Modeling Steep Terrain Harvesting Risks Using GIS

JEFFREY D. ADAMS, RIEN J.M. VISSER, AND STEPHEN P. PRISLEY

Abstract: When preparing to harvest timber on steep terrain, it is necessary to assess a variety of risks, including slope failure, excessive erosion, residual stand damage, and job-related injury. A number of the risks associated with steep terrain harvesting can be modeled using terrain and soil characteristics such as slope gradient, slope form, soil strength, and soil erodibility. Once assessed, these risks can often be mitigated through detailed harvest planning, an important part of which is the selection of an appropriate harvesting system. This paper describes the development of a steep terrain harvesting risk assessment model using ArcObjectsä. The model operates within the Visual Basic for Applicationsä (VBA) environment embedded in ArcMapä, and accepts soil and digital elevation data as inputs into a decision matrix containing key steep terrain harvest system parameters. Model outputs include maps depicting debris slide hazard, soil strength hazard, soil erosion hazard, and harvest system recommendations. The intended use of the model is to serve as a decision support system in the strategic planning phase of forest management, facilitating the identification of high-risk areas and long-term harvesting system requirements. An application of the model is demonstrated on approximately 500 hectares of mountainous terrain in southwest Virginia.

INTRODUCTION

In many mountainous regions, planning forest management activities can be complicated by a variety of terrain factors (slope gradient, slope form, topographic complexity, etc.) and host of soil characteristics (strength, erodibility, etc.). This is particularly true in southwest Virginia, where the topography is extremely diverse due to the convergence of the Appalachian Plateau, Ridge and Valley, and Blue Ridge physiographic provinces. In many locations throughout the region, it is necessary to assess a number of potential environmental hazards when planning timber harvesting operations.

The more prominent hazards associated with conducting timber harvesting operations on mountainous terrain include soil erosion, soil compaction, and debris slides. Depending on the severity and extent of the hazard, each can potentially lead to significant adverse environmental and economic impacts if not properly assessed and managed. Soil compaction can retard the growth of regeneration as well as lead to increased soil erosion (Martin 1988). Soil erosion, a common byproduct of timber harvesting on steep terrain, can lead to decreases in forest site productivity, water quality, and stream habitat (Rice, et al. 1972). Debris slides can rapidly deliver sediment and woody debris to waterways resulting in high turbidity, bank scouring, channel aggradation, and potential damage to roads and other improvements in their paths (Washington State Forest Practices Board 2000). In addition, steep terrain harvesting operations carry a greater risk of equipment damage and personal injury than operations conducted on flat terrain. Equipment damage and personal injury can often lead to significant direct and indirect costs for companies and injured parties.

The factors that contribute to the existence of the abovementioned hazards are often unalterable features of the terrain. However, many of the adverse impacts associated with the hazards can be mitigated through informed planning. To properly assess the severity and extent of the hazards, it is often necessary to conduct detailed field investigations in which site-specific data is collected and analyzed. When properly assessed, one of the more effective ways to mitigate the identified hazards is to select and apply an appropriate harvesting system. For the purposes of this research effort, harvesting system will refer specifically to the equipment and techniques used to move felled trees from the stump to the landing. Harvesting systems commonly used in mountainous terrain include wheeled skidder, track skidder, cable, and helicopter systems.

The objective of this research was to design a GIS model that could serve as a decision-support tool during both the strategic (long-term) and tactical (short- and medium-term) planning phases of forest management planning. During the strategic phase, when forest-level management concerns are being addressed, the model can be used to assess long-term harvesting system requirements. The model provides estimates of the proportions of a land base that might be appropriate for the different harvesting systems, which can help forest managers and planners refine projected harvesting costs and determine whether the necessary equipment or an adequate supply of harvesting contractors is available. Model outputs also include the relative location, severity, and geographic extent of the environmental hazards associ-

ated with steep terrain harvesting. During the tactical phase of management planning, these hazard assessments can be used to prioritize field investigation activities. To maximize the model's operability and accessibility, data requirements were limited to widely distributed, publicly available spatial data. To provide examples of model output, an analysis was conducted on approximately 500 hectares of mountainous terrain that serves as a teaching and demonstration forest for Virginia Polytechnic Institute and State University.

STEEP TERRAIN HARVESTING RISKS

When conducting timber harvest operations in steep terrain, it is necessary to mitigate a number of risks. The sedimentation of waterways resulting from increased surface erosion is often cited as the primary concern associated with forest management activity in steep terrain. Many of the streams originating in or flowing through steep forested terrain provide important habitat for aquatic species and represent important sources for water supplies, recreation, and a number of other uses. Sedimentation of these streams can have adverse impacts on water quality and aquatic habitat, as well as lead to increased flood potential (Virginia Department of Forestry 2002). As a result, many states have established Best Management Practices (BMP) for forest management activities. BMPs identify forest management activities that mitigate increased erosion. Management activities that are commonly identified as potential contributors to increased surface erosion include logging operations, road construction, grazing, and site preparations associated with planting and fire (Toy, et al. 2002, Virginia Department of Forestry 2002). Of the above listed activities, road construction is widely recognized as the biggest potential contributor to increased surface erosion. Although some degree of increased erosion may be unavoidable, measures can be taken to minimize the severity and extent of erosion (Rice, et al. 1972).

Another concern associated with steep terrain harvesting is the compaction of soil caused by the ground pressure exerted by heavy harvesting equipment. Soil compaction alters the physical properties of a soil by reducing the amount of macropore space and increasing density. While soil compaction is a hazard that should be assessed for any harvesting operation, the amount of ground pressure exerted by harvesting equipment is greater when operating on uneven or sloping terrain (Adams 1998). The physical changes brought about by compaction can have significant adverse impacts, including restricted rooting depths for regeneration, restricted water and nutrient cycling, increased water runoff, and increased surface erosion hazard (Adams 1998, Krag, et al. 1986, Martin 1988, Miller and Sirois 1986, Rice, et al. 1972, Schnepf 2002). Compacted soils can be restored given an adequate period of time and the proper environmental conditions. The amount of time required to restore compacted soils depends on the severity of the disturbance,

and can range from a few years to decades (Martin 1988, Schnepf 2002).

Quite often, debris slides represent the dominant erosional process in steep mountainous terrain (Wu and Sidle 1995). Debris slides are mass failures in which the internal strength of soil is exceeded by a variety of stressors, including gravity, soil pore pressure, and material weight (Dietrich, et al. 1986, Shaw and Johnson 1995). They commonly occur in convergent topography, where water, sediment, and organic debris become concentrated (Dietrich, et al. 1986). Areas prone to debris slides will infrequently experience recurrent activity, usually triggered by intense rainfall events. While debris slides are a natural process, certain forest management activities are believed to increase the frequency and severity of debris slide activity. As with surface erosion, the management features commonly associated with debris slide activity are poorly located or constructed roads.

In addition to environmental damage, conducting poorly planned timber harvest operations in steep terrain can result in equipment damage and worker injury. Logging is one of the most hazardous occupations, with a rate of occupational death, illness, or injury approximately 3 times greater than the average incident rate for all private industries. As slope gradient increases, so too does the potential for injury and accident. Most ground-based harvesting equipment such as wheeled and track skidders possess relatively high centers of gravity and can overturn in steep or uneven terrain (Conway 1982). The majority of ground-based and aerial systems (cable and helicopter) require manual felling. Falling materials (i.e. trees, snags, and branches) and poor felling practices are common causes of injury and death for tree fellers. This is especially true in locations characterized by complex stand structures and steep terrain, such as the mixed hardwood stands of the Appalachians. The high-tension cables used in cable yarding operations pose additional threats to workers on the ground. Lastly, helicopter operations can be extremely dangerous, with crashes leading to severe injury or death to both pilots and loggers (Manwaring and Conway 2001).

HARVESTING SYSTEMS

Harvesting systems commonly used throughout the Appalachians and other mountainous regions include wheeled skidders, track skidders, cable yarders, and helicopters. Under a broad range of conditions, the wheeled skidder system represents the most efficient ground-based alternative. Wheeled skidders are rubber-tired vehicles specially outfitted to transport felled timber. They require a relatively low initial capital investment, are relatively inexpensive to maintain, and can move a given quantity of wood from the stump to the landing up to twice as fast as their tracked counterparts (Conway 1982). Wheeled skidders travel through harvested areas on a network of skid roads and skid trails. Skid roads, which are the primary routes from the harvested area to the landing, are often systematically located throughout

the harvested area and experience heavy use during a harvesting operation. In steep terrain operations, skid roads are often located on cut-and-fill slopes. Skid trails are secondary routes established while accessing felled timber and can be somewhat random in location. Skid roads and skid trails can be major sources of erosion in steep terrain (Gibson and Biller 1975, Krag, et al. 1986, Rice, et al. 1972).

Track skidders, often referred to as crawler tractors, are specially outfitted tracked vehicles used to transport felled timber. While slower and more expensive than their wheeled counterparts, track skidders can be much more versatile. They are capable of transporting larger payloads and can be used to construct roads and landings (Conway 1982). In some situations, soil disturbance impacts can be mitigated by switching from wheeled to track vehicles (Martin 1988). Track skidders spread their weight over a much larger area, which can significantly reduce the severity of soil compaction and rutting. This is particularly true for operations conducted on wetter sites, where wheeled skidders can also suffer significant decreases in pulling power (Conway 1982).

Aerial systems such as cable yarders and helicopters are commonly used in locations possessing gradients too steep for the safe and productive implementation of ground-based systems. In cable harvesting systems, felled trees are rigged to a suspended cable and pulled to the landing with winch systems called yarders. Depending upon the configuration of the system being used, felled trees are suspended either partially or fully off the ground. In general, the soil distur-

bance associated with cable systems is less severe and widespread than the disturbance caused by ground-based systems, due in most part to the lack of skid roads and trails (Krag, et al. 1986, Miller and Sirois 1986). A necessary feature of any cable system configuration is deflection, which is sag in the suspended skyline cable. In general, a minimum deflection of 5% is required for a skyline to possess an acceptable load-carrying capability. Cable operations are typically conducted on terrain characterized by concave ground profiles, which allow for adequate deflection.

Helicopter systems are the most expensive alternative and applied when all other systems are deemed inappropriate. For the most part, the use of helicopter systems is relegated to remote locations that are very sensitive to adverse environmental impacts. Trees are felled manually and then transported to the landing using a helicopter. The use of helicopters eliminates skid road construction, soil rutting associated with skid trails, and corridor damage associated with cable systems. However, large landings with access roads capable of heavy transport traffic are required, typically within a 3-mile distance of the harvested area (Sloan 2001).

METHODS

In order to provide an automated spatial assessment of the risks associated with terrain and soil conditions, a GIS-based model was developed. The model operates within the
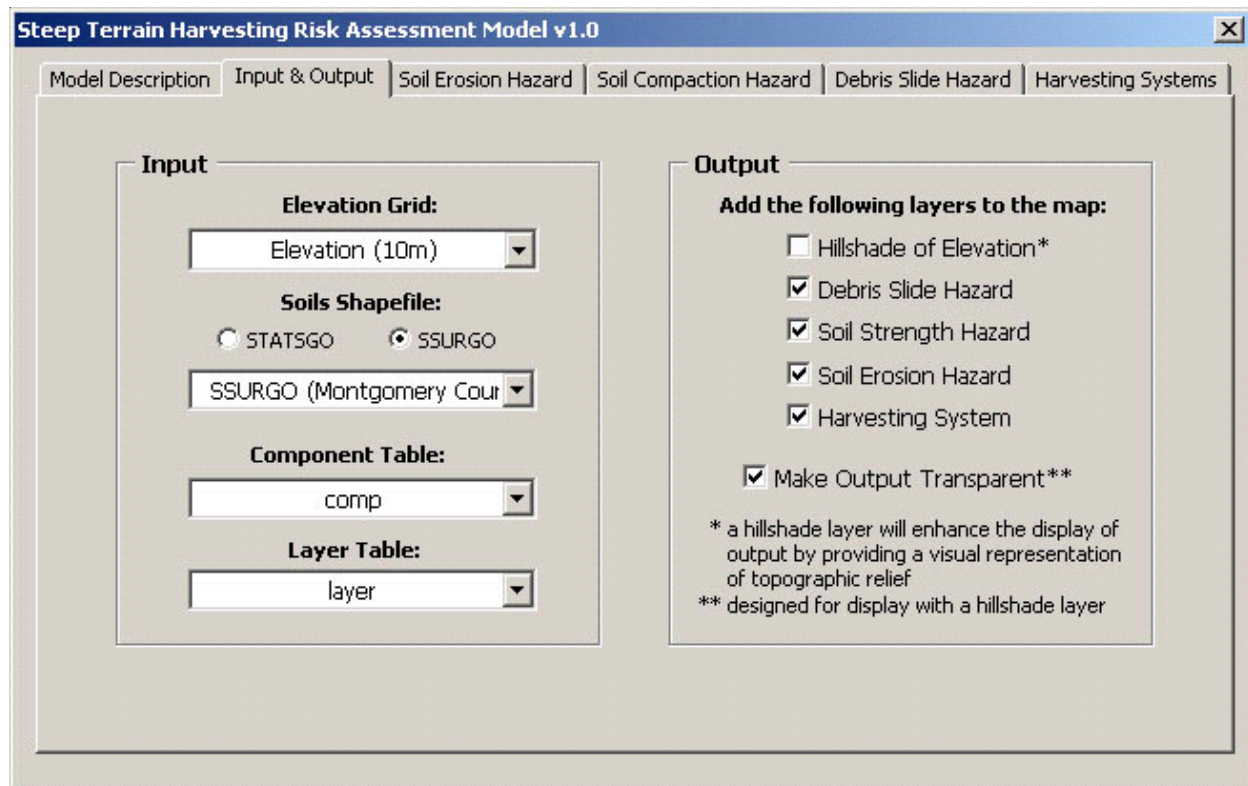

Figure 1. Screen capture of the user interface, which contains a set of tabbed pages on which the user identifies the model input, selects output options, and can adjust model parameters for the different hazards assessed.

Visual Basic for Applications™ (VBA) environment embedded in ArcMap™, and accepts soil and digital elevation data as inputs into a decision matrix containing key steep terrain harvest system parameters. The interface of the model contains a set of tabbed pages on which the user identifies the model input, selects output options, and can adjust model parameters for the different hazards assessed (Figure 1). Default parameter values are provided, however, adjustments can be made to suit local conditions or knowledge. Model outputs include tabular and spatial output depicting soil erosion hazard, soil compaction hazard, debris slide hazard, and harvest system allocation.

STUDY AREA

The study area selected to illustrate model operation is the Fishburn Forest, a teaching and demonstration forest owned by Virginia Polytechnic Institute and State University. The forest is situated on an isolated, east-west trending ridge in the Valley and Ridge province of southwest Virginia and is comprised of approximately 500 hectares of Appalachian hardwood and mixed pine-hardwood cover types. Elevations range from approximately 550–730 meters above sea level with a mean and standard deviation of 629 and 39, respectively. Slope gradients in the forest range from 0-112%, with a mean and standard deviation of 28 and 15, respectively. Within the boundaries of the forest, the following soil series are represented: Berks, Caneyville, Craigsville, Duffield, Groseclose, Jefferson, McGary, and Weaver series.

DATA REQUIREMENTS

The data requirements for the model include elevation and soil data, both of which represent important data sources for GIS applications in a variety of disciplines, including engineering, ecology, hydrology, natural resource management and geomorphology. With respect to elevation data, the model is designed to accept grid-based data with either 30-meter or 10-meter horizontal resolution. The United States Geological Survey (USGS) produces both 30-meter and 10-meter grid-based digital elevation models as part of the National Mapping Program (U.S. Geological Survey 1987). While the availability of 10-meter elevation data is still somewhat limited, 30-meter data is available to the public for a majority of the conterminous United States, Hawaii, and Puerto Rico.

With respect to soil data requirements, the United States Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS) distributes three spatial soil databases, including the Soil Survey Geographic (SSURGO), State Soil Geographic (STATSGO), and National Soil Geographic (NATSGO) databases. The databases consist of mapped soil units (polygons) and a collection of relational tables containing associated physical properties, chemical properties, and interpretations. The databases differ with respect to the intensity and scale at which the soil units are mapped, with SSURGO being the most detailed. The model is designed to accept either SSURGO or STATSGO data. The soil units in SSURGO datasets are mapped at scales ranging from 1:12,000 to 1:63,000 and can contain up to three different soil components. The availability of SSURGO datasets, while increasing, is currently limited to select locations throughout the conterminous United States, Alaska, Hawaii, and Puerto Rico. STATSGO datasets are available for the entire conterminous United States, Alaska, Hawaii, and Puerto Rico. STATSGO soil units can contain up to 27 different soil components, and with the exception of Alaska (1:1,000,000), are mapped at a scale of 1:250,000.

SOIL EROSION HAZARD MODELING

Soil erosion hazard is modeled using a combination of slope gradient classes and K_{ffact}. K_{ffact} is an experimentally determined value that quantifies the susceptibility of soil particles to detachment and movement by water (Natural Resources Conservation Service 1995). K_{ffact} values can range from 0 to 1, higher values indicating greater erosion potential. In both SSURGO and STATSGO datasets, each map unit can contain multiple soil components and each component is typically comprised of multiple layers, each of which is assigned a K_{ffact} value. To characterize soil erosion hazard, the model required that each map unit be represented by only one K_{ffact} value. For each soil component within a particular map unit, the relevant K_{ffact} value for the modeling of surface erosion is the K_{ffact} value associated with the soil layer constituting the thickest mineral horizon in the upper 15 cm of the component (Natural Resources Conservation Service 1998). As such, each map unit contained multiple soil components represented by the K_{ffact} value attributed to the soil layer meeting the above-described conditions. To provide the most conservative estimate of soil erosion hazard, the highest K_{ffact} value from the set of soil components contained within the map unit was attributed to the particular map unit. The representative K_{ffact} value and slope gradient were then combined to characterize relative soil erosion hazard.

The default soil erosion hazard classification criteria (Table 1) offered by the model is adapted from interpretive

Table 1. Default slope gradient classes and K_{ffact} values used to characterize relative soil erosion hazard.

Soil Erosion Hazard	$K_{ffact} < 0.35$	$K_{ffact} \geq 0.35$
Lower	0 - 25%	0 - 17%
Moderate	25 - 45%	17 - 35%
Higher	> 45%	> 35%

criteria used by the NRCS to rate potential off-road/off-trail erosion hazard (Natural Resources Conservation Service 1998).

SOIL COMPACTION HAZARD MODELING

Soil compaction hazard is modeled using a combination of Unified Classification soil group designations and slope gradient. The Unified Classification System was developed by the Army Corps of Engineers in 1952 and classifies soils into groups based on a number of characteristics, including grain size, gradation, liquid limit, and plasticity index (Cernica 1995). Unified Classification designations are used in a number of NRCS interpretive ratings as an indicator of soil strength for forestry-related activities.

Up to four different Unified Classification group designations are provided for each soil layer in a soil component. For each soil component, the relevant Unified Classification designations with respect to the modeling of soil compaction are the group designations attributed to soil layers located in the upper 15 cm of the component that are ≥ 7cm in thickness. For the purposes of modeling protocol, each map unit can only be represented by a single Unified Classification designation. As with the soil erosion hazard modeling described above, the algorithm used to obtain a map unit's representative Unified Classification group designation was designed to provide the most conservative estimate of soil compaction hazard. This was achieved by first selecting the most limiting of the multiple designations attributed to each layer located in the upper 15 cm of the component that were ≥ 7 cm in thickness. This designation was subsequently attributed to the component to which the layer belonged. The most limiting designation was then selected from the set of designations corresponding to the soil components in the map unit. The representative group designation was assigned to the map unit, and used to characterize the relative soil compaction hazard. The default classification scheme (Table 2) used by the model is based

on the criteria used by the NRCS to rate log landing suitability, natural surface road suitability, and harvest equipment operability (Natural Resources Conservation Service 1998). Where slope gradient exceeded 20%, lower and moderate ratings were shifted to moderate and higher ratings, respectively.

DEBRIS SLIDE HAZARD MODELING

Debris slide hazard is modeled using slope gradient and slope form. The protocol to produce hazard ratings is adapted from a slope morphology model developed by the Washington Department of Natural Resources (Shaw and Johnson 1995). Slope gradient is calculated from the elevation data and classified into low, moderate, steep, and very steep classes (Table 3).

Slope form is captured spatially using planform surface curvature, which proved to be very effective in the identification of the landforms commonly associated with debris slide occurrences. Planform surface curvature is also calculated from the elevation data and classified into convex, planar, and concave classes (Table 4). The combination of the slope gradient and slope form classes provide a matrix from which debris slide hazard classes are derived. The default matrix used by the model to rate debris slide hazard from the slope gradient and slope form classes is provided in Table 5.

Table 3. Slope gradient classification parameters used in the modeling of debris slide hazard.

Slope Gradient Class	Slope Gradient (%)
Low	0 - 25
Moderate	25 - 45
Steep	45 - 65
Very Steep	>65

Table 2. Default classification scheme used to characterize relative soil compaction hazard.

Soil Compaction Hazard	Unified Classification Group
Lower[1]	Other
Moderate[1]	CL, CH, CL-ML, ML, MH
Higher	OL, OH, PT

[1]hazard ratings shift to one class more limiting on slopes >20%

Table 4. Slope form classification parameters used in the modeling of debris slide hazard.

Slope Form Class	Planform Curvature[1]
Convex	> -0.1
Planar	-0.1 - -0.4
Concave	< -0.4

[1] the unit of measure in which planform curvature is expressed is 1 over 100 units

Table 5. Debris slide hazard matrix.

Slope Form Class	Slope Gradient Class			
	Low	Moderate	Steep	Very Steep
Convex	Lower Hazard	Lower Hazard	Lower Hazard	Moderate Hazard
Planar	Lower Hazard	Lower Hazard	Moderate Hazard	Higher Hazard
Concave	Moderate Hazard	Higher Hazard	Higher Hazard	Higher Hazard

Table 6. Classification scheme used to allocate harvest systems.

System	Equipment Operability (Slope Gradient)		Hazard Tolerance		
	Min (%)	Max (%)	Soil Erosion	Soil Compaction	Debris Slide
Helicopter	0	150	Higher	Higher	Higher
Cable	15	150	Higher	Higher	Higher
Track Skidder	0	45	Lower	Moderate	Moderate
Wheeled Skidder	0	30	Lower	Moderate	Lower

Table 7. Area in hectares by relative hazard category for the Fishburn Forest.

Relative Hazard	Soil Erosion	Soil Compaction	Debris Slide
Lower	223.2	159.8	436.0
Moderate	211.7	343.5	53.8
Higher	69.5	1.1	14.6

Table 8. Harvest system allocation for the Fishburn Forest.

Harvest System	Area (ha)
Wheeled Skidder	223.1
Track Skidder	173.7
Cable	104.4
Helicopter	3.2

HARVEST SYSTEM ALLOCATION

Harvest system allocation is dictated primarily by slope gradient and tolerance to the aforementioned environmental hazards. Slope gradient limitations on ground-based equipment are imposed based on a combination of production, environmental, and safety reasons (Conway 1982). For the aerial systems, maximum operable slopes are imposed predominantly for the safety of forest workers. Maximum tolerable ratings for soil erosion, soil compaction, and debris slide hazards are imposed based on the potential for adverse impacts associated with the different harvesting systems. The default classification scheme used by the model is contained in Table 6. When two or more systems are deemed appropriate, the model defaults to the least expensive alternative. For the purposes of this modeling effort, the wheeled skidder system is considered the least expensive alternative, followed by the track skidder, cable, then helicopter systems.

In addition to slope gradient and hazard tolerance, yarding distance and deflection are also factored into cable system allocation. While a number of different cable system configurations exist, the model assesses the suitability of a single span system with a default maximum yarding distance of approximately 450 meters. To ensure adequate load-carrying capacity, the algorithm for cable system suitability requires that a minimum mid-span deflection of at least 5% is attainable given the shape of the terrain and a yarder tower and tailhold of 18 meters and 2 meters, respectively.

RESULTS AND DISCUSSION

The analysis on the Fishburn Forest was conducted using elevation data obtained from the Blacksburg and Radford North 10-meter USGS 7.5-minute DEMs and soils data from the Montgomery County, VA SSURGO dataset. Tables 7 and 8 contain tabular results pertaining to the relative hazard assessments and harvest system allocation, respectively. Figure 2 contains spatial output depicting soil erosion hazard, soil compaction hazard, debris slide hazard, and harvest system allocation. Even with the conservative approach taken by the model, only a small portion of the forest was assigned K_{ffact} values indicative of greater potential erosion. Specifically, 24 hectares were assigned a $K_{ffact} \geq 0.35$ and were subjected to the more restrictive slope gradient ranges described in the erosion hazard assessment protocol outlined in Table 1. With respect to soil compaction hazard, all but 5 hectares were observed to have higher soil strengths as dictated by their Unified Soil Group designations.

However, due to the influence of slope gradient, a good portion of the higher strength soils was assigned a relative soil compaction hazard of moderate.

Although the model generates relatively precise tabular and spatial information, care must be taken in the interpretation and use of output. The purpose of the model is to serve as decision support tool during the strategic and tactical phases of forest management planning, and the algo-

rithms used to compute the relative ratings for the different hazards and harvesting system allocations are coarse representations of complex systems. For example, debris slides and excessive erosion are often initiated by intense or prolonged rainfall events, which are dynamic, localized features that are difficult to model spatially. Features such as canopy cover and time of year can have an impact on the all of hazards assessed. As such, care needs to be taken to avoid overstepping the intended utility of the model output. Appropriate inferences that can be drawn from the output of the Fishburn analysis include the following:

1. Efforts to mitigate soil erosion and soil compaction will have to be considered for over 50% of the forest.
2. The hazard of debris slide occurrence is low for most of the forest; however, a few locations will require detailed field investigation.
3. A majority of the forest can be harvested using ground-based systems, however, approximately 20% will most likely require the use of a cable system.

The coarseness of the algorithms is a function of the model's intended use and its reliance on datasets readily available to the public. The intended use of the model output is to supplement the planning of timber harvests at the strategic and tactical levels. The model is not intended to serve as an operational, site-specific guide for forest management activities. For example, it would be inappropriate to use the hazard and harvesting system allocation maps to delineate harvesting or site treatment boundaries without conducting detailed field analyses. With respect to data requirements, the model was designed to widely distributed datasets that were readily available to the public. As such, parameter selection is limited to variables that can be obtained from these readily available datasets. Though limited to the strategic and tactical phases, the model provides a quick first approximation of harvesting system requirements and can assist planners and managers in the prioritization of detailed hazard inspection.

The value of any model, spatial or nonspatial, is often assessed through verification and validation. Verification is a subjective assessment of the internal logic used by a model, given its intended purpose (Brady and Whysong 1999). With respect to verification, the protocol and default parameter values used by the model are based primarily on published research. Given the intended use and scale of model application, the protocol, algorithms, and data used by the model are believed to be more than adequate. Validation is an objective test of model behavior and performance. Because the hazard
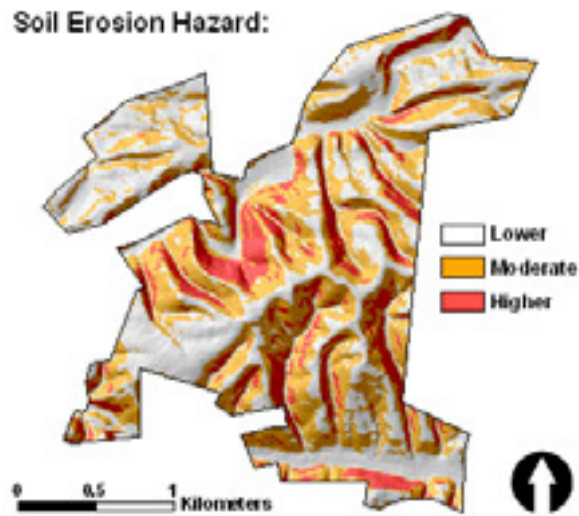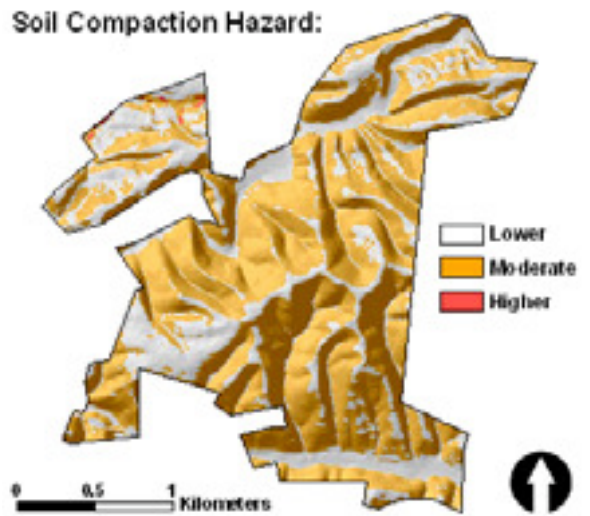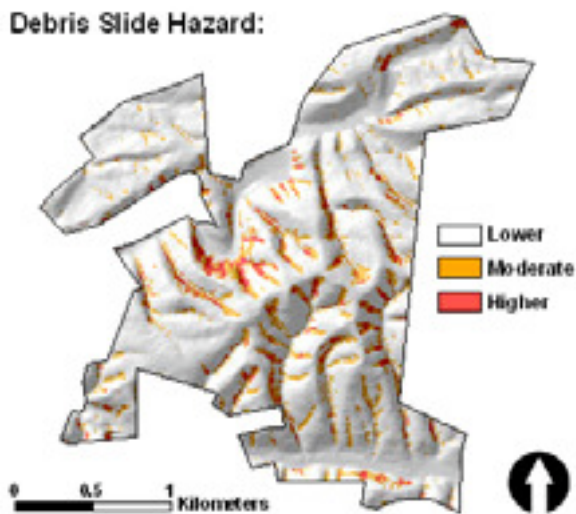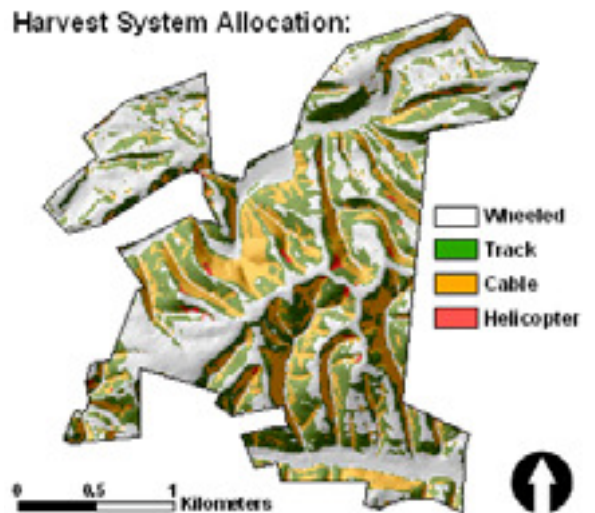
Figure 2. Model output depicting relative soil erosion hazard, relative soil compaction hazard, relative debris slide hazard, and harvest system allocation for the Fishburn Forest (classification schemes in black-and-white reproductions of model output are difficult to discern due to the hillshade effect used to convey topographic information).

assessments are qualitative (lower, moderate and higher hazard), validation will most likely take the form of sensitivity analyses, the results of which could vary significantly depending on the terrain characteristics of the study area. The flexibility built into the design of the model with respect to the ability to manipulate key parameter values and select datasets of varying scale and resolution greatly facilitates the user's ability to conduct sensitivity analyses. Analyses can easily be conducted to determine the sensitivity of the hazard assessments to perturbations in parameters values and to the use of datasets possessing different scales and resolutions. Similar types of sensitivity analyses could be conducted on the harvesting system allocation component of the model.

CONCLUSIONS

Information technologies such as Geographic Information Systems (GIS) have long been used to assist natural resources planning and similar models to the one presented herein have been developed (Bobbe 1987, Davis and Reisinger 1990). Existing models, however, do not specifically address the hazards associated with steep terrain, and their use is often limited by the need for specialized data. Acquiring the necessary spatial data is one of the biggest limitations in the modeling of complex natural phenomena. Database development typically constitutes a major expenditure with respect to both time and financial resources, often consuming up to 80% of a project's budget (Antenucci, et al. 1991, Green 1999). GIS models designed to utilize publicly available spatial data, such as the steep terrain harvesting risk assessment model presented in this research, free up resources that would otherwise be needed for data acquisition and are accessible to a wide audience of users.

LITERATURE CITED

Adams, P.W. 1998. *Soil Compaction on Woodland Properties.* Oregon State University Extension Service. 8p.

Antenucci, J.C., K. Brown, P. Croswell, M. Kevany and H. Archer. 1991. *Geographic Information Systems: A guide to the technology*. Van Nostrand Reinhold, New York, NY. 301 p.

Bobbe, T.J. 1987. An application of a geographic information system to the timber sale planning process on the Tongass National Forest - Ketchikan area. P. 554-562 in *Proc. of the GIS '87 - San Francisco: Second International Conference*, Exhibits and Workshops on Geographic Information Systems. American Society for Photogrammetry and Remote Sensing and the American Congress on Surveying and Mapping. San Francisco, CA.

Brady, W.W. and G.L. Whysong. 1999. Modeling. P. 293-324 in GIS solutions in natural resource management: Balancing the technical-political equation. S. Morain (ed.). *OnWord Press*, Santa Fe, NM.

Cernica, J.N. 1995. *Geotechnical engineering: Soil mechanics.* John Wiley & Sons, Inc, New York, NY. 453 p.

Conway, S. 1982. Logging practices: *Principles of timber harvesting systems.* Miller Freeman Publications, Inc., San Francisco, CA. 416 p.

Davis, C.J. and T.W. Reisinger. 1990. Evaluating terrain for harvesting equipment selection. *Journal of Forest Engineering* 2(1): 9-16.

Dietrich, W.E., C.J. Wilson and S.L. Reneau. 1986. *Hollows, colluvium, and landslides in soil-mantled landscapes.* P. 361-388 in Hillslope Processes. A. D. Abrahams (ed.). Allen and Unwin, Boston, MA.

Gibson, H.E. and C.J. Biller. 1975. A second look at cable logging in the Appalachians. *Journal of Forestry* 73(10): 649-653.

Green, K. 1999. Development of the spatial domain in resource management. P. 5-15 in GIS solutions in natural resource management: Balancing the technical-political equation. S. Morain (ed.). *OnWord Press*, Santa Fe, NM.

Krag, R., K. Higginbotham and R. Rothwell. 1986. Logging and soil disturbance in southeast British Columbia. *Canadian Journal of Forest Research* 16(6): 1345-1354.

Manwaring, J.C. and G.A. Conway. 2001. Helicopter logging in Alaska – surveillance and prevention of crashes. P. 9-20 in *Proc. of the International Mountain Logging and 11th Pacific Northwest Skyline Symposium*. P. Schiess and F. Krogstad (eds.). Seattle, WA.

Martin, C.W. 1988. Soil disturbance by logging in New England—review and management recommendations. Northern *Journal of Applied Forestry* 5(1): 30-34.

Miller, J.H. and D.L. Sirois. 1986. Soil disturbance by skyline yarding vs. skidding in a loamy hill forest. *Soil Science Society of America Journal* 50(6): 1579-1583.

Natural Resources Conservation Service. 1995. State Soil Geographic (STATSGO) Data Base Data Use Information.

Natural Resources Conservation Service. 1998. National Forestry Manual.

Rice, R.M., J.S. Rothacher and W.F. Megahan. 1972. Erosional consequences of timber harvesting: an appraisal. P. 321-329 in Proc. of the Watersheds in Transition Symposium. *American Water Resources Association,* Urbana, IL.

Schnepf, C. 2002. *Prevent forest soil compaction - designate skid trails.* UI Extension Forestry Information Series, Forest Management No. 8. 1 p.

Shaw, S.C. and D.H. Johnson. 1995. Slope morphology model derived from digital elevation data. in *Proc. of the Northwest ARC/INFO Users Conference.* Coeur d' Alene, ID.

Sloan, H. 2001. Appalachian Hardwood Logging Systems; Managing Change for Effective BMP Implementation. in *Proc. of the 24th Annual Meeting of the Council on Forest Engineering*. J. Wang, M. Wolford and J. McNeel (eds). Snowshoe, WV.

Toy, T.J., G.R. Foster and K.G. Renard. 2002. *Soil erosion: Processes, prediction, measurement and control*. John Wiley and Sons, Inc., New York, NY. 338 p.

U.S. Geological Survey. 1987. *Digital Elevation Models Data User's Guide 5*. U.S. Department of the Interior, USGS. 38 p

Virginia Department of Forestry. 2002. *Virginia's Forestry Best Management Practices for Water Quality*. 216 p.

Washington State Forest Practices Board. 2000. Washington Forest Practices Board Manual (Section 16) - *Guidelines for evaluating potentially unstable slopes and landforms*. Washington State Department of Natural Resources, Forest Practices Division, Olympia, WA.

Wu, W. and R.C. Sidle. 1995. A distributed slope stability model for steep forested basins. *Water Resources Research* 31(8): 2097-2110.