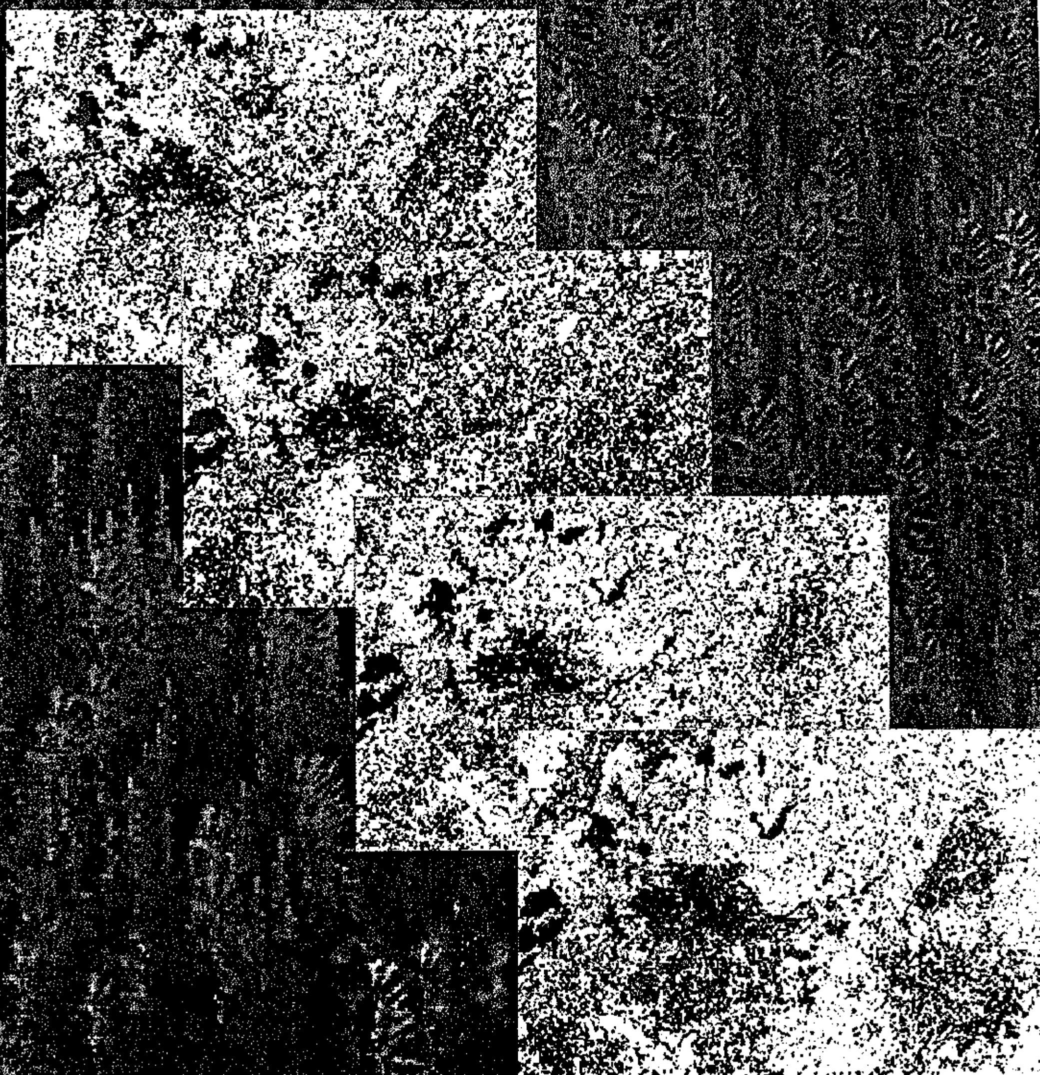
Spatial Modeling of Forest Landscape Change

Approaches and Applications

Edited by David J. Mladenoff and William L. Baker

Gustafson, Eric J.; Crow, Thomas R. 1999. HARVEST: linking timber harvesting strategies to landscape patterns. In: Mladenoff, David J.; Baker, William L., eds. Spatial modeling of forest landscape change: approaches and applications. Cambridge, UK: Cambridge University Press: 309-332.



Spatial modeling of forest landscape change: approaches and applications

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CAMBRIDGE UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011-4211, USA www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia
Ruiz de Alarcon 13, 28014 Madrid, Spain

First published 1999

Printed in the United Kingdom at the University Press, Cambridge

Typeset in Bembo 11/13pt [wv]

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication data

Spatial modeling of forest landscape change:
approaches and applications/[editors, David J. Mladenoff, William L. Baker].
p. cm.
Papers presented at symposium in Albuquerque, New Mexico, USA, 1997.
Includes index.
ISBN 0 521 63122 X (hardback)
1. Forest dynamics – Computer simulation – Congresses. 2. Landscape ecology – Computer stimulation – Congresses. I. Mladenoff, David J.
II. Baker, William L. (William Lawrence)
QK938.F6S668 1999
577.3′01′13–dc21 98-50552 CIP

ISBN 0 521 63122 X hardback

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HARVEST: linking timber harvesting strategies to landscape patterns

Eric J. Gustafson and Thomas R. Crow

Introduction and rationale

Providing a balance among the various benefits and values derived from forest lands has always been a challenge for managers. Determining this balance will be an even greater challenge in the future as increasing human populations consume greater amounts of natural resources from a decreasing land base. Obviously, not all multiple uses are compatible. Past attempts to reduce conflict have resulted in separate land allocations such as natural areas, developed recreation sites, non-motorized and semi-primitive areas, research natural areas, botanical areas, and so on. Most often these designations are made piecemeal, without a comprehensive spatial plan, resulting in *de facto* zoning of land use. Such an approach works only when there is a large land base available to make designations, and only when a small portion of this land base has already been designated.

Multiple use and sustained yield remain the guiding principles for managing many forest lands in the United States. In the case of national forests, these management principles have been codified into law as the Multiple-Use Sustained-Yield Act of 1960. In this Act, multiple use is defined as managing "the national forests so that they are utilized in the combination that will best meet the needs of the American people". Likewise, sustained yield in the context of this legislation refers to "the achievement and maintenance in perpetuity of a high-level annual or regular periodic output of the various renewable resources of the national forests". Although the emphasis is on utilization and outputs, the concepts of multiple use and sustained yield apply to a broad spectrum of benefits and values that are derived from forest land.

Dealing with the complex problem of integrating commodity production with other values and benefits requires a more comprehensive and spatial approach than has been traditionally applied to managing forest ecosystems (Brown and MacLeod, 1996). By taking a landscape perspective, combined with improved analytical tools, forest managers add consideration of both space and time to the multiple use and sustained yield mandates (Crow and Gustafson, 1997*a*,*b*). In this chapter, a management tool is described that combines remote sensing and geographic information systems (GIS) in a computer model that allows planners and managers to examine the long-term ecological consequences of management decisions and to compare the impacts of alternative management approaches in both a spatial and temporal context. The tool is a timber harvest allocation model (HARVEST) that generates landscape patterns with spatial attributes resulting from the initial landscape conditions and potential timber harvest activities. The model is simplistic in that it does not attempt to optimize timber production or quality, nor is it useful to predict the specific locations of future harvest activity, because it ignores many considerations such as visual objectives and road access. Instead, the model stochastically mimics the allocation of stands for harvest by forest planners, using the constraints imposed by the standards and guidelines, and management boundaries. Modeling this process allows experimentation to link variation in broad management strategies with the resulting pattern of forest openings and age class structure. HARVEST was designed to operate with minimal data input requirements, and readily simulates management on large areas ($>10^6$ ha). Therefore, it is a strategic, not a tactical, planning tool.

HARVEST was developed as part of a research project to compare the landscape patterns that would result under different management plans for the Hoosier National Forest (Indiana, USA). The initial goal was to reduce the harvesting standards and guidelines of each management plan to a set of rules that could be applied to the landscape. A simulation model approach was adopted that allowed flexible input of parameters related to the standards and guidelines for timber harvest, and incorporated spatial information (in the form of GIS maps) about the boundaries of management areas where various management goals were assigned. With HARVEST, the object is not to find a scheduling solution (i.e., determining the order in which individual stands should be harvested), but to assess the spatial pattern consequences of general management strategies.

The conceptual basis for simulation of cutting patterns at landscape scales can be traced back at least to Franklin and Forman's (1987) paper in *Landscape Ecology*. Other similar pattern-generation models include LSPA (Li *et al.*, 1993), CASCADE (Wallin *et al.*, 1994, 1996), and the DISPATCH model of Baker (1995; this volume) as modified to simulate disturbance by timber harvest. Harvest scheduling programs, e.g., FORPLAN (Johnson and Rose, 1986), SNAP (Sessions and Sessions, 1991), STEPPS (Arthaud and Rose, 1996) have much greater data requirements, and were not designed for this type of strategic landscape pattern assessment.

Description of the model

HARVEST is a cell-based (raster) model designed to simulate harvest methods that produce openings greater than one cell in size. It was designed to simulate even-age silvicultural methods such as clearcutting, shelterwood and seed-tree, and the uneven-age group selection method. The group selection algorithm can also be used to simulate patch cutting, in which several small clearcuts are dispersed throughout a stand. HARVEST is not able to simulate other uneven-age harvest systems such as single-tree selection or variable retention (Franklin *et al.*, 1997) unless the cell size is smaller than the size of a tree crown.

HARVEST simulates one time step per model run. The length of time represented by the model run is input by the user. Although this feature requires the user to initiate a run at each time-step of a simulation of long time periods, it allows for modification of the management parameters at each step. The inputs to the model for multiple time steps are typically recorded in a batch file, so that real-time intervention is not required. This also allows replicates of simulations to be easily produced.

A number of simplifying assumptions were made in the development of HARVEST to reduce input data requirements, and enable it to quickly simulate harvest activity over a relatively large area. The first is that harvest allocations within timber production zones typically take a spatially random distribution over the period represented by the time-step of the model run. However, this assumption does not nullify the spatial constraints most important in management planning: harvest allocations are constrained by the locations of existing stands that are older than the rotation length, and by the boundaries of management zones. It is important to note that spatially clustered harvests can readily be produced by HARVEST when timber production zones are delineated to force clustering. For example, HARVEST simulations reported in Gustafson (1996) demonstrate the spatial effects of varying degrees of clustering harvests. It is only within timber production zones that HARVEST distributes harvests randomly. The spatially random assumption is based on an analysis of stands reaching rotation age, and past harvest allocations. Using nearest neighbor analysis (Davis, 1986) on ten subsets of Hoosier National Forest (HNF; located in southern Indiana, USA) stand maps (mean size of subsets = 3366 ha, s.d. = 1062 ha), the observed mean nearest-neighbor distance between stands of similar age was compared to the distance expected if stands were randomly distributed, and a *z*-statistic was computed. The null hypothesis that stands are randomly distributed could not be rejected at the 95% confidence level for eight of the ten subsets (see Gustafson and Crow, 1996).

HARVEST also ignores specific forest types, with the exception of a single, secondary generic class (e.g., conifer), for which the user can (optionally) define a different size distribution for harvests. This feature was incorporated into HARVEST to allow larger harvest units on conifer plantations. Stands of forest types that will not be harvested at all should be excluded from the input map presented to HARVEST. If some forest types will not be harvested in proportion to their abundance within the timber land base, then harvest of various forest types would need to be simulated independently, and the results mosaicked using a GIS. HARVEST uses age as a surrogate for merchantability, and ignores stocking density and size class. Access and operability are assumed to be uniform across the land base. Significantly large areas known to be inoperable should be excluded from the timber land base for the simulations. Remember that HARVEST was designed to allow comparison of the impacts of broad management strategies on forest spatial pattern over large areas, and not for more detailed, stand-specific decisions.

HARVEST uses a number of parameters that are commonly specified in the standards and guidelines of management plans. These include harvest size distributions, total area harvested, rotation length (understood by HARVEST to mean the minimum age of stands that can be harvested), silvicultural method (even-age or group selection) and the width of buffers that must be left around harvests. An important capability of HARVEST is the ability to allocate harvests only in portions of the landscape that are designated for harvest. Equally important is the ability to apply different management strategies to different portions of the landscape (management areas). The primary output is a forest age map that includes the location(s) of canopy-removing harvest activity. The age of even-age regeneration can be used as a surrogate for a number of forest structure characteristics including canopy closure and seral stage. Successional change (from one forest type to another) is not modeled by HARVEST.

HARVEST was written in FORTRAN 77, and was originally developed using ERDAS Toolkit routines to run within the ERDAS v. 7.4⁺ GIS environment. The ERDAS version is still available as Version 3.2. Version 4.1 is independent of ERDAS, allowing use of data exported from other raster GIS systems. Utility programs are available at the HARVEST Web site (URL given below) to convert map files in various text formats to the ERDAS 7.4 format, and to convert the output ERDAS files back into text format. These utilities can read and write data values in 1- , 2- , 3- and 4-digit integer formats, and also 8- and 16-bit ASCII characters. Input data must be in fixed column format. ARC/INFO users may use the command GRIDIMAGE to convert ARC grids into ERDAS 7.4 GIS files. However, ARC does not produce a full-length final record for ERDAS files, and so the files are not directly compatible with HARVEST. For ARC users, there is also available a utility that can be used to convert ARC-generated ERDAS files to a format that can be read by HARVEST. ARC/INFO users can use IMAGEGRID to convert HARVEST output files into ARC grid files.

Input data requirements for HARVEST are minimal: a stand age map, a stand ID map, and an optional forest type map if it is necessary to distinguish between two forest types (e.g., deciduous and conifer) that have different size distributions of harvest units. Timber harvest allocations are made by HARVEST using the stand age map, where grid-cell values reflect the age (in years) of the forest in that cell, and areas that are not to be harvested have a value of zero. HARVEST takes this GIS age map as input, and produces a new age map incorporating harvest allocations, where harvested cells take a value of 1 and unharvested non-zero cells increase in age by the time-step specified by the user. HARVEST also requires a map that contains a stand identification number for each forested cell. HARVEST records harvest information for each stand harvested (described below), which can be spatially linked to the landscape through this stand ID layer. This map is typically produced by passing the stand age map through a GIS clumping procedure so that contiguous cells of the same age are assigned the same stand ID number. Alternatively, an existing stand ID map can be used, provided that each stand has a unique ID value. The third (optional) input map is a land cover map that (minimally) contains the second forest type (e.g. conifer).

The parameters that are controlled by the user are listed in Table 12.1, with brief descriptions of their meaning and use. HARVEST allows control of the size distribution of harvest openings, the total area of forest to be harvested, and the rotation length (by specifying the minimum age on the input age map where harvests may be allocated). HARVEST generates a normal distribution of harvest sizes with a user-specified mean and standard deviation, and the user may truncate either tail of the distribution if desired. HARVEST allows the user to specify a different size distribution of harvests for up to one additional specific land cover type (for example, conifer). Should the user wish to harvest entire stands regardless of their size, HARVEST provides an option to constrain harvests by stand boundaries. The user can enter a very large mean size value, and each harvest will terminate when the stand becomes completely harvested. This option is also useful if management activity is to be constrained by existing stand boundaries. The model also allows buffers to be left between harvests, and between harvests and non-forested habitats. There are few parameters affecting the behavior of the model that are not under user control. Exceptions are: (i) the user cannot control the value assigned to harvested cells in the output age map (always a "1"), and (ii) the rules used to determine the type of forest found in the focal stand are fixed (described below). The random number generator is part of the source code, and can be examined or modified by interested users.

An ASCII file containing a record for each stand is produced on the first run of HARVEST, in which is recorded a user-specified integer code ("treatment code") for each stand harvested during that model run. This "treatment file" can be used on subsequent runs to control how HARVEST allocates harvests in stands that were treated during a previous run, and to record allocations made during the current run. For example, the user may specify minimum and maximum "treatment code" values, and HARVEST will not allocate harvests in stands with "treatment codes" outside that range. The user can also use this file to force HARVEST to revisit group selection stands at the appropriate time, and/or to prevent additional harvests in partially harvested stands. This file is the link between successive model runs, and represents institutional memory of previous management activity.

The two algorithms built into the model for determining the spatial dispersion of allocations are a random dispersion and a group selection dispersion. Under both algorithms, HARVEST selects initial harvest locations randomly within the timber management zones, checking first to ensure that the forest is old enough to meet rotation length requirements. Under the random dispersion algorithm, this suitable cell becomes the focal cell around which a harvest allocation will be made. Under the group selection algorithm, the stand in which this cell is located becomes the focal stand in which group openings will be allocated.

Group selection is implemented by HARVEST such that a proportion of a group-selected stand is cut during each entry. The number of cells (n) harvested

Table 12.1. *Parameters used by HARVEST to simulate alternative management strategies*

Parameter	Valid range	Data type	Description
Time step	≥1 (years)	Integer	Number of years represented by a model run. This value is added to the age of each (non-zero) cell in the input age map prior to harvest allocations.
Mean harvest size of primary forest type (PFT)	≥ 1 (cells)	Real	Specifies the mean value of the distribution of harvest sizes for the primary forest type.
Standard deviation (PFT)	≥ 0.0 (cells)	Real	Controls the width of the distribution of harvest sizes for the PFT.
Minimum size (PFT)	≥ 1 (cells)	Integer	Specifies the minimum allowable harvest size for the PFT. Enables user to truncate the left tail of the size distribution.
Maximum size (PFT)	≥ Minimum size (cells)	Integer	Specifies the maximum allowable harvest size for the PFT. Enables user to truncate the right tail of the size distribution.
Mean harvest size of secondary forest type (SFT)	≥ 1 (cells)	Real	Specifies the mean value of the distribution of harvest sizes for the secondary forest type. (optional)
Standard deviation (SFT)	≥ 0.0 (cells)	Real	Controls the width of the distribution of harvest sizes for the SFT. (optional)
Minimum size (SFT)	≥ 1 (cells)	Integer	Specifies the minimum allowable harvest size for the SFT. Enables user to truncate the left tail of the size distribution. (optional)
Maximum size (SFT)	≥ Minimum size (cells)	Integer	Specifies the maximum allowable harvest size for the SFT. Enables user to truncate the right tail of the size distribution. (optional)
Harvest mode:	"Group", "non-group"	Character	Group: small openings scattered within randomly selected stands; Non-group: harvests allocated at random locations.
Proportion (p) of a stand cut under group-selection	$0.0 < p < 1.0$	Real	How much of each group-selection stand will be allocated to small openings during the current model run.

Table 12.1. *cont.*

Total area to be harvested	≥ 1 (cells)	Integer	Total number of cells to be harvested. The model run is terminated when this number is reached.
Rotation length	≥ Time step (years)	Integer	Minimum age-value for cells to be harvested. Must include the time step that was added to ages at initialization.
Maximum age	< maximum age in map (years)	Integer	Maximum age-value for cells to be harvested. Must reflect the time step that was added to ages at initialization.
Width of buffers	0–20 (cells)	Integer	Distance (in cells) that must be left between harvested cells and any cells with value of 1 (prior harvests) or 0 (excluded areas).
Stay-within-stand option	"Y", "N"	Character	A switch to force HARVEST to stay within the stand boundaries for each allocation.
Treatment code	1–255	Integer	User-specified integer to flag all stands harvested during the current model run. For group-selection re-entries, this value is used to identify stands to be re-entered.
Minimum and maximum treatment codes	0–255	Integer	HARVEST will not allocate harvests in stands with "treatment codes" outside the range specified here.
Work array size	5–169 (cells)	Odd integer	Specifies the size of the work arrays. Used to improve performance when the harvest size distribution is small.
Random number seed	0–(2^{31}–1)	Integer	If a zero is entered, the random number generator is seeded using the system clock.

in a stand during each entry is calculated by HARVEST as a user-specified proportion (p) of the size of the stand (A):

$$n = (A \times p)$$

Selection of new stands for group selection is achieved with the "Generate" option of HARVEST, in which stands are randomly selected from those stands with an age greater than the prescribed rotation length, and small openings (groups of trees) within those stands are then randomly placed, with at least the user-specified distance between openings. Re-entry into previously group selected stands is achieved with the "Lookup" option, in which HARVEST allocates groups in all stands with a specific "treatment code" value stored in the "treatment file". During re-entry, groups are allocated on previously unharvested cells within the stand. The stands are allocated in numerical order by stand ID. The user must ensure that re-entries occur by invoking the "Lookup" option and specifying the same "treatment code" used to initiate the group-selected stands that are to be re-entered in the current model run. Because the group-selection algorithm disperses openings throughout a stand, it could be used to mimic single tree selection if the cell size is smaller than a tree crown. However, the ecological significance of such openings may be different than those produced when using HARVEST at the broader scale(s) for which it was designed.

Portions of the land base can be excluded from timber harvest by presenting HARVEST with an age map of only areas where harvest is allowed. Independent runs of HARVEST on different portions of a larger map may be used to simulate different management strategies on different portions (management areas) of the landscape. These management areas can later be mosaicked with the rest of the land base (using a GIS) to produce a map that characterizes the entire land base. A detailed example of the mechanics of implementing HARVEST is given in Gustafson (in press).

HARVEST has modest runtime memory requirements (approximately 390K), even for very large areas because the input maps are not loaded into memory. HARVEST uses an algorithm to access portions of the maps for processing. A log file is produced for each model run, recording all the input parameters and a summary of the runtime results.

HARVEST is relatively simple to use. The digital input maps can be derived from spatial data commonly maintained by land managers (i.e., stand maps with associated inventory information). The model parameters are relatively intuitive, and can often be derived from management planning documents. The (non-graphical) model interface requests parameter input from the user, and the model requires little technical skill to install and run. The user documentation is modeled after the ERDAS 7.5 user manual. HARVEST is useful as both a planning/management tool and a research tool. The model was developed to make it useful to strategic planners who wish to get coarse-filter answers to broad questions about potential alternatives, without the need for extensive training and technical support. Its initial development was spurred by research questions related to the landscape pattern consequences of forest management alternatives on the Hoosier National Forest. This dual role is consistent with the concept of management plans as working hypotheses (Levins, 1966; Baskerville, 1997). HARVEST allows exploration of the spatial consequences of management alternatives, and the results can be linked with other models relating spatial pattern to specific ecological processes (e.g., habitat suitability related to the pattern of fragmentation).

Algorithms

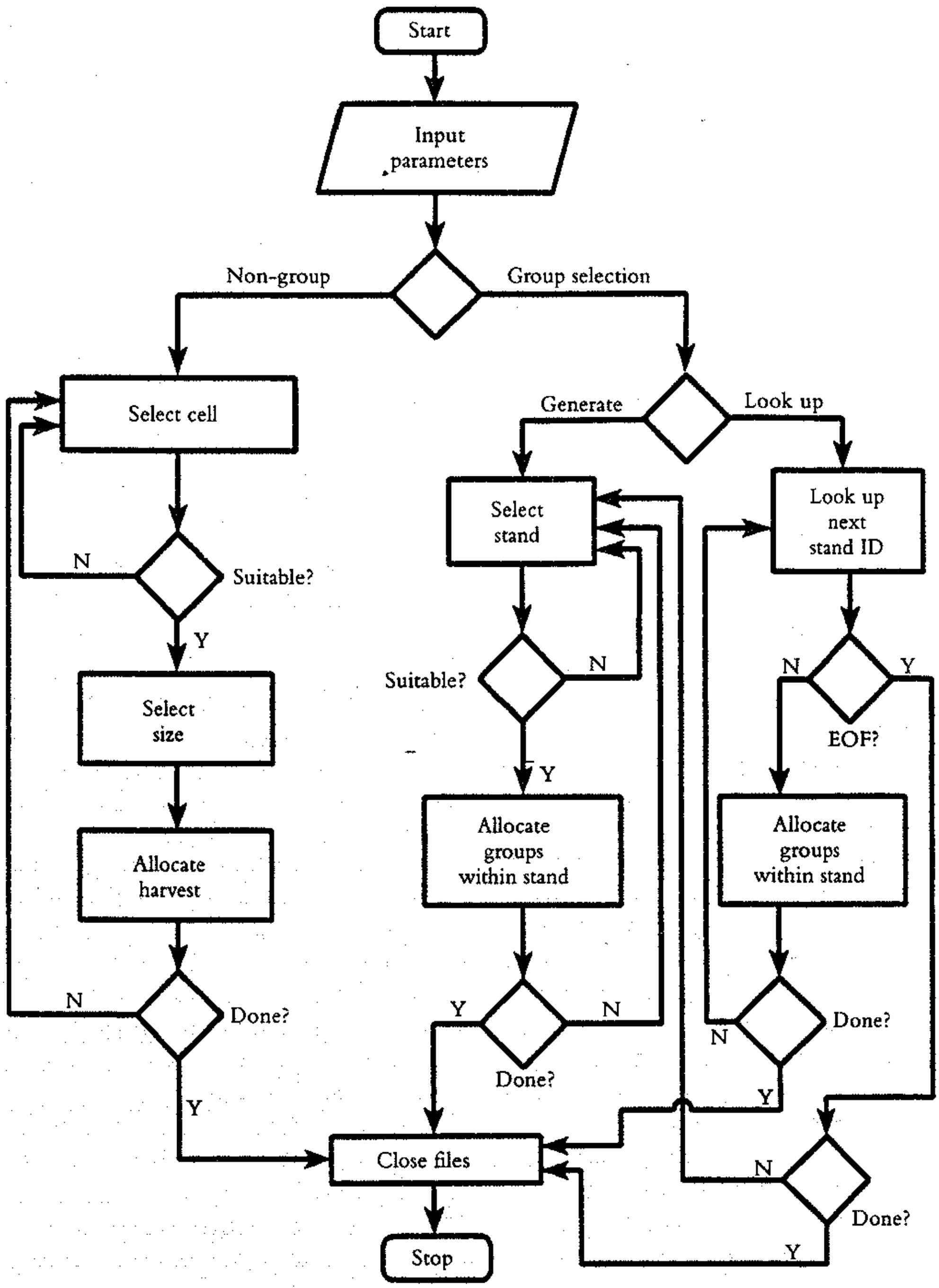
Simulations are implemented by HARVEST following the general algorithm shown in Fig. 12.1. After the files are open and the parameters input, HARVEST enters either the group-selection mode or the non-group mode, depending on the user's choice. Harvests are allocated until the specified number of cells have been harvested. The model run is terminated after the "treatment file" has been updated and all files closed. Because HARVEST was developed to run in an MS-DOS environment, memory limitations prohibited loading the input maps into memory. Harvest allocations are made by loading a portion of the map into a work array, modifying the cells harvested, and then writing the work array back into the map. The size of this array is controlled by the user, allowing faster execution speed when the expected size of harvest units is small (e.g., group selection).

Non-group harvest allocations

A randomly selected cell on the input map is examined to see if: (i) the cell is forested, (ii) the forest on the cell is older than the rotation length, and (iii) previous harvest activity has made the stand in which the cell is located unsuitable for harvest. If the cell is not suitable for harvest, new cells are chosen until a suitable cell is found. If HARVEST cannot find a suitable cell, it will notify the user and terminate. This suitable cell functions as a focal cell around which other cells will be harvested. HARVEST examines the land cover of the cells in a 17 × 17 cell neighborhood to determine the relative abundance of the primary and secondary generic forest type (e.g., conifer). The secondary type harvest size distribution is used if the abundance of the secondary type is >33%. A harvest size is then randomly selected from the appropriate harvest size distribution. If the size is outside the user-specified minimum and maximum, a new size is randomly generated.

The portions of the age map and stand ID map surrounding the focal cell are loaded into two work arrays. The data in these work arrays provide information used to determine whether individual cells meet the criteria for harvest as described below. Two logical arrays having the same dimensions as the work arrays are used to track the allocation of individual cells to the current harvest. The initial state of each array element is .FALSE. except for the center element (focal cell). Cells are added to the harvest in concentric rings (squares) around the focal cell. The algorithm uses a local Boolean expand operator, as described by James (1988, Chapter 6.) The two logical arrays are alternatively passed and returned as arguments to a subroutine that expands the current harvest by one additional concentric ring. Before a cell is actually harvested (set to .TRUE.) a check is made to verify that the cell is: (i) older than the rotation age, (ii) within the same stand as the focal cell (if the user has specified that harvests must stay within stand boundaries), and (iii) not too close (i.e., beyond the buffer distance) to another harvested cell or excluded area (zero valued cell). Thus harvests are usually square in shape, although

Fig. 12.1. Flow chart outlining the algorithm used by HARVEST to simulate timber harvest allocations. Input parameters are given in Table 12.1. The model run terminates (DONE?) when the user-specified number of cells have been harvested. See text for more details of the algorithms used in specific processes.



they do wrap around obstacles (e.g., cells within a buffer zone, or stand boundaries), and can take the shape of stands when large harvests are constrained to stay within stand boundaries. This allocation algorithm can only allocate contiguous cells. If the selected harvest size cannot be achieved because not enough suitable cells are contiguous, or the stand is too small, the allocation is made using the available cells. However, if the selected harvest size cannot be achieved because the work array is too small, HARVEST notifies the user, and records this event in the log file. The harvested cells are recorded by mapping all .TRUE. cells in the final logical array to a value of 1 in the age map work array. This array is then written back into the age map file, and the current "treatment code" is stored in the stand record for the stand of the focal cell in the "treatment file". The model continues to select new focal cells, iterating the allocation process until the total number of cells to be harvested is reached.

Group-selection harvest allocations

Group selection is simulated in two distinct modes: "Generate" (where group selection is first initiated in stands) and "Lookup" (where previously initiated stands are re-entered to allocate additional groups.) The "Generate" mode is implemented so that stands are selected randomly from the input age map, and then small openings (groups) are randomly placed within the stand boundaries. Stands are selected by randomly selecting cells using the procedure just outlined for non-group harvests. The cell is checked to determine if it meets the suitability requirements as outlined above. If it does, the stand containing the selected cell becomes the focal stand, and HARVEST loads the portion of the map containing the stand into the work arrays, and calculates the size of the stand. The total number of cells to be harvested within the stand is calculated as a proportion (input by the user) of the size of the stand. Each group (small opening within the stand) is allocated using the approach described for non-group harvests, except that all harvest allocations (groups) must be located within the focal stand.. The size of a group is chosen from the size distribution input by the user. (Forest types are not considered under group selection.) A random cell is chosen from within the stand, and it is checked to determine that it meets the age and buffer distance requirements. If it does, then the cell becomes a focal cell, and additional cells are allocated using the procedures outlined for non-group harvests. Groups are allocated until the proportion of cells to be harvested is reached. The age map work array is updated by the logical arrays and written back into the age map file, and the stand record in the "treatment file" is updated with the current "treatment code". The model continues to select new focal stands, iterating the allocation process until the total number of cells to be harvested is reached.

Group selection usually requires that stands be re-entered at intervals, to harvest additional groups. HARVEST provides the "Lookup" option to re-enter previously group-selected stands. In this case, HARVEST does not randomly select stands, but examines the "treatment file" to identify stands with a specific "treatment code" (input by the user). For each stand having the specific "treatment code," HARVEST finds the location of that stand, loads it into the work array, and allocates new groups on previously unharvested cells within that stand. If the total number of cells to be harvested has not been reached after all the stands to be re-entered are harvested, HARVEST enters the "Generate" mode to locate additional stands to be harvested by group selection (Fig. 12.1). The user is responsible to invoke the "Lookup" option at the appropriate time step(s), and to indicate the appropriate "treatment code" to properly simulate re-entries into the stands.

Model behavior and testing

HARVEST has been tested and used extensively by the authors since 1993, and it is well established that the model functions as it was designed. The behavior of the model has been demonstrated by testing the sensitivity of the results to variation in the main parameters (Gustafson and Crow, 1994). Mean harvest size was varied between 1 and 100 ha, in 10-ha increments, with a standard deviation of 10% of the mean; and total area harvested per decade was varied between 0 and 8% of the forest area within 23 593-ha forested landscapes, in 1% increments. We assumed that canopy closure occurred 20 years after harvest, and the amount of forest interior and forest edge habitat was calculated for each scenario using a GIS (Fig. 12.2). Group selection produces amounts of forest interior comparable to that produced in non-group mode when the number of stands harvested is held constant, because the same number of stands have canopy openings. However, when the number of cells harvested is held constant, group selection requires many more stands to reach the target, and fragmentation is usually higher (Gustafson and Crow, 1994, 1996). Group selection invariably produces more edge because of the higher perimeter-area ratios of smaller openings. Increasing the width of buffers that must be left around harvests reduces the amount of interior habitat when harvest levels are high, because the buffers serve to reduce clustering of harvest openings. Our studies have consistently shown that amounts of interior increase as harvests are clustered (Gustafson and Crow, 1996; Gustafson, 1996). However, the reduction of interior by increased buffer widths is negligible compared to the effect of dispersing harvests throughout a landscape at each time step (Gustafson and Crow, 1996; Gustafson, 1998*b*; Crow and Gustafson, 1997*b*). Forest fragmentation levels are most sensitive to the spatial restriction of timber harvests, even if these restrictions are temporary and their locations move across the landscape over time (Gustafson and Crow, 1996; Gustafson, 1996). Our experience has also shown that the variability in measures of forest fragmentation produced by replicates of model runs is generally quite low, and three replicates are usually adequate for robust results.

To verify that HARVEST produces patterns that mimic those produced by timber management, the past two decades of timber cutting were simulated on three study areas on the HNF (size range 34 053–49 515 ha). The ages of stands in 1968 and 1978 were reconstructed by subtracting 20 and 10 years, respectively, from each stand age in the 1988 stand age map. Stands with a calculated value >1

Fig. 12.2. Response surface showing (a) *the area of forest interior (>210 m from an edge or forest stand <50 years of age), and* (b) *showing the total length of forest edge (forest adjacent to an opening or forest stand <50 years of age) as a function of mean clearcut size and total area of forest harvested per decade. Simulations conducted using the landscape on a portion of the Pleasant Run Unit of the Hoosier National Forest.*

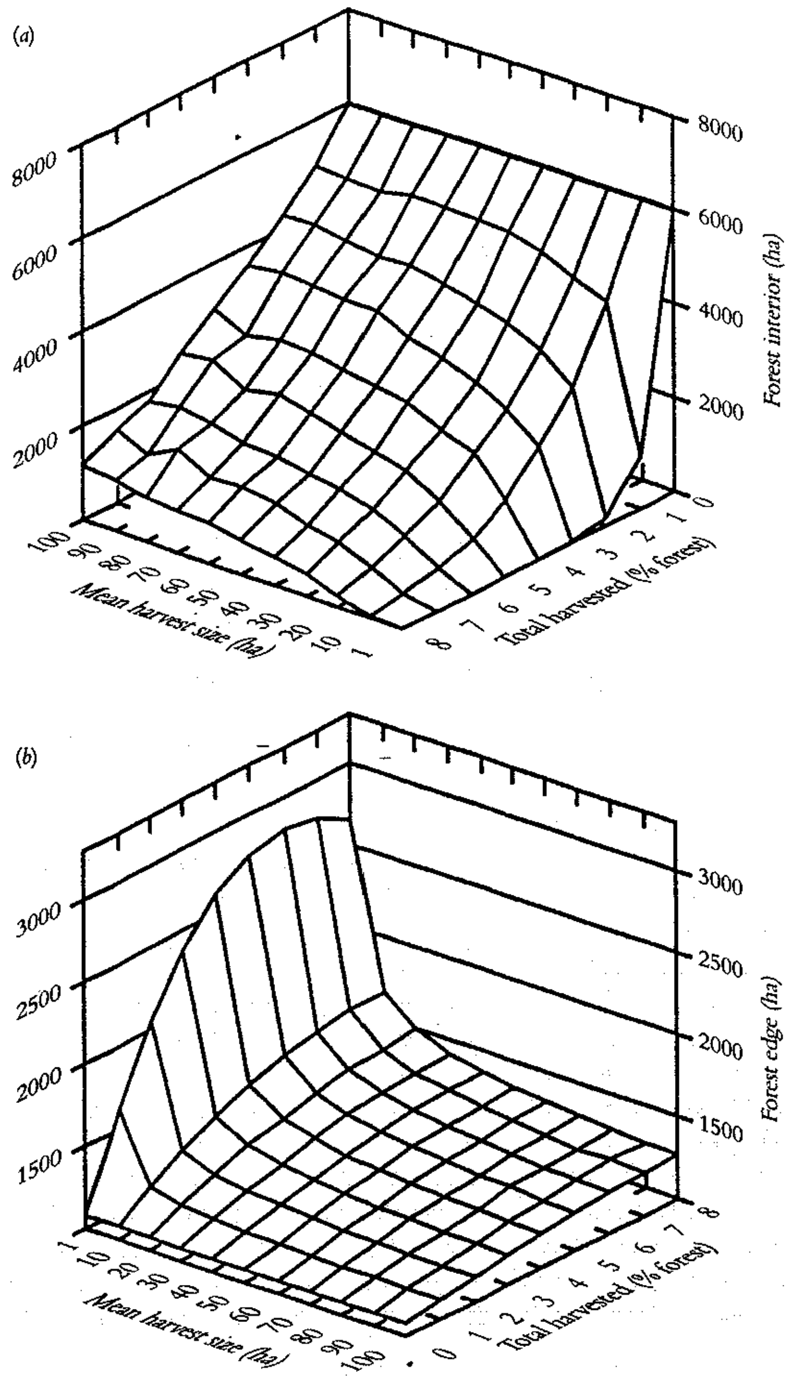
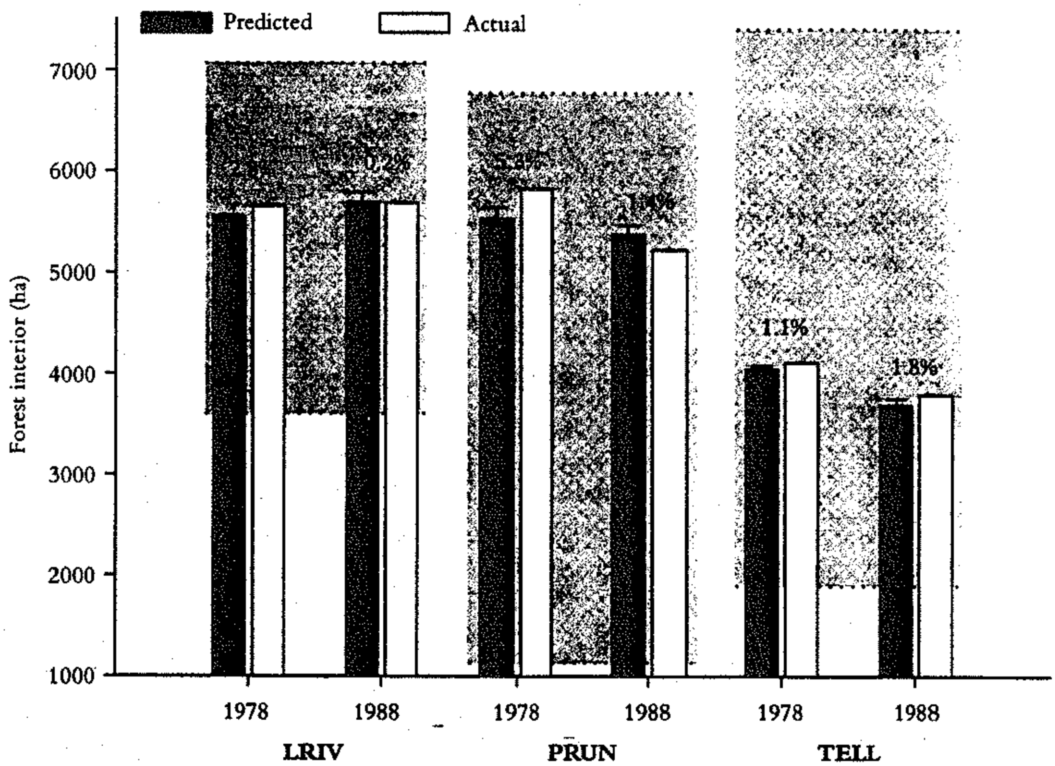


Fig. 12.3. Comparison of amounts of forest interior predicted by HARVEST and actual amounts estimated on three study areas (Lost River (LRIV), Pleasant Run (PRUN) and Tell City (TELL): see Gustafson and Crow, 1996 for more details) on the HNF. Error bars show 1 standard deviation based on three replicates. The possible range of values on each study area is shown by stippling, and the deviation from the actual amount as a percentage of the range is shown for each comparison.



were likely regenerated during the interval, and it was assumed that these stands were closed-canopy forest prior to regeneration. The mean size and total area of stands actually regenerated in each decade were determined by analyzing the size distribution and total area of stands that had their year of origin within each decade. These values were used as parameters to simulate harvest during the two decades since 1968, and the amount of forest interior and edge predicted by HARVEST compared to the amounts derived from the 1978 and 1988 age maps. A forest opening was defined as a harvested area <20 years of age, and the amount of forest interior (forest >210 m from a harvest opening or forest edge) and linear forest edge on each study area calculated for each decade. The amount of forest interior on a managed landscape is the result of the spatial distribution of forested lands, harvests, and areas reserved from harvesting. The possible range of forest interior on each study area given the current configuration of non-forested lands and HNF ownership is shown by stippling in Fig. 12.3. HARVEST predicted the amount of forest interior within 3% of the range possible on each landscape except PRUN in 1978, where the mean prediction departed from the actual by 5.3% (Fig. 12.3). Predicted amounts of forest edge deviated little from the actual amounts (not shown). This is not surprising since edge is related more to the size of harvests than their spatial location, and HARVEST is able to closely match the size distribution of the actual harvests. These results suggest that the simple rules used by HARVEST can mimic patterns produced by forest planners who typically allocate harvest units under complex constraints. The prudent user should verify that the assumptions of HARVEST do not diverge appreciably from practices to be implemented on the planning unit(s).

Applications of HARVEST

Most applications of HARVEST have been made on the Hoosier National Forest in conjunction with their forest planning. The 1985 Forest Plan for the HNF specified primarily clearcutting across most of the Forest. Due to public opposition to this Plan, an Amended Forest Plan in 1991 specified primarily group selection (removal of small groups of trees), limited to a much smaller portion of the Forest. Using stand information and Landsat TM imagery from 1988 as initial conditions, we simulated the effects of implementing each plan over a 150-year period (Gustafson and Crow, 1996). Assessments were made in terms of the amount of forest edge and the amount of interior forest produced by each over the simulation period. Despite the 60% decrease in timber production in the 1991 Plan compared to the 1985 Plan, the treatments proposed in the 1991 Plan produced almost as much forest edge due to the reliance on small harvest units with large perimeter-to-area ratios. Further, the restriction of harvesting to a more limited area in the 1991 Plan had a greater effect on landscape pattern than did differences in harvest intensity between the two Plans. If the management goal is to reduce forest fragmentation, our simulations suggest that the most effective strategy is to establish areas managed to maintain a continuous canopy along with areas of intensive harvesting, rather than reducing cutting intensity across the entire forest (Gustafson and Crow, 1996).

Our prior work has assumed that canopies are not opened by harvest practices on the private land interspersed throughout the HNF. Currently, most timber is harvested on private land using a diameter-limit harvest method (cutting every tree with a DBH >16–18″), and less than 2% of privately-owned timber is removed by clearcutting (Jack Nelson, personal communication). However, approximately 30% of diameter-limit harvests remove most of the canopy, leaving only sapling-size (<4″) trees (Glen Durham, personal communication) To determine the possible effects on forest fragmentation of timber harvesting on private land, canopy-removing harvest activities were simulated on 32% of private land (over a five-decade period), and those results linked with simulations of the two HNF Forest Plans reported elsewhere (Gustafson and Crow, 1996). Private lands tend to be on the margins of the contiguous forested blocks in this area, and our objective was to determine whether private timber cutting has the potential to significantly increase forest fragmentation. Our simulation of cutting on 32% of private land may represent a worse-case scenario. Six scenarios were simulated using a 3 by 2 factorial: three harvest regimes on the HNF (1985 Plan, 1991 Plan and no harvest) and two regimes on private land (harvest and no harvest). Three replicates of each scenario were produced. Parameters defining the size distribution of harvest openings on private land were derived from a sample of open-canopy harvests on private land using aerial photographs (1:40 000). Parameters for harvests on the HNF were derived from published Forest Plans (USDA Forest Service, 1985, 1991).

A portion (34 053 ha) of the Pleasant Run Unit of the HNF was used as a study area, in which 32.8% of the area is under private ownership (Fig. 12.4). Although the stand size distribution on private land is not known, conversations with local county foresters suggest that stand sizes are similar to those on the HNF. Because a stand age map of privately owned land was not available, a stand age map was generated with stand size and age distributions similar to those found on adjacent HNF land. This was done by simulating past harvest activity on private land since settlement (120 years), beginning with a homogeneous forest. The simulation of past activity was implemented so that the total area of stands produced each decade was varied to produce a stand age distribution similar to that found on the adjacent HNF land within the study area. Although today there are differences between private and public forest management, stands now reaching maturity were initiated when the (now) public land was privately owned, so it is not unreasonable to assume that such stands would have similar size and age distributions even though some are now under public ownership.

To evaluate the simulation results, a forest opening was defined as a harvested area <20 years of age, and calculated the amount of forest interior (forest >210 m from a harvest opening or forest edge) and linear forest edge at each time step for each scenario. The variation in forest interior over time was a consequence of: (i) a recent timber cutting moratorium on the study area that caused relatively high levels of interior in decades 0–2 due to regeneration, and (ii) the establishment of an equilibrium pattern under each harvest regime (Fig. 12.5(*a*)). Levels of forest interior and edge approach an equilibrium at decade 5 that persists for ten more decades (Gustafson and Crow, 1996). Two striking features are seen in the spatial distribution of forest interior: (i) cutting on private land has minimal impact on forest interior because it primarily occurs on the margins of contiguous forested blocks (compare Fig. 12.6(*a*) and (*c*) and (*b*) and (*d*)), and (ii) locating areas reserved from canopy-opening cutting within large contiguous blocks of forest can produce significant amounts of continuous canopy (compare Fig. 12.6(*c*) and (*e*)). Differences in the amount of cutting on private land also had very little impact on linear forest edge (Fig. 12.5(*b*)). Harvesting on the HNF under the 1991 Plan was primarily by group selection, with amounts of edge comparable to that produced by the 1985 Plan, even though the total area cut was much less.

Additional insights into strategies for minimizing forest fragmentation were

Fig. 12.4. Location and map of the study area showing the distribution of public and private land. HNF refers to land owned by the Hoosier National Forest, COE to land owned by the Corps of Engineers, and the remainder is privately owned. HNF land within the "reserved" polygons were withdrawn from timber production under the 1985 Land and Resource Plan and the 1991 Amended Plan.

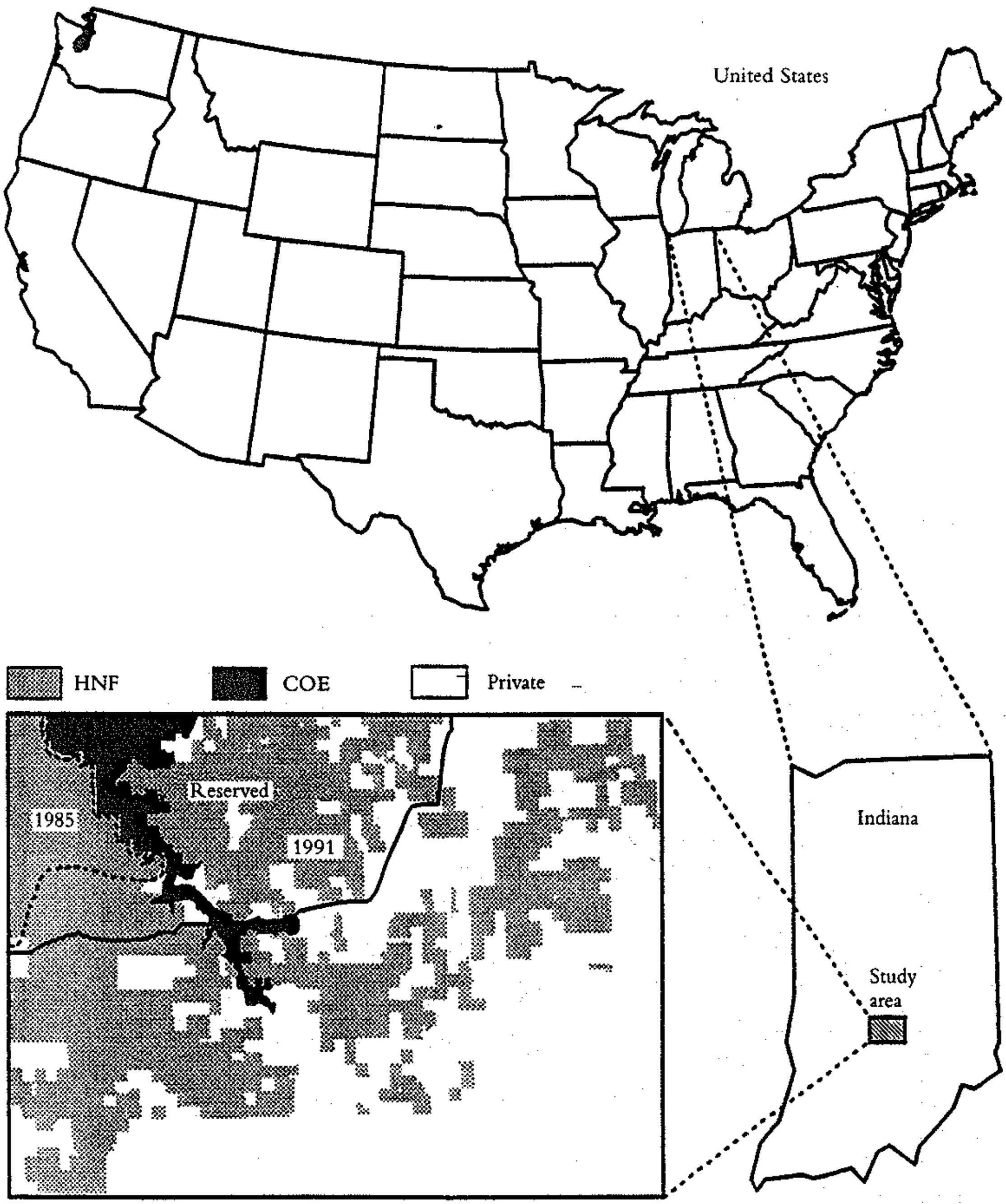


Fig. 12.5. Changes in the amount of (a) *forest interior habitat (forest >210 m from an edge or forest stand <20 years of age) and* (b) *linear forest edge over time resulting from simulation of timber harvest and no-harvest scenarios on the HNF and on private land. 85 HNF refers to harvests simulated under the 1985 Plan, 91 HNF refers to the 1991 Amended Plan, and No HNF represents no harvest openings produced on HNF lands. Private refers to harvest openings produced on 32% of privately owned land during the five decades simulated, and No Private refers to no harvest openings produced on private lands.*

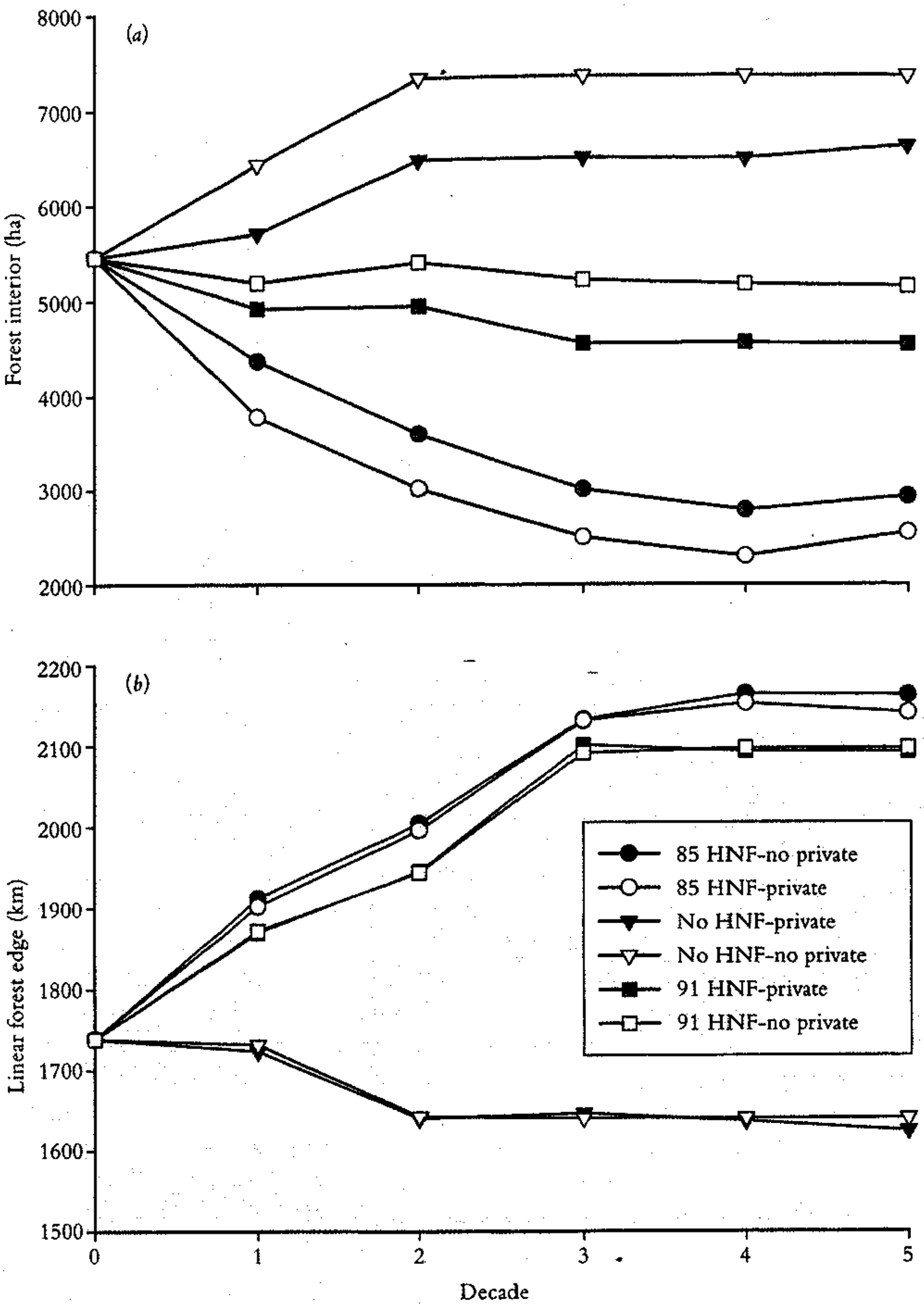


Fig. 12.6. Maps of forest interior (forest >210 m from an edge or forest stand <20 years of age) at decade 5 under alternative timber harvest scenarios: (a) *harvesting as specified in the 1985 Plan on the HNF, no harvest openings on private land;* (b) *no harvest openings on the HNF, harvest on private land;* (c) *harvesting as specified in the 1985 Plan on the HNF, harvest on private land;* (d) *no harvest openings on the HNF, no harvest openings on private land; (e) harvesting as specified in the 1991 Plan on the HNF, harvest on private land. Openings located on COE and Reserved lands (see Fig. 12.4) represent non-forest land cover that existed at the beginning of the simulation (1988) that were assumed to persist throughout the simulated period.*

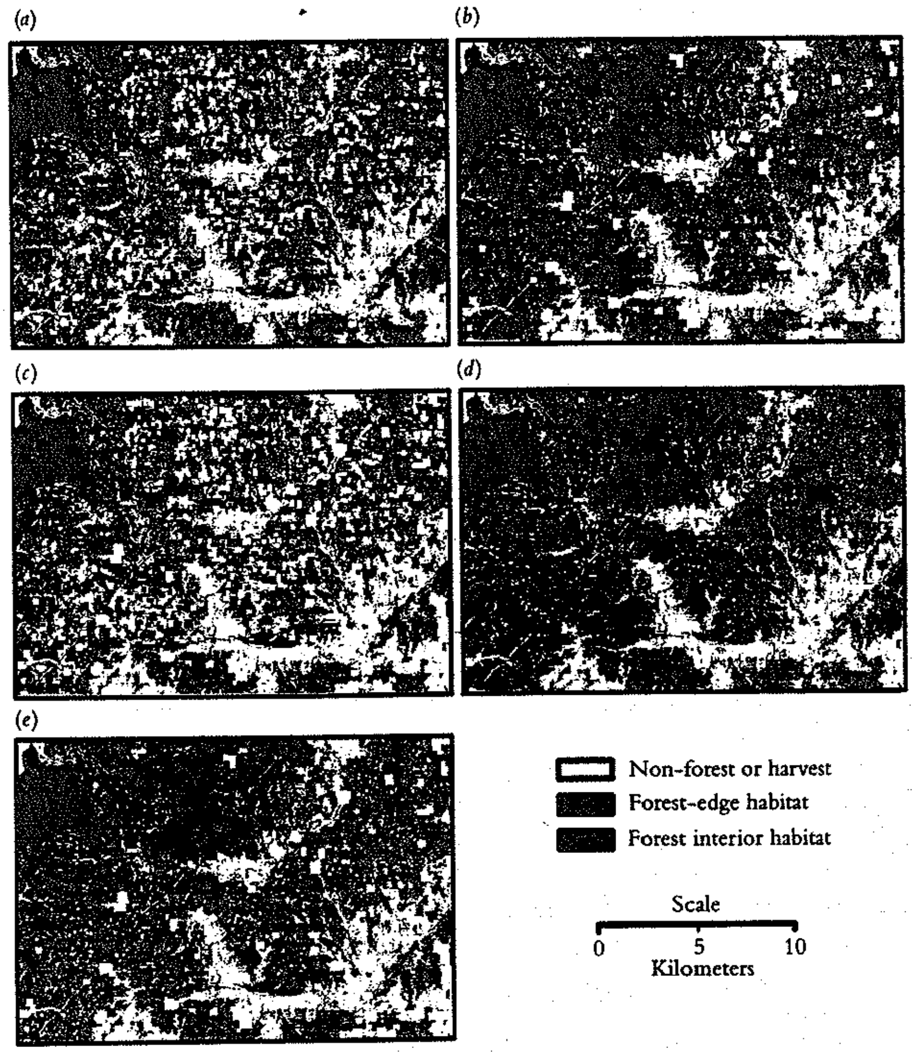
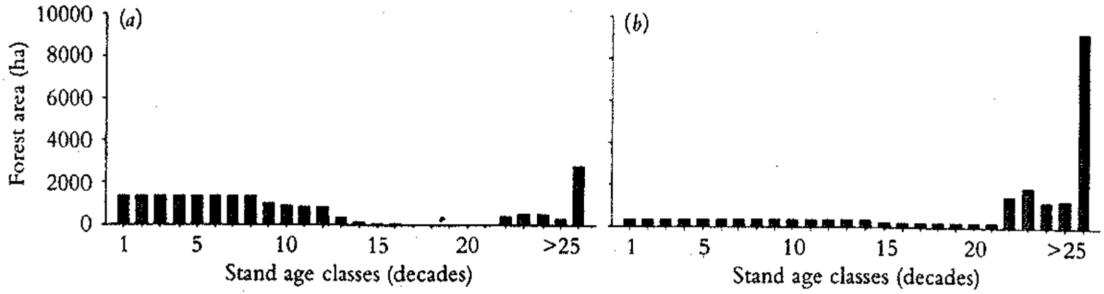


Fig. 12.7. Stand age distributions after 210 years of timber harvests under the (a) *1985 HNF Forest Plan, and* (b) *1991 HNF Forest Plan. Adapted from Gustafson and Crow (1996).*



gained by applying HARVEST in both a temporal and spatial domain (Gustafson, 1996, 1998*a*). Again, based on simulations with real landscapes on the HNF, harvest strategies that produced the greatest clustering in time and space provided the greatest reductions in forest fragmentation when considered over the entire forest. This approach, called "dynamic zoning" (Gustafson, 1996), allowed increased timber production while reducing forest fragmentation. It illustrates the importance of thinking along scales of time and space when considering harvest allocations, and more generally, when contemplating alternative landscape designs for multiple uses. It is also a good example of the investigation of the spatial consequences of novel management paradigms. With the aid of HARVEST, the ability to explore the spatial and temporal elements of the multiple-use concept has been added.

Changes in age-class structure as related to alternative harvest strategies can also be studied with HARVEST. Again, using HNF simulations as examples, striking age-class distributions result when a static management strategy is maintained over long periods (Fig. 12.7). In the case of the 1985 Plan, even distributions of young age-classes occur up to rotation age. In this case, two-thirds of the timber base was to be managed with a rotation length of 80 years. The harvest strategy proposed in the 1991 Plan resulted in a preponderance of young and old stands, with a dramatic reduction in mid-age stands (Fig. 12.7) when simulated over 150 years. The premise that management applications can be held constant over long periods is obviously questionable. However, the ability to identify age-class distributions and potential gaps in the distributions that are produced by various management alternatives has great value for forest planners and managers.

Linking pattern with process

While predicting changes in landscape structure using spatially explicit models is relatively straightforward, understanding the impacts of these changes on ecological processes is more difficult. In an attempt to understand the relation between landscape pattern and ecological process, Liu *et al.* (1994) linked a spatially explicit model with an object-oriented model to simulate the population dynamics and extinction probability of Bachman's Sparrow (*Aimophila aestivalis*) in landscapes with different amounts and distributions of mature pine. Schulz and Joyce (1992) investigated the spatial application of a pine marten (*Martes americana*) habitat model. Hastings (1990) provided a more general discussion about incorporating spatial heterogeneity in population models. We have assessed the potential consequences of alternative patterns produced by HARVEST for a generalized neotropical migrant forest bird using a GIS model predicting the spatial distribution of the relative vulnerability of forest birds to brood parasitism by brown-headed cowbirds (Gustafson and Crow, 1994). While most models that relate ecological process with landscape pattern are simplistic – they generally deal with a single species, or at best, a guild of species – they serve as useful prototypes for future work in understanding the relation between land management, biological process, and ecological function.

Future utility for HARVEST is envisioned as a generator of forest patterns that can be used as input to models of population dynamics and other ecosystem processes. The premise of landscape ecology is that there is a strong relationship between the spatial pattern of ecosystem elements and ecological processes. The coupling of ecological process models to patterns expected under specific management alternatives provides a link that is desperately needed by management planners. HARVEST also holds promise as a tool for the investigation of the effects of scale (resolution and extent) on the representation and quantification of spatial pattern as it is related to forest ecosystems. These issues remain unresolved, but are critical to the practical implementation of ecosystem management (Wiens, 1997; Gustafson, 1998*b*).

Significance of approach

HARVEST is a timber harvest allocation model designed for efficiency and flexibility. The model simulates the impacts of even-age harvest (clearcut and shelterwood) and group selection on landscape pattern through time. Realism in the model is provided through application to existing landscapes by using classified Landsat TM imagery and digitized maps of stand ages as model inputs. Further, the rules controlling the allocation and size of harvest units can be based on the actual standards and guidelines developed in forest management plans. Other input variables include the rotation age (specified as a minimum age for harvest) and the percent of forested area to be harvested per unit time.

The utility of HARVEST is enhanced by using digital maps for both input to and output from the model. HARVEST is designed to be used in conjunction with a grid-cell geographic information system (GIS), with routines for direct input and output of ERDAS files along with support for moving files from other raster-based GIS programs. Timber harvest allocations are made by HARVEST using a digital stand map, where grid-cell values represent the age of the forest in that cell. Using the stand age map as input, HARVEST then produces a new stand age map incorporating harvest allocations. The output from the model can be integrated with a landscape map produced from other sources (e.g., satellite imagery). While landscape patterns incorporated in these maps can be quantified using any number of landscape metrics, comparisons among management alternatives can be expedited by simple visual comparisons of simulated landscape patterns (e.g., Fig. 12.6.). This spatially explicit tool, when applied through time, allows for considering both the spatial (where?) and temporal (when?) components of resource management questions (Crow and Gustafson, 1997*a*,*b*). Because the model requires little technical skill to install and run, and because it has minimal data requirements, it provides a strategic modeling tool that can be useful to planners seeking to assess general and perhaps novel management alternatives. Consideration of the most creative and novel alternatives are discouraged when their evaluation is costly and time-consuming. HARVEST represents a tool that that may encourage exploration of creative and risky options at the beginning of the planning process. It is at this stage that such options have the greatest likelihood of becoming viable. It is the large-scale decisions about the spatial zoning of timber management activities that have the most profound impact on spatial pattern and ecological processes, and the ability to simulate large-scale strategic options is critical for effective and efficient land management decisions.

Availability of HARVEST

HARVEST is available without cost on the Internet. Detailed user documentation, the software and source code can be downloaded from the North Central Forest Experiment Station World Wide Web site (http://www.ncfes.umn.edu) under "Research Products". Information about how to contact the authors is kept current at the Web site. A Windows version of HARVEST will be available on this web site by summer of 1999.

Acknowledgments

The development of HARVEST was funded by the North Central Forest Experiment Station of the US Forest Service, and by the Hoosier National Forest. Critical comments by W. L. Baker and an anonymous reviewer improved the manuscript.

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