Assessment of Sustainability in Intensively Managed Forested Landscapes: A Case Study in Eastern Texas

João C. Azevedo, X. Ben Wu, Michael G. Messina, and Richard F. Fisher

Abstract: We developed a methodology to analyze the effects of management practices on landscape structure and function to be used in the assessment of sustainability in intensively managed forest landscapes. It is based on modeling and simulation of landscape and stand structure as well as biological and physical processes. The methodology includes a landscape structure model and several forest stand-level models to simulate the dynamics of landscapes and stands as a function of management rules. It also includes habitat models to evaluate landscape quality and spatial characteristics of vertebrate habitat, and a hydrologic model to simulate water and sediment yield at the subarea and watershed levels. The application of this methodology to the Sustainable Forestry Initiative (SFI) program in eastern Texas indicated that this is an effective way to evaluate effects of sustainable forestry programs on landscape structure and processes. During simulation years, the habitat of pine warbler, the species used as an example to illustrate the methodology, became apparently fragmented under the SFI scenario. This fragmentation was caused mainly by narrow, forested streamside management zones dissecting pine stands and should have little negative influence on the pine warbler habitat. Sediment yield at the landscape level decreased by the implementation of SFI measures, particularly by the reduction of channel degradation. FOR. SCI. 51(4):321–333.

Key Words: Sustainable forestry, landscape model, growth and yield models, hydrologic model, SFI.

SUSTAINABILITY IS A MAJOR ISSUE for politicians, managers, scientists, and the public (Christensen et al. 1996, Mebratu 1998). In forestry, sustainability has become an important goal in planning and management. Several initiatives started defining concepts, guidelines, and strategies for sustainable management at global, regional, and local scales. The United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro in 1992 was the first major international effort addressing sustainability in forests. The Statement of Forest Principles and the Convention on Biodiversity defined priorities and guidelines for sustainable management of forests. The Montréal Process in North and South America, Russia, Asia, and Oceania, and the Helsinki Process in Europe assumed the importance of sustainable forestry at the global and continental scales and defined principles and practices to be adopted by signatory states. Virtually every country is currently defining and/or applying sustainability measures for its forests (Rametsteiner and Simula 2003).

In the United States sustainability has become the goal in national forests (Thomas 1995, USDA Forest Service 2000) that have been managed according to approaches such as ecosystem management (Szaro et al. 1998), ecosystem health (USDA Forest Service 2000), or ecosystem integrity (Vora 1997). The Sustainable Forestry Initiative (SFI) currently defines principles and practices of forest sustainability for much of the forest products industry (Cantrell 1998) and others. Several programs are available to nonindustrial private forests such as the American Tree Farm System, Forest Stewardship Program, and Green Tag Forestry, among others.

Different concepts of sustainability in forests have been presented, including sustainable ecosystem management (Swanson and Franklin 1992, Szaro et al. 1998), sustainable forestry (Cantrell 1998), or sustainable forest management (Peng 2000). However, these concepts overlap to a great extent. All are management concepts, all are based on the maintenance of vital structures and functions of the forest ecosystems, and all require the integration of environmental, social, and economic perspectives in the management of forest ecosystems.

Addressing sustainability requires a multiple-scale approach (Christensen et al. 1996). Broad-scale considerations have been central in land planning, nature conservation, and land management and are essential to address sustainability in both natural and managed systems (Lubchenco et al. 1991, Forman 1995). In forestry, problems related to biodiversity, water quality, and management practices also require a landscape approach (Andersson et al. 2000). Many

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of the criteria and indicators of international forest certification programs require broad-scale criteria to be defined and applied (e.g., Montréal Process Working group 1999, Ministerial Conference on the Protection of Forests in Europe 2003). Criteria such as water, habitat and species conservation, maintenance and encouragement of productive functions of forests, or maintenance of ecosystem health, rely strongly on the spatial characteristics of the ecosystems considered at broad scales. Many specific guidelines at the landscape scale are provided in national forestry programs, such as the SFI in the United States.

Landscape-scale implications of forest management practices have received particular attention by researchers. Considerable amounts of work have focused on either the study of the structure of the forested landscapes according to different management strategies or plans (e.g., Spies et al. 1994, Crow et al. 1999) or modeling of structure as determined by management practices such as regeneration method, harvesting frequency, and spatial pattern of harvest (e.g., Gustafson and Crow 1996, Baskent 1999, Shifley et al. 2000). Landscape structure implications of forest policy have also been investigated through simulation (Hagan and Boone 1997, Cissel et al. 1998).

We developed a methodology for assessing the sustainability of forest landscapes by combining landscape structure and biophysical processes in a modeling and simulation approach. This methodology uses available and reliable models and aims to provide planners and managers with a tool useful in testing planning and management decisions with spatially explicit assessment of the structure and functions of landscapes. Vertebrate habitats and hydrologic processes are used as key components of landscape function to be related to forest and landscape structure. We applied this methodology in a case study to assess the influence of the SFI on the sustainability of forest landscapes in eastern Texas.

The SFI program was launched in 1994 and has been applied to 55 million hectares of forestland (American Forest & Paper Association 2003), >90% of all the industry-owned forest in North America (American Forest & Paper Association 2002). The current SFI standard is provided in American Forest & Paper Association (2005). To be in compliance with SFI guidelines, forest products companies are implementing landscape-level measures such as establishment of buffer zones along streams, establishment of wildlife corridors, limitation on size of harvest units, and application of adjacency rules. Some of these requirements, such as buffer zones along streams, were originated before SFI and are part of state Best Management Practices and have been used as part of an effort to improve sustainability by SFI participants. Although established with the purpose of minimizing negative effects of forestry on water, soil, and wildlife, these measures have not been explicitly analyzed in a landscape context.

Several other modeling approaches have been developed that simulate landscape pattern and process, and the influence of management. Hansen et al. (1992) integrated a habitat model with a landscape pattern simulator to analyze effects of landscape change on avian communities. The LEEMATH model (Li et al. 2000) was designed to evaluate management strategies at the landscape level based on timber production and habitat quality in the Southeast. TELSA simulates the effects of management on plant succession and disturbance (Kurz et al. 2000). LANDIS (Mladenoff and He 1999) integrates succession, windthrow, fire, and management in forest landscape dynamics. It also allows other model components to be integrated, providing a way of simulating effects of management or natural changes on timber harvesting (Gustafson et al. 2000), plant processes (He et al. 2002b), metapopulation dynamics (Akçakaya 2001), fire spread (Pennanen and Kuuluvainen 2002), or climate change (He et al. 2002a). Weber et al. (2001) integrated an ecological and a hydrologic model with an agro-economical simulation model to analyze impacts of land use change on economics, landscape pattern, biodiversity, and water processes in agriculturally dominated landscapes.

The methodology presented here shares many aspects with the models mentioned above. It differs from them, however, in that it uses available models that are suitable for eastern Texas, is relatively simple to use, and requires minimal input data. Additionally, the methodology is focused on the dynamics of intensively managed forested landscapes that rely on short rotations and fine temporal and spatial resolutions.

Methodology Development

Approach, Criteria, and Indicators

A landscape approach to forest sustainability requires integration of structure and function at several scales in a multidisciplinary perspective. However, modeling and simulation are often the only alternatives in landscape studies given the difficulty in performing experiments at this scale (Turner 1989) and the immediate need of results to support management decisions. The methodology presented here includes a landscape model and several forest stand-level models to simultaneously simulate the dynamics of landscapes and forest stands as a function of management rules and initial conditions. Quality and spatial pattern of wildlife habitat, as well as hydrologic processes, are evaluated at both scales (Figure 1).

For the purposes of this work, we considered sustainable forestry to be the management of forest systems ensuring that essential ecological structures and functions are maintained. Criteria of sustainable forestry are the elements defining the scope and outputs of forest management (Brand 1997), including environmental, social, and economic dimensions. The criteria selected here were water, soil, and biodiversity maintenance. Water and soils were selected because they are key physical components of the ecosystem. These components correspond to criterion 5 of the Helsinki Process (Ministerial Conference on the Protection of Forests in Europe 2003) and criterion 4 of the Montréal Process (Montréal Process Working Group 1999). Biodiversity was used to represent the biotic components of the ecosystem

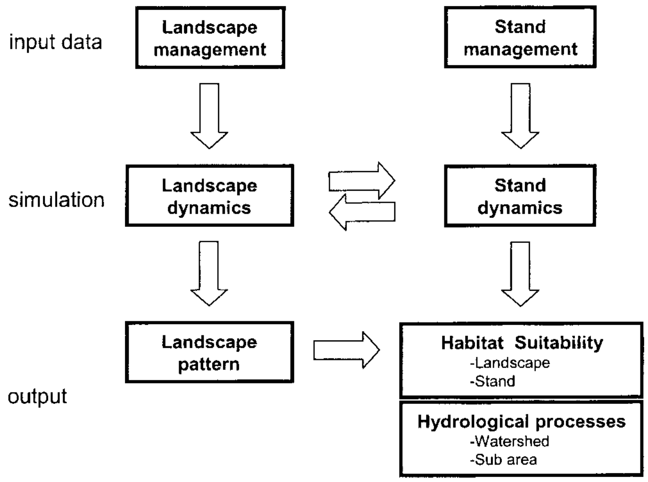

Figure 1. Representation of the methodology and relations among components.

and usually is vulnerable to human activities. It corresponds broadly to criteria 4 and 1 of the Helsinki and Montréal Processes, respectively.

Indicators are measurable features of the criteria (Brand 1997) or variables that could be used to measure the status of a system or process (Mendoza and Prabhu 2003). The indicators considered here include soil loss, water yield, and the amount, quality, and spatial pattern of habitat for vertebrate species. Soil loss is a good indicator of ecosystem and landscape degradation, and a considerable amount of data on soil loss is available for many conditions in different regions. The amount and pattern of water yield, besides indicating the water available for other uses, are critically important for stream ecosystems and reflect the condition of the vegetation in the watershed. Simulated annual and monthly water yields can be compared with data from watersheds to evaluate the impacts of management on this component. Although the use of indicator species is a controversial matter (Simberloff 1998), the analysis of structural elements of ecosystems and landscapes related to habitats of species is an acceptable approach for accessing biodiversity (Lindenmayer and Franklin 1997, Lindenmayer et al. 2000).

Components

Landscape Simulation

The model HARVEST 6.0 (Gustafson and Rasmussen 2002) was selected to simulate management measures at the landscape level. This is a raster model designed to simulate the spatial deployment of even- and uneven-aged silvicultural systems. HARVEST incorporates parameters used in forest management such as silvicultural method, harvest unit size, total area harvested, rotation length, and green-up interval, among others (Gustafson and Crow 1999). As inputs, it requires maps on forest types, age of stands, management zones, and stand identification. Time step length is variable with the minimum being 2 years, which is adequate for short-rotation systems. This model has been extensively used in analysis of forest pattern as affected by forest management (e.g., Gustafson and Crow 1996, Gustafson and Crow 1998, Gustafson and Rasmussen 2002).

Stand Simulation

Stand-level attributes were simulated using growth and yield models. These models provide data required for the analysis of habitats and hydrologic processes. We chose a set of models based on the characteristics of the forest ecosystems and the typical silvicultural systems of the West Gulf Coastal Plain. Other models should replace the ones used in this study to better describe composition, growth, and silviculture of forest stands in other regions.

We used Compute P-Lob (Baldwin and Feduccia 1987) for planted even-aged loblolly pine (*Pinus taeda* L.) stands. This is a stand-level model for thinned and unthinned site-prepared loblolly pine plantations. P-Lob estimates height, basal area, density, biomass, and volume distributions by diameter classes. It simulates stand management practices in terms of initial density, site index value, age and number of thinnings, and residual basal area or density of thinning operations.

SouthPro (Schulte et al. 1998) was chosen for uneven-aged stands. This is a site- and density-dependent, multi-species matrix model that estimates growth of uneven-aged stands of loblolly pine and hard and soft hardwoods (Lin et al. 1998). Regeneration, growth, and mortality are affected by stand density, site productivity, and interactions among trees of different species and sizes (Schulte et al. 1998). SouthPro calculates distributions by diameter class intervals based on initial distributions and according to target distributions. This model was used for uneven-aged loblolly pine, hardwood, and pine-hardwood mixed stands. It is particularly relevant for streamside management zones (SMZs), buffer strips along perennial and intermittent streams assumed to be managed by uneven-aged management to maintain a minimum basal area of 11.5 m^2/ha as required in Texas (Texas Forest Service 2000).

The forest vegetation simulator (FVS) (Donnelly et al. 2001) is an individual tree growth model used in this work to simulate hardwood stands managed by the clearcutting system. It is the only model found that is suitable for simulating dynamics and management in the hardwood stands in this region.

Habitat Suitability

Habitat suitability was evaluated at the stand and landscape levels using habitat suitability index (HSI) models (Schamberger et al. 1982). These single-species models were developed in the 1980s with the purpose of quantifying impacts of water or land use changes (Schamberger et al. 1982). Although their utility as habitat models has been criticized (Roloff and Kernohan 1999), HSI models provide an expedient and standardized way of quantification of habitat suitability on a 0 to 1 scale assuming a direct linear relationship with carrying capacity (US Fish and Wildlife

Service 1981). These are not carrying capacity models, however, because other variables affecting abundance (e.g., predation, weather, competition) are not included (Schamberger and O'Neil 1986).

HSI is calculated based on quantitative relationships between suitability and measurable components of the habitat, particularly structural components. For many forest vertebrate species, habitat variables can be obtained from inventory data or estimated from vegetation or growth and yield models. HSI at the landscape level was calculated as HSI average weighted by the size of the stands. The spatial pattern of suitable habitat areas was analyzed based on landscape metrics calculated with FRAGSTATS (McGarigal and Marks 1995), version 3.3, for maps resulting from the classification of the HSI values in the following classes:

- Class 0: HSI = 0.
- Class 1: 0.01 < HSI ≤ 0.25.
- Class 2: 0.25 < HSI ≤ 0.5.
- Class 3: 0.5 < HSI ≤ 0.75.
- Class 4: 0.75 < HSI ≤ 1.

Hydrologic Processes

The effects of management on water yield and soil loss were simulated with the Agricultural Policy/Environmental eXtender (APEX) model, version 1310 (Williams et al. 2000). This is a mechanistic model that combines the EPIC model (Environmental Policy Integrated Climate) (Williams 1995) with routing capabilities, allowing the analysis of processes occurring simultaneously at the field and watershed levels. The main purpose of APEX is to estimate long-term sediment, nutrient, and pesticide yields from whole farms and small watersheds (Williams et al. 2000). Processes include runoff, sediment deposition and degradation, nutrient transport, and groundwater flow in the subarea and landscape (Williams et al. 2000). The model has been recently modified to describe hydrology in forested areas (Saleh et al. 2003). APEX is able to account for the effects of buffer strips, one of the major management measures of sustainable forestry programs.

Information Exchange among Models

The models were run stand-alone and information exchange among them occurred external to individual models. HARVEST produced landscape maps every two years of the simulation period using landscape structure maps prepared in a GIS according to management criteria as inputs. Stand ID, age, management type, and site index were used to link individual stands in the GIS coverage with stand structure data simulated in the growth and yield models for the respective management type and site index and with HSI scores calculated according to the HSI models. HSI variables and final scores were calculated at the stand level externally to the GIS, using information provided by the growth and yield models. HSI maps from the GIS were used as inputs in the landscape metrics calculation performed in FRAGSTATS. APEX files used information obtained from maps provided by HARVEST and particular characteristics of the stands provided by the growth and yield models.

Case Study

A case study using the methodology was conducted in a 5,773-ha area located in Angelina County, Texas, and part of the watershed of Shawanee Creek, Neches River (Figure 2). The area was dominated by a large riverine bottomland. Overall, the terrain shapes were smooth and slopes average only 2%. Soils were predominantly Ultisols (Rosenwall series) and Alfisols (Diboll series). Elevation ranged from 41 to 113 m above sea level. Mean annual rainfall was 1,054 mm and mean annual temperature was 19.4 C. Most of the area was owned by Temple-Inland Forest Products Corporation, Diboll, TX, and managed for industrial forestry. Forest types were mainly loblolly pine (82% of the area), hardwoods (14%), and pine-hardwood mixed stands (4%). Approximately 70% of the area is managed by even-aged silviculture with the clearcutting regeneration method.

Modeling and Simulation
Landscape Level

A scenario where SFI management practices were simulated (SFI scenario) was compared with a reference scenario managed without these practices (non-SFI scenario). The non-SFI scenario is constructed to compare SFI to possible past management and does not imply current practices elsewhere in the state under the guidelines of the state Best Management Practices. The SFI scenario resulted from the application of the following constraints:

- Harvest unit size limit: pine, 49 ha; hardwoods, 12 ha.
- Buffer zones: SMZs, 30 m or wider along perennial and intermittent streams.
- Adjacency: units must have 3-year-old trees before adjacent areas can be harvested.

A GIS coverage of the study area provided initial conditions for defining management scenarios. Buffer zones were created around all temporary and permanent streams,

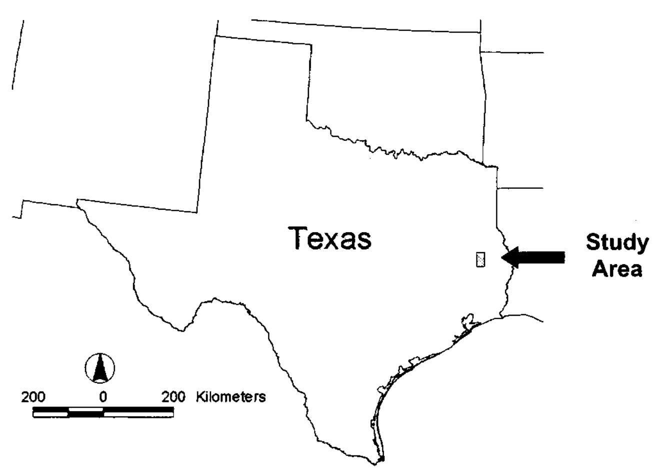

Figure 2. Location of the study area.

and pine stands larger than 49 ha were subdivided. Forest type classes were pine, hardwood, and pine-hardwood according to the percentage of basal area of each tree species group in the stand. Stands that had more than 70% of their basal area in pine were called pine stands, stands with more than 70% of their basal area in hardwood were called hardwood, those that fell between these limits were called pine-hardwood stands. Management types considered included the (1) pine-clearcutting system, (2) hardwood-clearcutting system, (3) pine-selection system, (4) hardwood-selection system, and (5) pine-hardwood-selection system (Table 1; Figure 3). Group selection was used in all of the selection system management types. It was assumed that SMZs would be composed of hardwoods and would be managed by the hardwood-selection system.

The reference scenario (non-SFI) was developed by modifying the initial GIS coverage: mixed stands were converted into pine stands; existing SMZs were dissolved into the pine stands and no new SMZs were established; stands with similar forest type, age, and site index were merged. Forest types were pine and hardwood only and management types were reduced to (1) pine-clearcutting system, (2) hardwood-clearcutting system, and (3) pine-selection system (Table 1).

Average harvest unit sizes resulting from the process above were 15 and 39 ha for the pine-clearcutting system and 5 and 19 ha for the hardwood-clearcutting in the SFI and non-SFI scenarios, respectively. For the pine-clearcutting system in the SFI scenario, 44% of the area was in harvest units larger than 30 ha and 24% in units larger than 40 ha. In the non-SFI scenario these values were 85 and 80%, respectively.

Simulations in HARVEST included harvestings for pine- and hardwood-clearcutting only. For pine-clearcutting the "fill stands" option was checked to ensure that the entire stand was harvested simultaneously. Detailed settings for this management type for both scenarios are presented in Table 2. For hardwood-clearcutting, given the size of the existing stands compared to the maximum size allowed per clearcut, harvesting followed a stochastic process according to the settings in Table 2. Adjacency constraints among management types were applied in the SFI scenario only.

We ran HARVEST for 400 years to analyze the behavior of the system in a long period of time. We used a 2-year time step because it describes better the detail of short rotation management. For each scenario, five replicate runs were conducted using independently generated random number seeds.

Stand Level

The management scheme established for the pine-clearcutting system in Compute P-Lob (Baldwin and Feduccia 1987) included a plantation of 1,360 trees/ha, thinned at age 15 for a residual BA of 13.8 m^2/ha, and clearcut at age 30. Runs were made for each site index (50 years) observed in the study area, ranging from 24 to 40 m.

Management of hardwoods by the clearcutting system in the forest vegetation simulator (Donnelly et al. 2001) included natural regeneration after harvesting, thinning at age 20 (from below; residual density of 494 trees/ha), and harvest after age 40. All hardwood stands in this management category were considered to be bottomland hardwoods. Composition of these stands was established based on Hodges (1994) and Messina et al. (1997). Initial density (7,413 trees/ha) was established through simulation and according to observations in Messina et al. (1997): sweetgum (*Liquidambar styraciflua* L.), 2,471 trees/ha (33%); water oak (*Quercus nigra* L.), 3,212 trees/ha (43%); American hornbeam (*Carpinus caroliniana* Walt.), 618 trees/ha (8%); swamp chestnut oak (*Q. michauxii* Nutt.), 618 trees/ha (8%); and cherrybark oak (*Q. pagoda* Raf.), 494 trees/ha (7%).

Initial distributions for uneven-aged stands simulated in SouthPro (Schulte et al. 1998) were based on actual data on the stands. Target distributions for pine and hardwoods were defined by the BDq method, with q = 1.44 (5-cm dbh classes), BA = 13.8 m^2/ha, minimum dbh = 10 cm, and maximum dbh = 63.5 cm. Length of management cycle was set to 10 years. Site index (50 years) ranged from 17 to 35 m for pine and 21 to 32 m for hardwoods. Target distributions for pine-hardwood mixed stands were also defined by the BDq method, with q = 1.44 (5 cm dbh classes), pine BA = 8 m^2/ha, hardwood BA = 5.7 m^2/ha, minimum dbh = 10 cm, maximum dbh = 63.5 cm. Length of management cycle was 10 years. Site index (50 years) ranged from 21 to 33 m.

Habitat Suitability

The habitat suitability index model for pine warbler, *Dendroica pinus*, (Schroeder 1982) was selected to illustrate the application of the methodology to the SFI case. This species is associated with mature pine habitat conditions and allows debate on area and edge sensitivity issues that are relevant at the scale at which we approached sustainable forestry. This is a breeding season habitat model

Table 1. Area by management type in the SFI and non-SFI scenarios

Management Type	Forest Type	Silvicultural System	SFI		Non-SFI	
			ha	% area	ha	% area
1	Pine	Clearcutting	3964.3	68.7	4993.3	86.5
2	Hardwood	Clearcutting	265.8	4.6	595.2	10.3
3	Pine	Selection	164.4	2.8	183.5	3.2
4	Hardwood	Selection	1260.4	21.8	—	—
5	Mixed	Selection	116.9	2.0	—	—

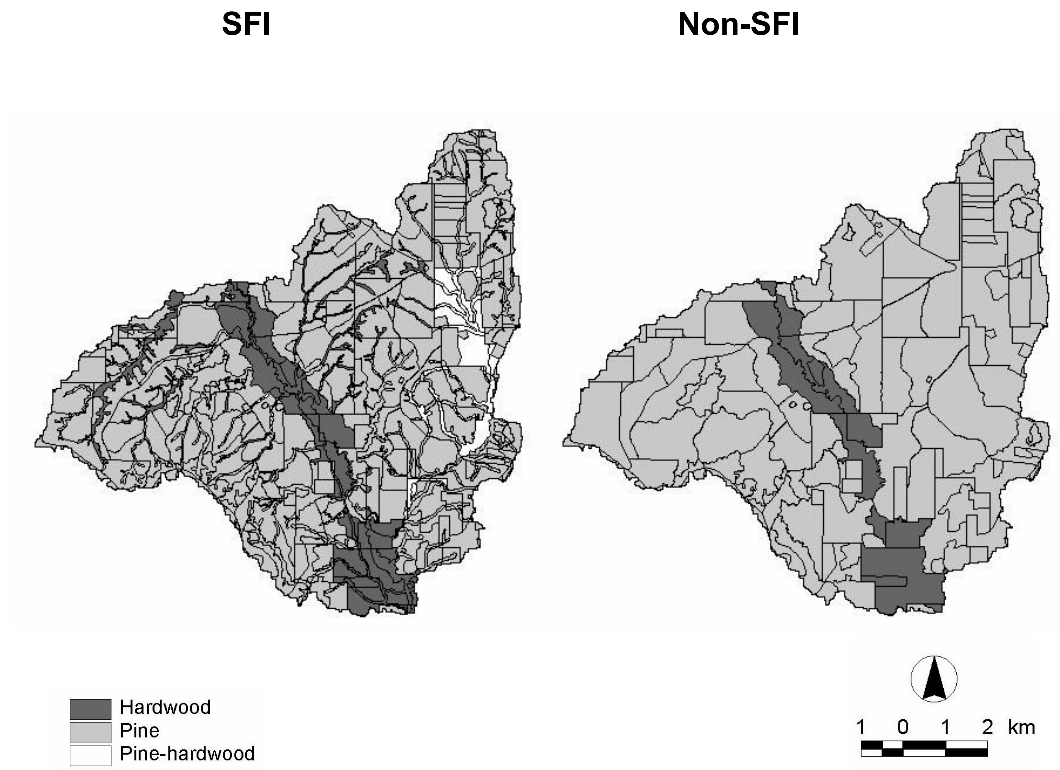

Figure 3. Study area classified by forest type classes for SFI and non-SFI scenarios.

Table 2. Settings used in HARVEST for management types 1 and 2 in the SFI and non-SFI scenarios

	SFI		Non-SFI	
Settings	Management Type 1	Management Type 2	Management type 1	Management Type 2
Forest type	Pine	Hardwood	Pine	Hardwood
Harvest size (ha)				
Average	Fill Stands	12	Fill Stands	50
Standard deviation	—	4	—	20
Minimum	—	0	—	4
Maximum	—	12	—	50
Dispersion method	Dispersed	Dispersed	Dispersed	Dispersed
Minimum age for harvest (yr)	30	40	30	40
Amount to harvest	100%	100%	100%	100%
Adjacency constraints	Yes	Yes	No	No
Green-up interval (yr)	3	3	—	—
Riparian buffers[1]	No	No	No	No

[1] Buffers are included in the management zone map for SFI.

that considers cover and reproduction in the same life requisite. Food availability is assumed to be always less limiting than cover and reproductive requirements (Schroeder 1982). Only forest types including pine trees were considered in the application of the model. Habitat suitability at the stand level was estimated by

$$HSI = (SIV1 * SIV2 * SIV3)^{1/2}$$

where SIV1, SIV2, and SIV3 are suitability indices correspondent to variables V1 (percentage tree canopy closure of overstory pines), V2 (successional stage of stand), and V3 (percentage of dominant canopy pines with deciduous understory in the upper one-third layer).

In pine stands tree canopy cover was estimated as the sum of the projected crown area of the trees obtained from the crown size–dbh relationship of Gering and May (1995) with data from the growth and yield models. Cover was corrected for overlap in uneven-aged pine stands using the equation in Crookston and Stage (1999) given the spatial distribution of trees in stands and occurrence of ingrowth.

To estimate V2 (successional stage of stand), pine stands were classified as pole or sapling if $>50\%$ of trees were <23 cm dbh and young if $>50\%$ of trees were ≥ 23 cm dbh. Mature or old-growth stands were not considered because the oldest stand observed during the simulations was 37 years old. Uneven-aged stands were considered as mature for the purposes of this model.

The third HSI variable (V3) was calculated as the ratio of dominant pine cover to the hardwoods cover in the upper one-third in the mixed stands. Estimation of tree height was based on the empirical equations of Lin et al. (1998) used with SouthPro. Canopy cover was calculated as the sum of cover for all the species corrected for overlap with the equation in Crookston and Stage (1999). Dbh distributions from SouthPro were used with the crown size equations of Francis (1986) for sweetgum representing soft hardwoods, and water oak (willow oak, *Quercus phellos* L., equation) representing hard hardwoods, and Gering and May (1995) for loblolly pine.

A full understanding of the effects of SFI on wildlife habitats can be achieved only by using sets of species covering a broad range of habitat conditions. Pine warbler was selected to demonstrate the application of the methodology and the interpretation of the results of this study should consider the fact that only one species was used.

Hydrologic Processes

A watershed from the study area was selected to analyze the effects of the SFI program on sediment loss and stormflow volume. The SFI and non-SFI scenarios simulated provided the landscape pattern in the presence and absence of SFI measures, respectively. Soils were exclusively Alfisols of the Diboll and Alazan series. Slopes were very gentle, on average 1.5%, maximum 3%.

The "watershed delineation" module of SWAT2000, ArcView interface (Di Luzio et al. 2002), was used in the delineation of subareas with DEM data (USGS, 30-m resolution) and a streams coverage. These subareas were further subdivided to reduce variability in soil and to represent forest stand pattern, each forest stand within a subarea delineated in SWAT constituted a subarea for modeling purposes.

Stands were managed by individual operation schedules according to their composition and age. Plantation and harvesting year for each pine stand were defined according to the sequence of clearcuttings in HARVEST. Stands were planted at an initial density of 950 trees/ha and thinned, at age 15, to a density of 475 trees/ha. The stands were kept fallow between clearcutting and planting (Apr. to Dec.). Thinning was applied in Aug. Buffer zones (SFI scenario) were composed of sweetgum stands. For simplification, SMZs were considered with a constant density of 450 trees/ha.

Subareas files (subfiles) were built using an application developed by J.R. Williams (Texas A&M Blackland Research and Extension Center, Temple, Texas, personal communication, 2003) using as inputs soil and operation schedule file codes, area, channel length and slope, upland slope, and reach length and slope when applicable. The model was run 30 years before the period of interest to allow stabilization of the system and stand growth. Weather data were generated by APEX based on parameters for Lufkin, Texas. Three seed number sequences were followed in the runs to allow for variability of weather conditions.

Results and Discussion

Landscape simulations produce a regular temporal pattern in the study area in both scenarios. After an initial adjustment period of a few rotations, harvests became distributed cyclically in the landscape. Every cycle broadly matched the rotation for loblolly pine stands, 30 years. Given the periodicity of the pattern observed, analysis of results in terms of habitats and hydrologic processes was limited to a period of 30 years, specifically between simulation years 144 and 174. Because variability among runs was low, just replicates 1, 3, and 5 from the initial five for each scenario were considered.

Pine Warbler Habitat

The overall landscape HSI for pine warbler was higher in the non-SFI scenario, ranging from 0.17 to 0.28, than in the SFI scenario (0.15–0.23). Given the small variability among runs for the same scenario, differences were statistically significant ($P < 0.001$; repeated measures analysis of variance (ANOVA) with management (SFI or non-SFI) as a fixed effect, and subjects, runs, as a random effect). Temporal variation of HSI within scenarios during the 30-year observation period was also very small.

Differences between scenarios were attributable to changes in proportions of area in forest-management types. From SFI to non-SFI there was a 20% increase in area submitted to the pine-clearcutting system (Table 1) that resulted in the increase in the average HSI value from 0.19 to 0.23. HSI at the stand level changed according to the management type reaching maximum values of 0.71 for pine clearcutting and 0.50 for pine-selection.

Although the amounts of HSI class 3 ($0.5 < \text{HSI} < 0.75$), the highest reached in the landscape, were relatively similar in the SFI and non-SFI scenarios, the spatial configuration of this HSI class differed between scenarios (Figure 4; Table 3). There were more patches of much smaller size in SFI than in non-SFI. Patches in the non-SFI scenario were more aggregated and farther apart. Edges were more abundant in SFI. Core areas were more numerous and smaller in size in SFI whereas total core area was larger in the non-SFI scenario. These differences suggest fragmentation of the most valuable breeding habitat in the SFI scenario when compared with the non-SFI scenario. Although the harvest unit size and adjacency rules for the simulation of SFI scenario might have contributed to the fragmentation, creation and maintenance of the SMZs were likely the most important contributing factors to the fragmentation.

Responses of pine warbler to the apparent fragmentation may depend on its sensitivity to patch size and edges. It is not clear whether pine warbler is an area-sensitive interior species (Rodewald et al. 1999). In Ontario, Canada, it is considered area-sensitive, requiring a minimum habitat

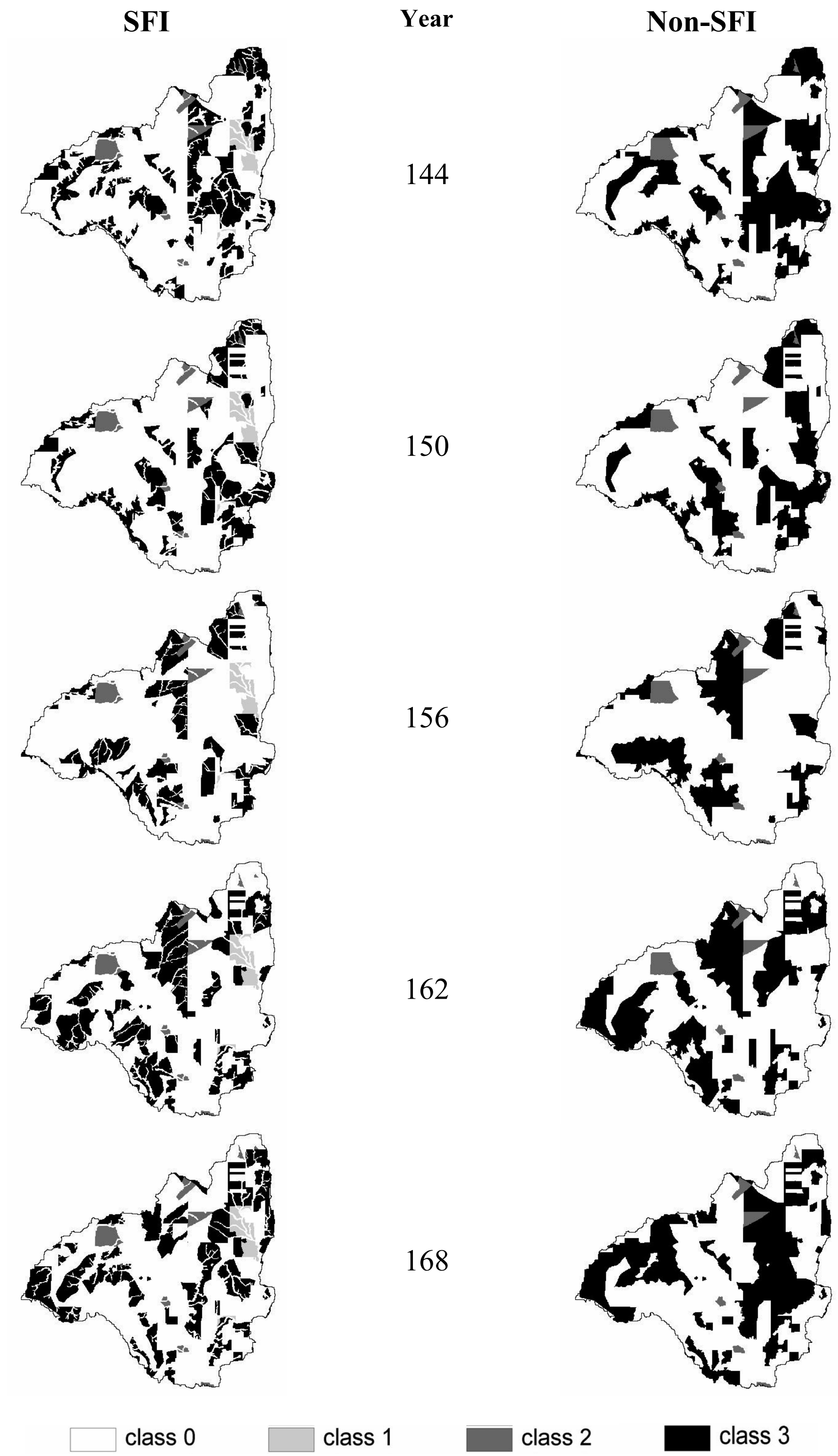

Figure 4. Distribution of suitable habitat according to the pine warbler HSI model for five dates within the simulation period for the SFI and non-SFI scenarios. Pictures from run no. 1 in both scenarios.

from 15 to 30 ha (OMNR 2000). In the HSI model, Schroeder (1982) considered a minimum habitat area of 10 ha for the species, but Rodewald et al. (1999) indicated that minimum area size can be as large as 30 ha for breeding populations. Boulinier et al. (1998), however, described pine warblers as a nonarea-sensitive species, based on the work of Robbins et al. (1989) and Whitcomb et al. (1981).

Assuming the species is area-sensitive and requires minimum suitable habitat patches of 10 ha, more than 87% of the total habitat area in the SFI scenario was composed of

Table 3. Selected landscape metrics for pine warbler habitat class 3

Variable	Class 3 SFI	Class 3 Non-SFI
Percentage of landscape (%)	25.8	32.9
Patch density (no./100 ha)	1.3	0.4
Edge density (m/ha)	37.4	19.7
Largest patch index (%)	2.9	13.7
Landscape shape index	15.0	7.5
Mean patch area (ha)	20.8	89.3
Mean fractal dimension index	1.10	1.09
Area-weighted mean fractal dimension index	1.13	1.13
Core area percentage of landscape (%)	4.8	17.3
Mean core area (ha)	3.9	47.0
Mean core area index (%)	8.2	19.9
Mean proximity index	334.1	447.0
Mean Euclidean nearest-neighbor distance (m)	80.6	212.2
Interspersion and juxtaposition index (%)	14.6	23.7

All values are averages for three simulation runs and 15 observation dates. All metrics calculated using FRAGSTATS (McGarigal and Marks 1995).

patches larger than that size. For the extreme case, patches larger than 30 ha always represented more than 60% of the total available area in class 3. In the literature it is not clear, however, if area refers to forested area, area of suitable habitat area required to maintain a breeding pair, or area required for the maintenance of a minimum viable population.

Sensitivity of pine warbler to edges is also not clear in the literature. It has been considered a forest interior species in Ontario (Environment Canada 1998), Missouri (Thompson et al. 1992), and Georgia (McIntyre 1995), but described as an edge-attracted species in hammocks in Florida (Noss 1991). Consequences of edge sensitivity are considerable in terms of availability of quality habitat for the species, more evident with growing area sensitivity, particularly in the SFI scenario (Figure 5).

Much of the reduction in habitat patch size observed in the SFI scenario resulted from the dissection of larger areas by SMZs. It is likely, however, that the pine warbler habitat patches separated by these narrow (~50 m wide), permanently forested, SMZ buffers had high connectivity; therefore, the reduced patch size due to SMZs in this scenario was possibly not a real concern. Similarly, the increased edge density due to the development and maintenance of the SMZs may not have an appreciable negative effect on the pine warbler habitat suitability. The edge contrast between the SMZs and suitable pine stands (19 years or older) was low, especially compared to the edges between forest and open areas usually considered in the literature. Therefore, pine warblers may not respond negatively to these edges. Although no study has shown an actual effect of these edges on pine warblers, the fact that pine warblers breed in scattered or grouped pine trees within hardwood stands (Rodewald et al. 1999) is supportive of the above argument. If we assume that these edges do not affect the breeding habitat of pine warblers, then the habitat structure in the SFI scenario would be similar to that in the non-SFI scenario for this species.

Water and Sediment Yield

Runoff and sediment loss observed during the simulations (Table 4) were generally small and within the range of values observed for forested watersheds in eastern Texas and other areas in the South (Yoho 1980, Ursic 1986, Ursic 1991b). The watershed when managed by the SFI program showed lower sediment yield than under non-SFI management (Table 4). Water yield was also lower but the difference was very small. Although sediment yield at the subarea level (YS) was not different between scenarios, at the watershed level (YW) it was considerably higher in the non-SFI scenario. This was mainly due to channel degradation occurring in the non-SFI scenario, particularly during intense storm events. Channel degradation is common in forested areas and often responsible for the erosion observed in forest watersheds (Ursic 1986, Blackburn et al. 1990, Marion and Ursic 1993). We considered that SMZs in the SFI scenario were responsible for the reduction in channel degradation in this scenario through reduction in runoff.

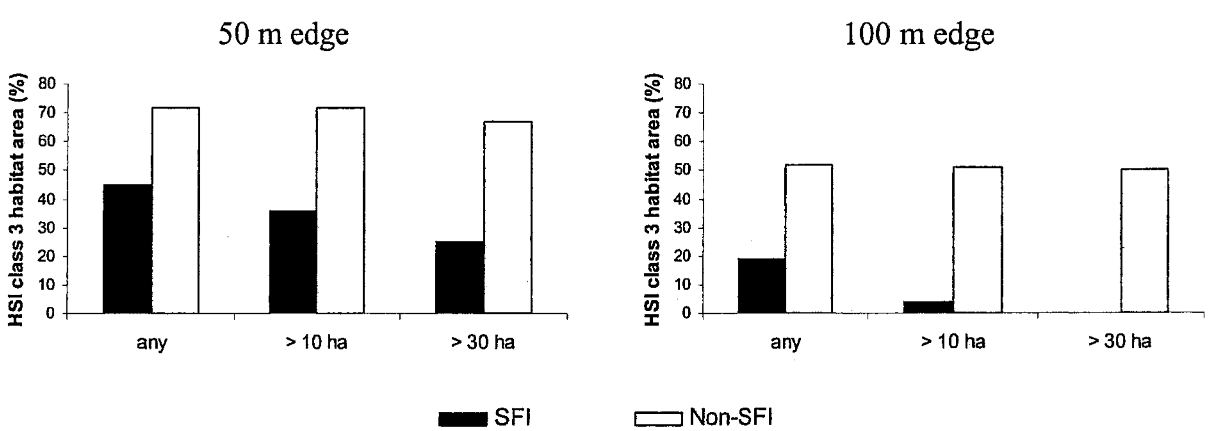

Figure 5. Average proportion of area of HSI class 3 habitat per management scenario considering edge width of 50 m (left) and 100 m (right) and patch size (any, >10 ha, and >30 ha).

Table 4. Average annual precipitation, runoff, and sediment loss in three simulations for the study watershed

Simulation	Precipitation	QSS	QSW	QTS	QTW	YS	YW
		....	.... (mm)	....	....	...... (t/ha)	......
SFI							
1	1093.9	20.70	20.59	26.48	26.34	0.02	0.04
2	1056	16.02	15.92	19.57	19.44	0.02	0.04
3	1074.2	18.75	18.64	23.39	23.25	0.02	0.03
Average	1074.7	18.49	18.38	23.15	23.01	0.02	0.04
Non-SFI							
1	1093.9	23.56	23.56	28.95	28.94	0.02	0.07
2	1056	18.36	18.36	22.16	22.15	0.02	0.06
3	1074.2	21.40	21.40	25.84	25.82	0.01	0.06
Average	1074.7	21.11	21.11	25.65	25.64	0.02	0.06

QSS, average subarea surface runoff; QSW, average watershed surface runoff; QTS, average subarea water yield; QTW, average watershed water yield; YS, average subarea sediment yield; YW, average watershed sediment yield.

Most sediment was produced in a small number of years (Figure 6). Within these years it was concentrated in a small number of months, corresponding to periods of very high precipitation during which evapotranspiration and soil storage were much smaller than precipitation, increasing runoff considerably. There also were usually a small number of subareas contributing to most of the yield observed. High runoff volumes also exacerbated channel erosion, increasing sediment at the watershed level.

There was not an increase in sediment yield following harvesting in the simulations. This might be due to the absence of site preparation functions in the operation files though harvesting in gentle slopes may have very limited and infrequent effects on sediment yields (Ursic 1986, Ursic 1991a, Marion and Ursic 1993).

Summary

The methodology developed in this work constitutes a useful tool for comparing effects of management practices on landscape patterns and processes in intensively managed forested landscapes in eastern Texas. This methodology is simple to implement, relies on simple models that require minimal data, and provides results helpful in the evaluation of management alternatives. Because it provides direct information on ecological processes, it is useful in linking pattern with process, a major concern of landscape ecology. This is also an open methodology in the sense that other models can be integrated to evaluate additional effects of management on the forest system, such as economics, esthetics, carbon sequestration, or others, or to adapt it to particular local conditions.

The application of the methodology to the case study in eastern Texas shows that the implementation of the SFI program affects both the habitat of pine warbler and sediment yield at the watershed level. There is an increase in the fragmentation of the most suitable habitat in the area managed according to this program, reflected by an increase in the number of patches and amount of edges and a decrease in patch size, core area size, and core area in the landscape. The fragmentation detected was caused mainly by SMZs that dissected existing pine stands. Considering, however, the composition and permanent character of these features, the forested landscape context in which the suitable habitat was included, and the behavior of the species, it is unlikely that pine warblers would be strongly affected by this type of fragmentation. Other species will likely show different

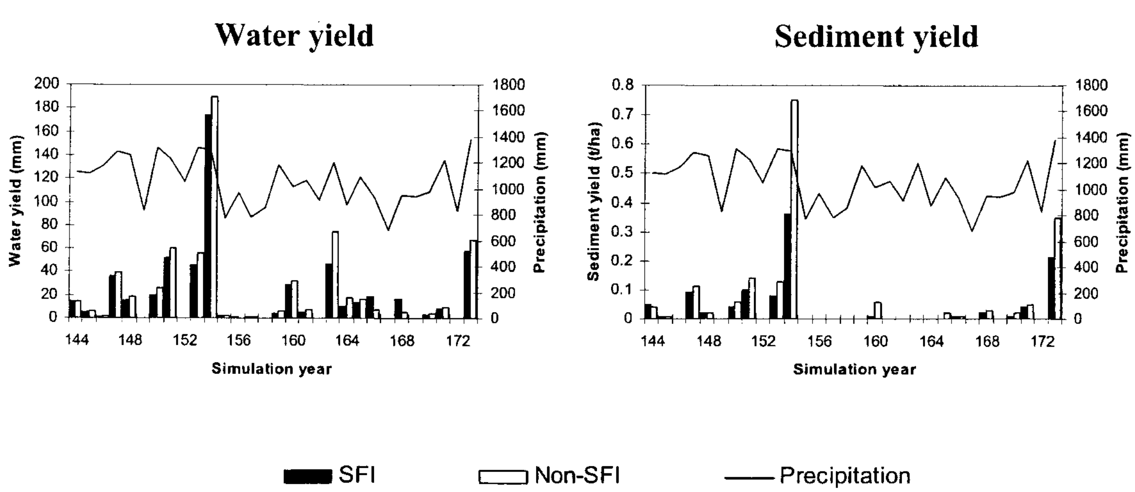

Figure 6. Average annual precipitation and water and sediment yield within the 30-year period of observations for the two management scenarios in run no. 2.

effects, and therefore this conclusion needs to be considered merely as an exemplification of the application of the methodology based on a single species.

The two management scenarios showed relatively similar runoff volume and sediment yield at the subarea level. At the watershed level, sediment yield was considerably higher in the non-SFI scenario due to increasing channel degradation. The lower sediment yield in the SFI scenario was related to the presence of SMZs that reduced runoff.

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