) Slope and aspect of a cell are derived from the spatial data base.

2) At the initiation of a wildfire event, wind speed above tree level and wind direction are randomly selected and held constant for the duration of the event. Wind speed is derived from a normal distribution with a mean and standard deviation of 32.0 and 8.1 km per hour, respectively. These values were derived to provide a reasonable range of wind speeds for wildfire simulations. The wind speed used in the calculation of fire behavior on a cell, however, is adjusted to the speed at mid-flame height (ca. 6.09 m). This adjustment is based on the topographic position of a cell. The latter is represented by a slope-position index (Hatfield, 1996), scaled from 1 (valley bottom), to 9 (mountain top) (Table 4).

Table 4. Wind-speed reduction modifier by slope-position index.

Slope-position index	Wind speed reduction modifier	Slope position index	Wind speed reduction modifier
1	0.3	6	0.6
2	0.4	7	0.65
3	0.5	8	0.65
4	0.55	9	0.7
5	0.55		

3) NFFL fuel models are stylized representation of fuel characteristics for 13 forest-fuel types (Andrews, 1986). The NFFL fuel models specify fuel characteristics such as loadings by size classes, surface-area to volume ratios, fuel-bed depth, moisture of extinction, and other factors. LandMod only tracks dead-wood fuel loadings. Other fuel characteristic are derived from the NFFL fuel model with fuel loadings most similar to those of a cell. Using modeled fuel loadings and borrowing other fuel characteristics from the standard NFFL fuel models, a unique fuel model is created for each cell for use in the fire-behavior calculations.

4) LandMod uses maximum fuel-moisture values supplied at program initiation to derive ambient moisture conditions for each fire event. Maximum values can vary by time intervals during a simulation as a means to emulate different fire regimes. A one-tailed normal distribution is used to randomly select ambient moisture levels from the maximum values. Ambient moisture values are held constant during a wildfire event, but are adjusted at the cell level to reflect site-specific conditions. Cell-level moisture values are modified based on elevation, aspect, and the proximity to streams. Fuel and crown moisture values are decreased on southerly aspects and increased on northerly aspects. Fuel and crown moisture values also increase with increasing elevation. The rate at which moisture values increase with elevation is randomly determined at the beginning of a wildfire event and held constant. Another adjustment to moisture values occurs in riparian zones. Fuel and crown moisture values for cells adjacent to streams are adjusted upward to reflect meso-scale differences in humidity between upslope and riparian areas. Moisture modifiers serve to emulate the complex variability in fuel moisture on a landscape. In practice, modifiers are calibrated to produce desired fire-severity trends.

Standard surface-fire attributes are derived whenever a cell ‘burns’. These include spread rate, flame length, fire-line intensity (FLI), crown-scorch height, lethal-heat residence time, and a sundry of other measures. Additionally, calculations of crowning and, in turn, spotting are performed after the surface-fire calculations.

Only passive crown fires are modeled in the current version of LandMod. Standard crowning algorithms use the ground-fire FLI and the height of the overstory canopy to determine passive crowning (i.e., a crown fire above the surface fire). This approach, however, ignores the potential influence of ladder fuels. In LandMod, ladder fuels influence the potential for crowning. Starting with the shortest trees on a cell, the potential for foliage ignition is assessed using the ground-fire FLI as the crown-fire FLI. If foliage ignition occurs, the crown FLI is incremented by the energy (i.e., FLI) of the ignited foliage. This adjusted crown FLI is then used in subsequent calculations of foliage ignition of taller trees. Crowning, per se, occurs whenever the overstory canopy (i.e., the upper 20% of tree heights on a cell) experiences foliage ignition. If the overstory canopy ignites, the average dbh and height of overstory stems are recorded and used in the spotting calculations. All stems experiencing foliage ignition are considered killed and are immediately transferred to either the snag or log pools (see wildfire effects).

The simulation of active crown fire is not fully implemented in Version 2.0. Active crowning is where crown fires spread among trees without the influence of a surface fire, and occurs whenever the crown FLI exceeds a critical threshold value. Active crown-fire spread may be added in future versions, depending on application needs.

Spotting occurs whenever the intensity of a crown fire is sufficient to send embers aloft. Spotting calculations in LandMod follow those outlined by (Albini, 1979), with modification. The equations for deriving flame height and duration, and the initial height of a fire brand in LandMod are greatly simplified variants of those reported in Albini. This was achieved by regressing results of the extensive calculations on independent variables similar to those used in the nomographs in Albini's publication. This simplification effectively reduces the number of tedious calculations to a handful of linear and curvilinear equations that are solved quickly, with only a nominal reduction in accuracy. Species-specific considerations for steady flame height and duration calculations are eliminated by only deriving equations for the predominant species of the western Cascades, Douglas-fir. Two additional simplifications pertain to the number of emitted fire brands and to the deposition of a fire brand. For simplicity, only a single fire brand is emitted by a crown fire in a cell. The distance a fire brand actually travels employs the maximum distance estimate derived from Albini's equation F22, but additionally involves a random component. Using the calculated maximum spotting distance, a negative-exponential distribution is generated assuming a fire brand has a 10% chance of traveling the maximum distance. A uniform random variate is selected to indicate the proportion of area under the curve of the negative-exponential distribution that is passed over by the fire brand. A numerical integration of the distribution then determines the distance traveled. The direction that a fire brand travels also is randomly determined, but constrained by wind direction. The potential direction of travel is equal to the wind direction of the fire event plus a randomly derived deviation. This deviation is normally distributed with a standard deviation of 10 degrees. The randomly selected azimuth and spotting distance determines the cell receiving the fire brand. The fire brand will start a new fire front if a forest cell is selected and if the cell has not burned in the current time step. Spotting-distance equations used in LandMod are documented in Appendix B.

Fire-spread Algorithm. Fire spreads in two ways, by spotting and by spreading across the ground. The spotting procedures are described above. Surface-fire spread is where a fire spreads from a burning cell to its neighboring cells. The processing of surface spread is regulated by an internal fire clock that is initiated at the beginning of a fire event. The fire-clock time-step is internally calculated using the primary grain and an upper spread rate of 335 m/minute. For all practical purposes, this derivation ensures that surface fires will move a maximum of 1 cell per tick of the fire clock. The logic used for modeling surface spread requires this maximum constraint. Surface spread is initiated whenever a cell is 'burned'. As indicated above, when a cell burns surface-fire metrics are derived, such as fire-line intensity and maximum spread rate and direction, and crowning and spotting are determined. Additionally, the amount of time required for the fire to travel from the center of the burning cell to the edge with each of its eight neighboring cells and the amount of time required for a fire to spread from each edge to the center of the neighboring cell are determined. Equations from the Vector subroutine of BEHAVE are used to derive spread rates among cells. The sum of the center-to-edge distances plus the respective spread rates determine the amount of time required for a surface fire to reach the center of a neighboring cell. The sum of this time and the current time on the fire clock is internally stored as the time of ignition (TOI) for a neighboring cell. When the fire-clock time equals the TOI of a cell, the cell is 'burned', and TOI values of its neighbors are, in turn, calculated and stored. A fire can not spread into cells that already burned during the 5-yr time step. Also, cells classified as non-vegetation (e.g., rock, water) can not burn. Fire spread continues among adjacent cells until the flaming front abuts against non-flammable cells or the specified maximum fire size has been achieved. To expedite processing, the minimum and maximum row and column of cells with TOI values are maintained to limit the number of cells examined in a fire-clock time step. Row and column limits are automatically adjusted to accommodate burning cells that originate from spotting.

Wildfire Effects

Simulated wildfire effects include the reduction of fuel loadings, the consumption of snags and logs, and tree mortality. Fuel loadings are reduced based on fuel moisture and the moisture of extinction of the fuel model used to burn a cell (Peterson and Ryan, 1986). Snags are eliminated based on the maximum diameter of trees experiencing crown fires. Snags smaller than the maximum diameter of crowning trees are assumed to have been consumed by fire. For simplicity, these snags are eliminated from the cell; fire-consumed snags do not enter the log or detrital pools. Flaming reduction of mean log diameter of cohorts is derived from the residence time of lethal bole heating, and assumes a diameter reduction of 2.5-cm per two minutes (Hall, 1991). In turn, diameter reduction is used to adjust the mean volume of a log cohort. The probability of tree mortality is calculated as a function of percent of crown that is damaged and the degree of cambial injury (Ryan and Reinhardt, 1988). Cambial injury is based on residence time of lethal heat and bark thickness. The calculated probability of mortality is compared to a uniform random variate to determine if a stem dies. Killed trees are processed as if they died from natural causes. For stems not killed by a fire, the height of lethal crown scorch (Van Wagner, 1973) is compared to the crown-base height. If the scorch height is greater, the crown-base height is adjusted upwards to the scorch height. This assumes an inability of the scorched portion of the crown to ever produce foliage.

FOREST MANAGEMENT OPTIONS

LandMod is designed to implement a range of forest management options at the forest-cell level. Forest management prescriptions are specified as coded, spatial data layers. These data layers contain codes indicating the year and type of silvicultural prescriptions, and are translated into procedural calls by the forest-management interpreter inside LandMod. Management options include a range of thinning methods and densities, artificial regeneration, and artificial creation of snags and logs. Thinning methods include; from the top, from the bottom, and proportional. Thinning levels can be based on density, basal area, or percent canopy cover. Thinning levels between rotation harvests can be deterministic or dynamic based on specified target levels. For the latter, the user specifies a minimum and maximum Relative Density. LandMod dynamically determines and implements the thinning density required to achieve the minimum target level whenever the maximum is exceeded. Extracted merchantable volume is calculated using specified utilization standards, and is output for further processing. All coded data layers are generated outside of LandMod using customized pre-processing programs.

Note: Although the numerous forest-management options are functional, not all can be directly handled by the interpreter at this time. This short coming is due to changes in code architecture since implementing the interpreter. Upgrading the interpreter is ongoing. In the interim, code modifications are required to access specific functions.

SYSTEM I/O

INPUTS

Spatial Data Layers

Input data includes numerous spatial data layers, tree species parameters, initial forest-stand conditions, and process-control parameters. Spatial data layers define the static or initial attributes of each landscape cell (Table 5). Spatial data layers used in a simulation must be of the same gain size, with the exception of the stream-width layer. To facilitate estimation of wood delivery to streams, the stream-width layer can have a finer spatial grain than the primary grain size. The resolution of this stream layer determines the accuracy of wood-delivery calculations, and must be an integer division of the primary grain. For instance, when using a primary grain size of 50-m, the grain of the stream-width layer is limited to 1, 2, 5, 10, or 25 meters. All spatial data layers are flat-binary files with implied row and column dimensions.

Table 5. Summary of input spatial data layers in LandMod.

Data layer	Description/units
Topographic	
aspect	degrees
elevation	meters
slope	percent (*10)
slope index	coded as 1 (valley bottom), 9 (mountain top)
Environmental facet	
degree day	growing degree-day values (based on 5.5° C minimum)
soil type	coded soil type
Vegetation	
initial cover type	coded
Stream layers	
riparian zone	indicates if a cell is within 80-m slope distance of a stream and the dominant stream order
stream size	stream width (meters)
Harvest layers	
harvest options by years	indicates timber-management options
Misc.	
study area	defines actual study area; 0 = background, 1 = study area

Table 6. Summary of parameters used in LandMod*.

Parameters	Use
biomass	calculation of above-ground biomass components
crown diameter	calculation of crown diameters
diameter growth	calculation of diameter growth
diameter of sexual maturity	calculation of seed production
drought-day	calculation of drought-day growth reduction factor
growth reduction	calculation of growth reduction factors due to environmental conditions
height from diameter	calculation of total tree height
inside-outside bark diameter ratio	calculation of leaf area and wildfire effects
life form (hardwood, softwood)	calculation of leaf and needle inputs to detrital pools
maximum diameter	calculation of seed production
maximum seed dispersal distance	calculation of seed dispersal
maximum tree age	calculation of ambient mortality rates
mortality	calculation of stress-related mortality probability
sapwood-leaf area ratio	calculation of leaf area
sapwood thickness	calculation of leaf area
seed production & dispersal	calculation of seed rain
taper	calculation of volume, and diameter and height of bole segments

* parameter values and sources, and equations are listed in Appendix C.

Tree Species' Parameters

Tree species' parameters are used in allometric calculations and to model demographic processes (included in Table 6), and are input as ASCII files. Allometric equations, and species' parameter values and sources are listed in Appendix C.

Initial Forest Conditions

The initial forest conditions of each landscape cell is specified by a spatial data layer (see Table 5) and two ASCII filew. The spatial data layer contains a coded forest type for each forest cell. The two ASCII files contain initial live and dead-wood attributes for each coded forest type. At program initiation, the spatial data layer and ASCII files are used to set the internal tree and dead-wood data structures for each forest cell (Appendix D).

There is an inherent source of variability in the initialization process. As a standard, input conditions are specified on a per-hectare basis. Whenever the primary grain of the landscape is not an integer number of hectares, LandMod scales the input values to whole tree or dead-wood pieces for the primary grain. This is because LandMod tracks the number of stems or pieces on the cell, not on an area basis. As part of this scaling procedure, stem and piece numbers are randomly rounded up to derive an integer number. This random process uses the fractional component of a scaled value to determine the probability of rounding up. For instance, if scaling resulted in a value of 0.25 stems, LandMod would select a uniform random variate and round up to 1 if the random variate was ≤ 0.25. Otherwise, the stem record would be omitted. This random rounding process occurs on a cell by cell basis. Thus, cells of the same forest type can be initialized with slightly different initial conditions.

Disturbance Parameters

Parameters related to disturbance regimes are read at program initiation from ASCII files, and used to determine the frequency, intensity, and severity of disturbances. Currently, these inputs only pertain to wildfire, and include the mean fire return interval, mean size, and base-line fuel moisture values for specified periods of a simulation run.

Process Control

Process-control information is input as an ASCII-formatted list. Thms list includes the names of the spatial and ASCII input files, the names of the output files, the dimensions of the spatial data layers, the primary grain size, the grain of the stream width layer, the duration of a simulation, and import/export options. LandMod has the ability to export the dynamic state space of the landscape at the end of a simulation and to import the state space of a previous simulation. The dynamic state space includew all information stored in the tree and dead-wood data structures (e.g., Appendix D). Import and export files are binary representations of complex data structures, and are created and read only by the LandMod system. The ability to import and export was implemented for specialized cases, such as to record for further use the conditions of a landscape after an initialization period. Export files can be extremely large and should be use sparingly.

OUTPUTS

Four output formats are supported: 1) Information on live structure and composition, and on coarse-wood attributes for each cell is output each time-step. To optimize disk-space use, this output file is binary. Analyses with this information require customized post-processing programs. Recent LandMod applications use this information to assess landscape pattern, habitat diversity, and carbon sequestration. The format of this output file is listed in Appendix E. Note that most measures are output on a per-hectare basis. 2) The volume of wood delivered to streams is summed by stream order and output each time step in an ASCII format. These data are used to compare the relative effects of land-use and natural disturbance scenarios on aquatic habitat. 3) For forest-management scenarios, the total amount of extracted merchantable volume is output for each time step with thinning or rotation-harvest events. 4) When simulating wildfires, maps are produced showing the cells burned in a time step with wildfire. These maps do not distinguish among multiple fire events within a time step. Maps are formatted as signed short (i.e., two bytes), flat-binary files, with implied row and column dimensions.

PERFORMANCE ASSESSMENT

Performance assessments of the live-tree dynamics in LandMod (1.0) were previously conducted Garman (accepted). Assessments included comparisons of predictions between LandMod and the PNWGap model for natural successional sequences and thinning treatments, and with empirical observations of Douglas-fir stands. Results of these assessments showed that most LandMod predictions were within 15% of gap-model predictions and observations, but with elevated error levels for predictions of stem density. Two notable deficiencies uncovered in this initial assessment were the tendency for LandMod to grossly under-predict attributes of infrequent species (hardwood and conifer species other than western hemlock) compared to empirical observations, and to under-predict the number of very large, canopy-dominant boles in old-growth stands compared to the PNWGap model. Enhancements recommended to rectify these deficiencies included; deriving available light based on solar geometry (i.e., use gap-model methods), and incorporating 'natural' variability in diameter-growth estimates and in stem transfer among size classes. Both enhancements were implemented in version 2.0 (see *Diameter Growth*, pg. 9; Available Light, pg. 12).

Two of the previous comparisons were performed with version 2.0 to evaluate the efficacy of growth-transfer enhancements. These comparisons also used a new diameter-increment parameterization that was derived from a re-calibration of the PNWGap model (Appendix A, Table A1). LandMod predictions were first compared to observed trends in nine low-elevation Douglas-fir stands. Results of this comparison showed that predictions with the latest version of LandMod were only slightly better than with version 1.0. Prediction errors with LandMod (2.0) were <12% for most total and Douglas-fir attributes, with 16-21% prediction error for stem density at the end of observations (Table 7). Other species occurring on the observed plots were primarily western hemlock and big-leaf maple, both of which occurred in relatively small amounts. Predictions for these two species combined were poor (Table 7), and only slightly better than the predictions with version 1.0. The second assessment compared LandMod and PNWGap predictions of diameter distribution (all species combined) of a mid-elevation, old-growth stand. Results of this limited assessment indicated improvement in LandMod predictions (Fig. 5). Predicted frequencies of larger stems (i.e., >167 cm) were similar between models. However, LandMod tended to under-predict 157- to 167-cm stems, and over-predict regenerated stems compared to the gap model. Overall, however, previous assessments showed a greater discrepancy between model predictions. In general, the diameter-transfer modifications and the new parameterization improved predictions of forest structure, but only nominally improved predictions of forest composition. Reasons for under-predicting infrequent species need to be further evaluated.

Comparisons of wildfire predictions with empirical measures have not been pursued due to insufficient observations for conclusive assessments. However, verification (i.e., proper codification assessment) of the standard wildfire behavior and effects models was performed by comparing modeled output with calculations performed by hand and with published results (i.e., Andrews, 1986).

Table 7. Mean (± 1 se) percent error in predictions with LandMod (2.0) compared to observed trends in nine, low-elevation (400-500 m) Douglas-fir stands*. Comparisons were performed at 20 years after the initial observation and at the time of the last observation.

		Species		
Attribute	stand age (yrs)	All species combined	Douglas-fir	Infrequent species combined
Basal area (m^2/ha)	74	1.85 (0.67)	1.58 (0.65)	146.56 (94.16)
	84-144	10.73 (1.82)	8.95 (1.60)	100.81 (31.59)
Density (no./ha)	74	3.66 (1.28)	3.55 (1.19)	130.04 (90.04)
	84-144	15.62 (4.24)	20.75 (5.63)	117.63 (59.28)
Quadratic mean diameter (cm)	74	2.47 (1.01)	2.32 (1.01)	27.81 (14.82)
	84-144	9.39 (1.89)	11.70 (2.28)	19.88 (4.31)
Canopy-height Diversity Index**	74	2.01 (1.78)		
	84-144	11.50 (2.52)		

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* Observed data were DFGY (Douglas-fir growth and yield) plots in west-central Oregon (Acker et al., 1998). DFGY plots included (by Study-Id): WI01, WI02, WI03, GP01, GP02, GP03, GP05, GP07, GP09. Initial stand ages were ca. 54 yrs.

** Spies and Cohen (1992).

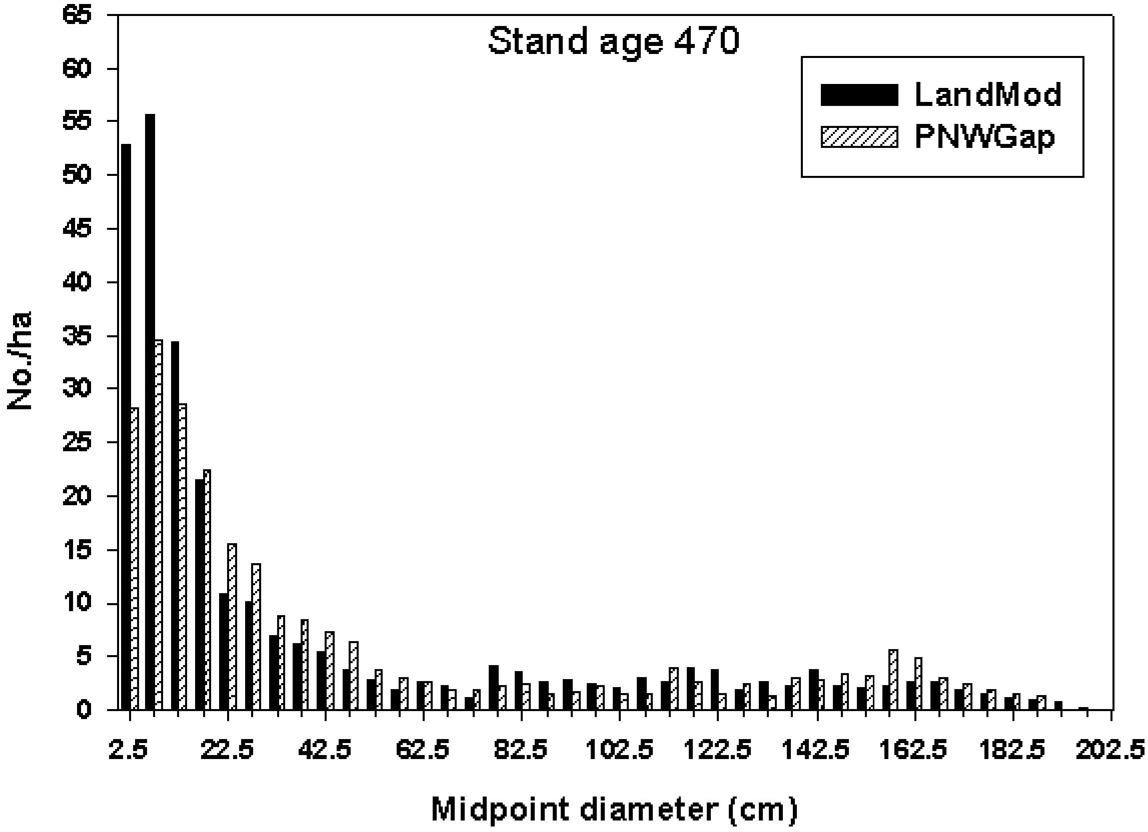

Fig. 5. Comparison of predicted diameter distributions between LandMod (2.0) and PNWGap (1.0) at stand age 470, 940 meter elevation. Distributions are averages of 10 replications. PNWGap was run using a 1-ha grid of 0.04-ha interacting plots. LandMod was run with a grain size of 0.25-ha; the diameter distribution of a replication was based on the average of four cells.

HARDWARE REQUIREMENTS & PROCESSING SPEED

HARDWARE REQUIREMENTS

The LandMod system is written in ANSI-C, and runs on PC or UNIX systems. The PC version of LandMod is compiled with the Windows C++.net compiler. The PC code can be ported directly to a Unix platform and complied with gnuC.

The hardware configuration required to run LandMod is determined by the simulation application. LandMod does not contain fixed dimensions for landscape size and number of cells. Instead, LandMod dynamically allocates memory at program initiation to store all static and dynamic information used in a simulation. This design emphasizes execution speed and enables the simulation of different-sized landwcapes without code changes. In general, the memory requirements of each LandMod application determines the necessary hardware configuration. For reference, simulating a landscape represented by 48,000 cells (e.g., 12,000-ha landscape with a 0.25-ha grain size) using eight possible tree species requires ca. 0.4 GB of memory. Memory requirements increase somewhat linearly with increasing number of cells. For example, applications involving 384,400 cells (ca. 8 X large than the example above) and eight possible tree species require ca. 2.7 GB of memory.

An addition consideration is the amount of accessible memory. Standard 32-bit PC operating systems, such as Windows XP & 2000, limit a process to 3.0 GB of RAM (physical plus virtual). Thus, applications with the current version of LandMod are, for all practical purposes, limited to ca. 388,000 cells. Applications involving a larger number of cells require Windows SQL & 2000 Server operating systems. These systems permit access to very large amounts of RAM (e.g., up to 16 GB). Accessible memory is less of an issue on Unix platforms, given the ability to create large amounts of virtual memory. However, performance substantially decreases when swapping. Extensive amounts of swapping should be avoided.

The 388,000-cell limit on 32-bit operating systems effectively limits the landscape area that can be simulated with these standard systems. Although cell size can be any size ≥0.04-ha, the most reliable results are achieved using a cell size of 0.25- to 1-hectare. Thus, the maximum landscape area that can be simulated on standard PC operating systems is between 97,000 and 388,000 hectares.

(NOTE: Ongoing enhancements continue to reduce the processing and memory load requirements of LandMod. E.g., recent assessments suggest a maximum landscape area of ca. 500 000 hectares with a 1-ha cell size. Contact the author for the most recent benchmarks on processing time and memory requirements).

PROCESSING SPEED

Recent applications with LandMod provide timing benchmarks for different sized landscapes and simulated disturbances. The following run-time values are averages for LandMod simulations run as physical-memory resident applications on a Xeon 3.06 GHz without the virtual aggregation feature activated, and with the standard output for each cell recorded every 5-yr time step. Simulating a 48,000-cell landscape for 200 years without disturbance requires ca. 7 s per time step. Under similar conditions but harvesting 6% of the landscape per 5-yr interval increases processing time to ca. 21 s per time step. Simulation of wildfire events on a 384,000-cell landscape over 1000 years requires about 130 s per time step. In general, LandMod simulations take about 0.7 - 3.4 s per time step per10,000 cells. Model speed has not been evaluated on different CPUs or for various computer-memory configurations. As a rule of thumb, memory swapping will add considerably to processing time.

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Appendix A. Regression coefficients in LandMod that were derived from the meta-model procedures with the PNWGap model (see text).

Table A1. Regression coefficients for the diameter increment function in LandMod. Coefficients are means estimates generated from standard Least-Squares procedures. All regressions models and coefficients were significant (*P* <0.0001).

	Coefficients (eq.2)						
Species	b_0	b_1	b_2	b_3	b_4	n	Adj. R^2
Big-leaf maple (*Acer macrophyllum*)	-4.772021	0.716173	-0.00008936	3.218103	3.219259	10000	0.94
Douglas-fir (*Pseudotsuga menziesii*)	-2.441345	0.137074	-0.00003489	2.921660	3.219270	12500	0.95
Mountain hemlock (*Tsuga mertensiana*)	-4.036981	0.436058	-0.00005317	2.950517	3.224781	10000	0.95
Noble fir (*Abies procera*)	-3.437120	0.061203	-0.00003515	3.825787	3.219278	10000	0.95
Pacific silver fir (*Abies amabilis*)	-3.703833	0.280620	-0.00011200	3.651085	3.047320	10000	0.72
Red alder (*Alnus rubra*)	-3.929713	0.582883	-0.00027500	3.708941	3.219256	5000	0.95
Western hemlock (*Tsuga heterophylla*)	-3.706155	0.384946	-0.00005128	2.942258	3.219240	10000	0.96
Western redcedar (*Thuja plicata*)	-4.074825	0.186118	-0.00003457	3.752609	3.219263	12500	0.95

Table A2. Covariance matrices for diameter-growth regression coefficients (eq. 2).

Bigleaf maple (ACma)

	b_0	b_1	b_2	b_3	b_4
b_0	0.003992702				
b_1	-0.000864334	0.000243318			
b_2	4.9440355E-8	-1.564779E-8	1.523782E-12		
b_3	-0.000893399	6.008888E-17	-3.58271E-21	0.0020135757	
b_4	-0.000893399	-2.21245E-17	1.180456E-21	3.530341E-17	0.0020135757

Douglas-fir (PSme)

	b_0	b_1	b_2	b_3	b_4
b_0	0.0023866324				
b1	-0.000507694	0.0001402173			
b_2	2.5025027E-8	-7.7756E-9	6.57282E-13		
b_3	-0.000531281	1.809144E-17	-8.37737E-22	0.0011974208	
b_4	-0.000531281	-2.33572E-17	1.127078E-21	1.503728E-17	0.0011974208

Mt. Hemlock (TSme)

	b_0	b_1	b_2	b_3	b_4
b_0	0.0024463767				
b_1	-0.000520403	0.0001437274			
b_2	2.5651475E-8	-7.970246E-9	6.737356E-13		
b_3	-0.00054458	1.854432E-17	-8.58708E-22	0.0012273956	
b_4	-0.00054458	-2.39419E-17	1.155292E-21	1.541371E-17	0.0012273956

Noble fir (ABpr)

	b_0	b_1	b_2	b_3	b_4
b_0	0.0027445758				
b_1	-0.000583837	0.0001612469			
b_2	2.8778241E-8	-8.941772E-9	7.558601E-13		
b_3	-0.000610961	2.080477E-17	-9.6338E-22	0.001377008	
b_4	-0.000610961	-2.68603E-17	1.296115E-21	1.729255E-17	0.001377008

Table A2. Cont'd

Pacific Silver fir (ABam)

	b_0	b_1	b_2	b_3	b_4
b_0	0.0521720265				
b_1	-0.011080094	0.0030506824			
b_2	5.5489892E-7	-1.706659E-7	1.455308E-11		
b_3	-0.011783031	0.0000523613	-7.027702E-9	0.0260970404	
b_4	-0.011783031	0.0000523613	-7.027702E-9	0.0001084356	0.0260970404

Red alder (ALru)

	b_0	b_1	b_2	b_3	b_4
b_0	0.0060654966				
b_1	-0.001557511	0.0005207765			
b_2	3.1222422E-7	-1.161776E-7	3.67586E-11		
b_3	-0.001359878	-3.5428E-17	7.639256E-21	0.0030649444	
b_4	-0.001359878	-2.57077E-18	8.113371E-23	8.924919E-17	0.0030649444

Western hemlock (TShe)

	b_0	b_1	b_2	b_3	b_4
b_0	0.0017687075				
b_1	-0.000376246	0.0001039136			
b_2	1.8545778E-8	-5.762413E-9	4.871046E-13		
b_3	-0.000393726	1.340737E-17	-6.20838E-22	0.0008873956	
b_4	-0.000393726	-1.73098E-17	8.352654E-22	1.114397E-17	0.0008873956

Western redcedar (THpl)

	b_0	b_1	b_2	b_3	b_4
b_0	0.002729698				
b1	-0.000580672	0.0001603728			
b_2	2.862224E-8	-8.893301E-9	7.517627E-13		
b_3	-0.000607649	2.069199E-17	-9.58157E-22	0.0013695435	
b_4	-0.000607649	-2.67147E-17	1.289089E-21	1.719881E-17	0.0013695435

Table A3. Regression coefficients for the stress mortality function in LandMod. All regressions models and coefficients were significant (*P* <0.0001).

Species	Coefficients (eq. 3)				n	Adj. R^2
	b_0	b_1	b_2	b_3		
Big-leaf maple	3.411904076	-0.136346649	-8.896625759	-4.955266536	10000	0.94
Douglas-fir	2.504101925	-0.108887048	-7.296973825	-2.041392553	12500	0.98
Mountain hemlock	1.487432766	-0.093757155	-7.239774890	-1.887944952	10000	0.98
Noble fir	2.087224896	-0.097609470	-7.142520430	-1.688087036	10000	0.98
Pacific silver fir	1.451741269	-0.099094357	-7.327145574	-1.559508276	10000	0.98
Red alder	3.823741754	-0.119934830	-7.721860300	-6.291407152	5000	0.95
Western hemlock	2.205636046	-0.092081963	-8.109368821	-1.967920536	10000	0.98
Western redcedar	2.365904514	-0.100754944	-7.643834319	-2.708449491	12500	0.96

Table A4. Regression coefficients for the drought-day function in LandMod. All regressions models and coefficients were significant (*P* <0.0001).

Aspect	Coefficients (eq. 4)							n	Adj. R^2
	b_0	b_1	b_2	b_3	b_4	b_5	b_6		
N	0.294273	-8.62E-4	0.018085	9.18000E-7	-0.001879	-3.15654E-10	5.4142E-5	6288	0.65
NE	0.223535	-5.75E-4	0.020057	5.68000E-7	-0.001777	-1.88579E-10	2.9995E-5	6780	0.69
E	0.082038	-1.03E-4	0.025691	7.19783E-8	-0.002699	-2.65450E-11	7.7637E-5	8404	0.62
SE	0.076554	-7.84E-5	0.029919	4.58417E-8	-0.003737	-1.78156E-11	1.4600E-4	11728	0.62
S	0.098794	-1.70E-4	0.031977	1.46000E-7	-0.004106	-5.23366E-11	1.6700E-4	12324	0.58
SW	0.157876	-3.46E-4	0.027567	3.10000E-7	-0.003449	-9.69923E-11	1.3500E-4	8924	0.51
W	0.250829	-6.92E-4	0.024568	7.05000E-7	-0.002878	-2.35647E-10	1.0200E-4	9740	0.62
NW	0.291185	-8.25E-4	0.018769	8.48000E-7	-0.002037	-2.83153E-10	6.3720E-5	10080	0.63

APPENDIX B - Equations used to derive maximum spotting distance of a wildfire

Flame height and flame duration are derived by**:**

$$\ln(\text{Flame\_hgt}) = 0.753012 \ln(\text{dbh}), \tag{B-1}$$

where, dbh is diameter at breast height (cm), and Flame_hgt is the 'steady' flame height (m).

$$\text{Flame\_duration} = 4.4347 + 3.518 \exp(-0.06912 \text{ dbh}), \tag{B-2}$$

where, flame_duration is the study flame duration (dimensionless).

$$\ln(\text{Flame\_hgt\_adj}) = 0.393037 \ln(\text{number}), \tag{B-3}$$

where, number is the number of trees burning at once, and Flame_hgt_adj is the steady flame height amplification factor.

$$\text{Flame\_duration\_adj} = 0.5459 + 0.5569 \exp(-0.2140 \text{ number}), \tag{B-4}$$

where, Flame_duration_adj is the steady flame duration

$$\text{Adj\_flame\_hgt} = \text{Flame\_hgt} \;\; \text{Flame\_hgt\_adj}, \tag{B-5}$$

where, Adj_flame_hgt is the adjusted steady flame height (m).

$$\text{Adj\_flame\_duration} = \text{Flame\_duration} \;\; \text{Flame\_duration\_adj}, \tag{B-6}$$

where, Adj_flame_duration is the adjusted steady flame duration (dimensionless).

Lofted firebrand height/steady flame height ratio is determined by:

$\mathrm{If(H/Adj\_flame\_hgt} \leq 0.5)$ (B-7)
$\mathrm{Ratio} = 4.655\ (1 - \exp(-0.7467\ \mathrm{Adj\_flame\_duration}))$
$\mathrm{else\ if(H/Adj\_flame\_hgt} \leq 1.5)$ (B-8)
$\ln(\mathrm{Ratio}) = 1.252121 + 0.395066\ \ln(\mathrm{Adj\_flame\_duration})$
$\mathrm{else\ if(H/Adj\_flame\_hgt} > 1.5)$ (B-9)
$\ln(\mathrm{Ratio}) = 1.43812 + 0.308885\ \ln(\mathrm{Adj\_flame\_duration})$

where, H is mean tree-top height (m), and Ratio is the lofted firebrand height/steady flame height ratio.

The initial height of the fire brand is derived by:

$\mathrm{Fire\_brand\_hgt} = \mathrm{Adj\_flame\_hgt}\ \ \mathrm{Ratio},$ (B-10)

where, Fire_brand_hgt is the initial fire-brand height (m).

Calculation of maximum spotting distance is directly from Albini (1979; - eq. F22): (B-11)

$X^* = 21.9U\ \mathrm{sqrt}(H/g)\ \ [0.362 + \mathrm{sqrt}(\mathrm{Fire\_brand\_hgt}/H)\ 0.5\ \ln(\mathrm{Fire\_brand\_hgt}/H)),$

where, g is the acceleration of gravity (9.8 m s^{-2}), U is windspeed at treetop height (km s^{-1}), and X* is maximum spotting distance (km).

APPENDIX C - Support functions and associated species parameters

Biomass - Biomass of five tree components are derived using one equation form and species-specific coefficients for each component. The five components include; foliage, live branches, dead branches, stem bark, and stem wood. Biomass for each component is derived by:

$$\ln(\text{Biomass}) = b_0 + b_1 \ln(\text{dbh}), \qquad \text{(C-1)}$$

where, dbh is diameter at breast height in cm, b_0-b_1 are species-specific coefficients for each tree component, and Biomass is in grams. Biomass coefficients (Table C1) are from the BIOPAK system (Means et al., 1994).

Table C1. Biomass coefficients (eq. C1).

	Foliage		Live branch		Dead branch		Stem bark		Stem wood	
Species	b_0	b_1	b_0	b_1	b_0	b_1	b_0	b_1	b_0	b_1
ABam	2.3591	2.1926	1.6708	2.6261	-0.17724	2.805	2.965718	2.3179	4.124354	2.497
ABpr	2.03496	2.1683	2.7261	2.3324	3.3788	1.7503	2.791887	2.4313	3.600994	2.6043
ACma	0.415955	2.5033	2.67176	2.43	4.7918	1.092	2.3338	2.574	3.4148	2.723
ALru	-2.4473	3.2434	-0.91194	3.4886	-0.707845	2.6243	2.265355	2.4617	4.238755	2.4618
PSme	4.0616	1.7009	3.2137	2.1382	3.3788	1.7503	2.902625	2.4818	4.841987	2.3323
THpl	4.2908	1.7824	3.6417	2.0877	3.3788	1.7503	2.38544	2.1987	3.862652	2.4454
TShe	2.7778	2.128	1.7588	2.778	-0.17724	2.805	2.766209	2.3474	4.176308	2.5353
TSme	3.0909	1.9756	1.6497	2.6045	-3.0371	3.2845	3.065042	2.3268	3.145412	2.6627

Crown Diameter - The diameter of tree crowns is-derived from dbh, and used to calculate percent crown area. Crown diameter is derived by:

$$\text{CrnDiam} = \exp(\ln(\text{dbh})\, b_0 + b_1), \qquad \text{(C-2)}$$

where, b_0-b_1 are species coefficients from Spies et al. (1990) and BIOPAK (Means et al., 1994) (Table C2), dbh is diameter at breast height in cm, and CrnDiam is crown diameter in meters.

Table C2. Crown diameter coefficients (eq. C-2).

Species	b_0	b_1	Species	b_0	b_1
ABam	0.5910499	0.052873	PSme	0.47674	0.0514
ABpr	0.47674	0.0514	TShe	0.5910499	0.052873
ACma	0.48754	0.6936	THpl	0.37183	0.56569
ALru	0.5212634	0.6300169	TSme	0.5910499	0.052873

Growth Reduction Factors

Available Light Growth Reduction Factor - Growth reduction due light levels is derived by:

$$\mathrm{AlrF} = a_1\,(1.0 - \exp(-a_2\ (\mathrm{Al} - a_3))), \qquad \text{(C-3)}$$

where, Al is calculated available light, a_1-a_3 are coefficients reflecting the shade tolerance of a species (Table C3), and AlrF is the available light growth reduction factor scaled between 0 and 1.

Drought-stress Growth Reduction Factor - Growth reduction due to moisture stress is derived by:

$$\mathrm{DrtF} = \mathrm{sqrt}\,((\mathrm{dt} - \mathrm{Drt})/\mathrm{dt}), \qquad \text{(C-4)}$$

where, dt is the species' drought tolerance (proportion of the growing season experiencing drought) (Table C3), Drt is the minimum of dt and calculated drought-day proportion, and DrtF is the drought-stress growth reduction factor scaled from 0 to 1.

Growing Degree Day Growth Reduction Factor - Growth reduction due to temperature limitations is derived by:

$$\mathrm{DegdF} = 4.0\ (\mathrm{Dedg}-\mathrm{ddmin})\ (\mathrm{ddmax} - \mathrm{Dedg})\ /\ (\mathrm{ddmax} - \mathrm{ddmin})^2 \qquad \text{(C-5)}$$

where, ddmin is the lower and ddmax is the upper growing degree limit of a species (Table C3), Dedg is the input growing degree day for a cell, and DedgF is the growing degree-day growth reduction factor scaled from 0 and 1.

Soil-nutrient Growth Reduction Factor - Growth reduction due to nutrient limitations is derived as:

$$FertF = f_1 \, (1.0 - \exp(f_2 \, (Sf - f_3))) \qquad \text{(C-6)}$$

where, f_1 - f_3 are coefficients reflecting species' tolerance to nutrient stress (Table C3), Sf is the ratio of annual biomass increment and the maximum allowable increment (10 Mg ha^{-1} yr^{-1}) scaled from 0 to 1, and FertF is the soil-nutrient growth reduction factor scaled from 0 to 1.

Table C3. Coefficients used to calculate growth reduction factors (GRF), (eqs. C3- C6).

	Available Light GRF (eq. C3)			Drought stress GRF (eq. C4)	Growing-degree day GRF (eq. C5)		Soil-nutrient GRF (eq. C6)		
Species	a_1	a_2	a_3	dt	ddmin	ddmax	f_1	f_2	f_3
ABam	1.02046	4.16533	0.03	0.3	118	1815	1.00892	-5.38804	0.12242
ABpr	1.25977	1.78588	0.12	0.3	442	1408	1.00892	-5.38804	0.12242
ACma	1.04689	3.29031	0.06	0.25	478	2361	1.00892	-5.38804	0.12242
ALru	1.25977	1.78588	0.12	0.2	400	3080	0	0	0
PSme	1.25977	1.78588	0.12	0.4	441	2461	1.00892	-5.38804	0.12242
THpl	1.04689	3.29031	0.06	0.3	292	2481	1.00892	-5.38804	0.12242
TShe	1.02046	4.16533	0.03	0.3	311	2480	1.00892	-5.38804	0.12242
TSme	1.02046	4.16533	0.03	0.3	100	1027	1.00892	-5.38804	0.12242

Height from DBH - Height from diameter at breast height (dbh) is derived with the Chapman-Richards function by:

$$Hgt = 1.37 + b_0 \, (1 - \exp(b_1 \, dbh))^{b2}, \qquad \text{(C-7)}$$

where, dbh is in cm, b_0-b_3 are species' regression coefficients from Garman et al. (1995) (Table C4), and Hgt is total height in meters.

Table C4. Height-diameter coefficients (eq. C-7).

Species	b_0	b_1	b_2
ABam	60.02491	-0.02025	1.32027
ABpr	78.60353	-0.01333	1.18514
ACma	30.41311	-0.03424	0.6821
ALru	35.55002	-0.02832	0.796024
PSme	76.85529	-0.01156	0.928818
TShe	63.13141	-0.01632	1.078909
THpl	60.18588	-0.013	0.937054
TSme	38.37431	-0.03153	1.509506

Leaf -area Calculations - Leaf area of a stem is derived from bole diameter at the base of the crown, sapwood width at the base of the crown, and species-specific sapwood-leaf area ratio. Leaf area is calculated with the following set of equations:

If $Hc > 1$ $\quad Dc = dbh\ (SQRT(\ b_0 - b_1\ (Hc/Ht) + b_2\ (Hc^2/Ht^2)))$ (C-8)
If $Hc \leq 1$ $\quad Dc = Br\ dbh$

$Rc = Dc/2.0$
$Sw = S_0\ (1 - \exp(-S_1\ dbh))$
$Sa = PI\ Rc^2 - PI\ (Rc - Sw)^2$
$LA = SLR\ Sa,$

where, Hc is height to base of crown (m), Ht is total height (m), b_0 - b_2 are species' taper coefficients (Table C9), dbh is in cm, Dc is the inside-bark diameter (cm) at the base of the crown, Br is the ratio of inside bark to outside bark diameter (Table C5), Rc is the radius (cm) of the bole at the base of the crown, S_0 - S_1 are species' coefficients for relating sapwood thickness to dbh (Table C5), Sw is sapwood width (cm) at the base of the crown, PI = 3.14159, Sa is sapwood cross-sectional area (m^2), SLR is the sapwood area at base of crown:leaf area ratio (Table C5), and LA is leaf area (m^2). Mean inside bark to outside bark diameter ratios were calculated using dendrometer data from study-id TV009 in the Forest Science Data Bank, Oregon State University (Garman, unpubl.). Sapwood thickness coefficients are from Urban (unpubl.), and sapwood-leaf area ratios are from Waring et al. (1982) and Waring and Schlesinger (1985).

Table C5. Coefficients used to derive leaf area (eq. C-8).

Species	Inside-outside bark diameter ratio (Br)	Sapwood area:Leaf area Ratio (SLR)	Sapwood thickness coefficients	
			S_0	S_1
ABam	0.95229	0.56	4.67	0.0341
ABpr	0.94404	0.56	4.67	0.0341
ACma	0.88715	0.21	15.1	0.0314
ALru	0.88715	0.21	15.1	0.0314
PSme	0.88981	0.54	5.43	0.0460
THpl	0.97162	0.56	4.67	0.0341
TShe	0.95649	0.46	16.3	0.0178
TSme	0.90485	0.46	16.3	0.0178

Maximum Tree Age - Maximum tree age is used to derive the probability of ambient mortality. Ambient mortality is derived by:

$$\text{ProbAmort} = -\ln(0.01) / \text{maxage}, \tag{C-9}$$

where, maxage is species' maximum tree age (yrs) (Table C6), and ProbAmort is the probability of ambient mortality. An assumption in the derivation of ambient mortality is that 1% of stems reach maximum age.

Table C6. Maximum tree ages (eq. C-9). Adapted from Waring and Franklin (1979).

Species	Maximum age (yrs)	Species	Maximum age (yrs)
ABam	600	PSme	1100
ABpr	600	TShe	500
ACma	300	THpl	1500
ALru	100	TSme	800

Seed Dispersal - Seed dispersal employs species-specific measures of seed production and seed-dispersal curves. An index of seed production subsumes the tracking of actual seed numbers, and is estimated for each species on a cell by:

$$\text{SeedPIndex} = \Sigma\ (\text{StemNum MaxSeed dbh/Maxdbh}), \tag{C-10}$$

where, Maxdbh is maximum diameter (cm) (Table C7), dbh (cm) is the diameter of a sexually mature stem (see Table C7), MaxSeed is an index of maximum seed production (an integer value ≥ 0) (Table C7), StemNum is the number of stems of the same diameter, and SeedPIndex is the index of seed production for a species.

Species-specific dispersal curves are assumed to be of a negative exponential form. The slope of the curve is derived from maximum dispersal distance (Table C7) and a specified proportion traveling the maximum distance (typically 1%) by:

$$-r = \ln(\text{Prop})/\text{MaxDist}, \tag{C-11}$$

where, MaxDist (m) is how far a proportion (Prop) of seeds will dispersal, and r is the slope of a negative exponential curve.

A dispersal curve is integrated to estimate the proportion of seeds (i.e., the proportion of the seed-production index) that is deposited at a specified distance:

$$\text{PropSeed} = a \exp(-r \text{ Distance}), \tag{C-12}$$

where, Distance (m) is the distance from the focal cell, PropSeed is the proportion of seeds (i.e., proportion of seed-production index) that is deposited, a is an intercept term and is derived by:

$$a = 1.0 - \exp(-r \text{ cell\_size}), \tag{C-13}$$

where, cell_size is the distance (m) between centroids of adjacent cells (i.e., length of a cell), and the constant 1.0 is equivalent to exp(-r 0).

In calculating seed rain, the seed-production index that is deposited on a cell is the product of equation C-12, where Distance is the distance between the source and destination cell, and equation C-10.

Seed rain is calculated at the beginning of each time step across the entire landscape. Only species with sexually mature stems are dispersed from a source cell. LandMod internally scales distance values in the above calculations from meters to number of cells based on cell size.

Table C7. Parameters used in the derivation of seed production and seed dispersal curves. Diameter of sexual maturity is derived from estimates of age of sexual maturity reported in Burns and Honkala (1990). Maximum seed dispersal distances are estimated from life-history reports in Burns and Honkala (1990). Maximum dbh is adapted from Waring and Franklin (1979).

Species	Diameter (cm) of sexual maturity	Maximum dbh (cm)	Maximum seed production index	Maximum seed dispersal distance (m)
ABam	20	200	10	250
ABpr	20	275	10	250
ACma	10	250	15	500
ALru	10	100	20	1000
PSme	15	300	10	250
TShe	20	225	20	250
Thpl	10	300	10	250
TSme	20	225	10	250

Taper Coefficients - Taper coefficients are used in the calculations of bole volume and bole dimensions at a given diameter or height. LandMod uses the older version of Kozak's taper equation (Kozak et al., 1969) because it can be solved analytically. Taper coefficients were derived from dendrometer measures of whole-tree bole segments from west-central Oregon (Garman, unpubl.). The raw dendrometer data are stored under study-id TV009 in the Forest Science Data Bank, Oregon State University. Data were fit to the following model,

$$d^2/dbh^2 = b_1\ ((h/H)-1) + b_2\ ((h^2/H^2)-1), \qquad \text{(C-14)}$$

where, H is the total height (m), h is the height (m) of a bole segment, dbh is diameter outside bark (cm) at breast height, d is inside bark diameter (cm) at height h, b_1 and b_2 are regression coefficients.

The intercept term, b_0, of Kozak's equation is derived from b_1 and b_2 such that $b_0 + b_1 + b_2 = 0$. Taper coefficients, sample sizes, and the adjusted Coefficients of Determination are provided in Table C8.

Table C8. Taper coefficients (eqs. C-8 & C-14).

Species	Taper coefficients b_0	b_1	b_2	min. - max dbh (cm)	min - max height (m)	no. segments - no. boles	AdjR^2
ABam	1.10084	-1.50585	0.40501	8.1 - 109.3	6.3 - 58.9	804 -143	0.81
ABpr	1.00511	-1.33944	0.33433	15.9 - 235.5	12.2 - 83.9	2013 - 307	0.97
ACma*	0.95997	-1.46336	0.50339	-	-	-	-
ALru*	0.97576	-1.22922	0.25347	-	-	-	-
PSme	0.87201	-1.48078	0.60877	17.2 - 215.0	12.8 - 96.1	1433 - 216	0.95
THpl	1.1921	-2.3842	1.1921	11.8 - 175.1	7.4 - 56.9	315 - 53	0.92
TShe	1.11125	-1.69534	0.58409	8.9 - 172.3	5.7 - 78.3	2142 - 352	0.85
TSme	0.94295	-1.46136	0.51841	11.5 - 125.7	6.2 - 49.9	3223 - 420	0.98

* from Kozak et al. (1969).

APPENDIX D - State space maintained for each forested cell on a landscape

For each forested cell:

- leaf area index
- kg of leaf & needle litter
- kg of dead branches <0.5-cm
- kg of dead 10-hr branches
- kg of dead 100-hr branches
- mean hgt (m) of tallest (upper 20%) boles

For each tree species on a cell:

- 5-cm size-class designation
- number of stems
- height to base of crown (m)

For each snag and log cohort:

- decay class (1-5)
- decay group (0-5) (see Table 1)
- number of pieces
- time since death (yrs)
- total volume (m^3/ha)
- mean diameter (cm) of pieces
- mean height or length of pieces (m)

APPENDIX E - Format of the standard output file in LandMod

Following information is output for each cell in the landscape

```
int      row;              /* row */
int      col;              /* col */
short    year;             /* simulation year */
float    ba;               /* total basal area (sq.m/ha) */
float    dbh80;            /* density (no./ha) of stems >=80cm dbh */
float    dbh100;           /* density (no./ha) of stems >100-cm dbh */
float    dbh40;            /* density (no./ha) of shade-tolerant stems >40-cm dbh */
float    cr1;              /* layer 1 of chdi [adjusted for cell size] */
float    cr2;              /* layer 2 “ */
float    cr3;              /* etc. */
float    cr4;
float    cr5;              /* layer 5 of chdi " */
float    snagd;            /* density (no./ha) of snags  >50-cm dbh */
float    snagv;            /* volume (m^3/ha) of snags >50-cm dbh */
float    snagm;            /* total mass (Mg/ha) of snags */
float    logm;             /* total mass (Mg/ha) of logs */
float    loglm;            /* total mass (Mg/ha) of logs >50-cm LED (large-end diameter)*/
float    livev;            /* total live-bole volume (m^3/ha) */
float    snagnhl;          /* density (no./ha) of snags in decay class 1 & 2 & >=50-cm dbh */
float    snagnhs;          /* density (no./ha) of snags in decay class 1 & 2 & <50-cm dbh */
float    snagnsl;          /* density (no./ha) of snags in decay class 3 & >=50-cm dbh */
float    snagnss;          /* density (no./ha) of snags in decay class 3 & <50-cm dbh */
float    logmhl;           /* mass (Mg/ha) of logs in decay class 1 thru 3 & >=50-cm LED */
float    logmhs;           /* mass (Mg/ha) of logs in decay class 1 thru 3  & <50-cm LED */
float    logmsl;           /* mass (Mg/ha) of logs in decay class 4 & 5  & >=50-cm LED */
float    logmss;           /* mass (Mg/ha) of logs in decay class 4 & 5 <50-cm LED */
float    soft1;            /* density (no./ha) of conifers <=10-cm dbh */
float    soft2;            /* density (no./ha) of conifers >10 <30cm dbh */
float    soft3;            /* density (no./ha) of conifers >=30 <50cm dbh */
float    soft4;            /* density (no./ha) of conifers >=50 <90cm dbh */
float    soft5;            /* density (no./ha) of conifers >=90 cm dbh */
float    hard1;            /* density (no./ha) of hardwoods <=10-cm dbh */
float    hard2;            /* density (no./ha) of hardwoods >10 <30cm dbh */
float    hard3;            /* density (no./ha) of hardwoods >=30 <50cm dbh */
float    hard4;            /* density (no./ha) of hardwoods >=50 <90cm dbh */
float    hard5;            /* density (no./ha) of hardwoods >=90 cm dbh */
float    hgt;              /* mean hgt (m) of canopy stems */
```

APPENDIX F - Articles using the PNW versions of the ZELIG model

Garman, S. L., S. A. Acker, and K. Oconnell. *Draft.* Simulating development of late-successional reserves. (Forest Ecology and Management)

Garman, S. L., J. Hagar, and A. Fiala. *Draft.* Response of songbirds to thinning Douglas-fir stands: a modeling assessment (Env. Management)

Garman, S. L., J H. Cissel, and J. H. Mayo. 2003. Accelerating development of late-successional conditions in young managed Douglas-fir stands: a simulation study. USDA Forest Service Pacific Northwest Research Stn., Gen. Tech. Report, PNW-GTR-557.

Cissel, J. M., J. M. Mayo, S. L. Garman, and F. J. Swanson. 2002. Application of landscape objectives to stand-level silviculture: Blue River Oregon. Pgs. 21-37 *in* S. Parker and S. S. Hummel (eds.). USDA Forest Service Pacific Northwest Research Stn., Gen. Tech. Report, PNW-GTR-546.

Busing, R. T. and S. L. Garman. 2002. Promoting old-growth characteristics and long-term wood production in Douglas-fir forests. Forest Ecology and Management 160:161-175.

Garman, S. L. 2001. Simulating alternative thinning strategies for the Young Stand Thinning and Diversity Study. Cascade Center for Ecosystem Management, Willamette National Forest, Blue River, OR. 45pp.

Garman, S. L. 2001. Development of meta-models for assessing ecological effects of alternative thinning regimes. Cascade Center for Ecosystem Management, Willamette National Forest, Blue River, OR 31pp.

Turner, D. P., S. A. Acker, J. E. Means, and S. L. Garman. 2000. Estimating leaf area index from sapwood area in young, mature, and old-growth Douglas-fir stands. Forest Ecology and Management 126:61-76.

Garman, S. L. 1999. Assessing potential development of snags - Young Stand Thinning and Diversity Study. Cascade Center for Ecosystem Management, Willamette National Forest, Blue River, OR. 34pp.

Urban, D. L., M. F. Acevedo, and S. L. Garman. 1999. Scaling fine-scale processes to large-scale patterns using models derived from models: meta-models. Pages 70-98 *in* D. Mladenoff and W. Baker (eds.). Spatial Modeling of Forest Landscape Change: Approaches and Applications. Cambridge Univ. Press.

Garman, S. L. 1996. Integrating wildlife-habitat diversity and landscape designs with simulation modeling. Intermountain Journal of Science 2:40.

Hansen, A. J., S. L. Garman, B. Marks, and D. L. Urban. 1996. An approach for managing vertebrate diversity across multiple use landscapes. Pages 331-350 *in* F. B. Samson and F. L. Knopf (eds.). Ecosystem Management - Selected Readings. Springer-Verlag, NY.

Hansen, A. J., S. L. Garman, J. F. Weigand, D. L. Urban, W. C. McComb, and M. G. Raphael. 1995. Alternative silvicultural regimes in the Pacific Northwest: simulations of ecological and economic effects. Ecological Applications 5:535-554.

Urban, D. L., M. E. Harmon, and C. B. Halpern. 1993. Potential response of Pacific northwestern forests to climatic change; effects of stand age and initial composition. Clim. Change 23, 247-266.

Garman, S. L., A. J. Hansen, D. L. Urban, and P. F. Lee. 1992. Alternative silvicultural practices and diversity of animal habitat in western Oregon: A computer simulation approach. Pages 777-781 *in* Proceedings of the 1992 Summer Simulation Conference, Society for Computer Simulation, Reno. (P. Luker, ed.). 1273 pp.

APPENDIX G - Acronym, scientific, and common name of tree species used in LandMod

Acronym	Scientific name	Common Name
ABam	*Abies amabilis*	Pacific silver fir
ABpr	*Abies procera*	Noble fir
ACma	*Acer macrophyllum*	Big-leaf maple
ALru	*Alnus rubra*	Red alder
PSme	*Pseudotsuga menziesii*	Douglas-fir
THpl	*Thuja plicata*	Western redcedar
TShe	*Tsuga heterophylla*	Western hemlock
TSme	*Tsuga mertensiana*	Mountain hemlock