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Ecosystem processes at the watershed scale: Mapping and modeling ecohydrological controls of landslides

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ABSTRACT

Mountain watersheds are sources of a set of valuable ecosystem services as well as potential hazards. The former include high quality freshwater, carbon sequestration, nutrient retention, and biodiversity, whereas the latter include flash floods, landslides and forest fires. Each of these ecosystem services and hazards represents different elements of the integrated and co-evolved ecological, hydrological and geomorphic subsystems of the watershed and should be approached analytically as a coupled land system. Forest structure and species are important influences on the partitioning of precipitation, the lateral redistribution of water, runoff and sediment production, weathering and soil development. Forest regulation of hydrologic dynamics contributes to the development of patterns of soil pore pressure and slope instability during storms or snowmelt. The spatial patterns of root depth, structure and strength, developed by the below ground allocation of carbon in the forest canopy in response to limiting resources of water and nutrients, contributes to slope stability and drainage, and the maintenance of stomatal conductance linking water and carbon cycling. This in turn provides the photosynthate required to build leaf area, stem and root biomass. The linked ecological, hydrologic and geomorphic systems are characterized by specific catenary patterns that should be captured in any coupled modeling approach. In this paper we extend an ecohydrological modeling approach to include hydrologic and canopy structural pattern impacts on slope stability, with explicit feedbacks between ecosystem water, carbon and nutrient cycling, and the transient development of landslide potential in steep forested catchments. Using measured distributions of canopy leaf area index, and empirically modeled soil depth and root cohesion, the integrated model is able to generate localized areas of past instability without specific calibration or training with mapped landslides. As the model has previously been shown to simulate space/time patterns of coupled water, carbon and nutrient cycling, the integration of slope stability as a function of hydrologic, ecosystem and geomorphic processes provides the ability to closely link multiple ecosystem services with a unified approach.

1. Introduction

Geomorphic and ecological systems are closely coupled in mountainous landscapes. Steep slopes, strong energy and water gradients, and orographic precipitation create dynamic environments characterized by high water and sediment flux, and heterogeneous topoclimate and habitat. Soil-mantled mountains often support extensive forest cover and create potentially large above and below ground carbon sinks. The forest canopy moderates the shallow groundwater system through evaporation, transpiration, interception, and modification of the geotechnical properties of soil. Soil water in turn affects the distribution of roots and root reinforcement of soils. A significant component of soil strength and stability on soil-mantled mountains and other sites is forest root biomass (Pollen and Simon 2005, Schmidt et al., 2001). In addition, tree or shrub species and hydraulic adjustments in root architecture in response to topographic position can be important ecologic controls on geomorphic characteristics and slope stability over short time scales (Hales et al., 2009). Over geologic time scales, vegetation cover and dynamics can have an important imprint on geomorphic evolution of hillslopes and stream networks (e.g. Hack and Goodlett 1960, Istanbulluoglu, 2009a,b, Langbein and Schumm 1958). The geomorphic form of mountains, in turn regulates forest canopy cover by influencing topoclimate (e.g. precipitation, snowpack, temperature and radiation patterns), soil water distribution, and soil properties.

Mountain watersheds provide a diverse suite of ecosystem services, defined as the goods and services provided by nature (e.g. Costanza et al., 1997, Westman 1977), on regional and global scales. In mountain regions these include the provision of freshwater quantity and quality, food, fiber and habitat, the regulation of nutrient cycling

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and export, hydrologic extremes (flood and drought), sedimentation, and fisheries. Much of the regulation of water quality and quantity, the amount of carbon sequestration, and sediment yield is based on the characteristics and extent of forest cover. The regulation of landslide magnitude and frequency is one form of ecosystem service provided by the forest cover. Slope stability is controlled by gradient, the thickness and strength of soils, species composition and rooting structure of plants, and localized development of high pore pressures (e.g. Montgomery and Dietrich, 1994, Sidle and Ochai, 2006). High pore pressures are jointly controlled by topographic, soils and ecosystem state, and short term meteorological conditions, particularly total storm depth, intensity and the occurrence of preceding storms (antecedent precipitation). An increase in heavy precipitation with increasing climate warming (Groisman et al., 2005, O'Gorman and Schneider, 2009, Trenberth et al., 2003), particularly in the warm season, may promote greater frequency of high pore pressures which contributes to increased landslide risk.

Key linkages between forest ecosystem processes and slope stability include the allocation of below ground carbon into root networks which contributes to soil cohesion and strength, the regulation of spatial and temporal patterns of soil pore pressures by interception, transpiration and lateral water redistribution, and the long term evolution of soil and topographic patterns. At the same time, the root network (and other canopy components) is also a key component of forest canopy carbon and nutrient cycling. As the production of ecosystem services are typically highly coupled within watersheds, the analysis and quantification of the linked processes resulting in these services should be tightly coupled. Integrated ecohydrological models of watersheds seek to couple the major processes of water, carbon and nutrient cycling tightly, such that a change in any one of the stores or fluxes of one of these components feeds back to the others. Spatially distributed models allow the mapping of these processes and feedbacks in space and time, such that the effects of a disturbance or management activity in one location can be followed locally and offsite based on spatial transport processes and dependencies. For the models to capture the coupled dynamics of geomorphic, ecosystem and hydrological processes, the covariation of canopy, soil and topography should be adequately represented, following fundamental principles of soil-landscape systems (e.g. Jenny, 1980).

One transient ecohydrologic model that can be used to derive the patterns of soil moisture, saturation zones and pore pressures, the canopy leaf area and root biomass contributing to total cohesion distributed over the landscape is the Regional HydroEcological Simulation System (RHESSys). This model was developed to simulate coupled water, carbon and nutrient cycling, and the resulting growth and aggradation of vegetation canopies over complex terrain (Band et al., 1993, 2000, 2001; Mackay and Band 1997; Tague et al., 2004) at time scales ranging from sub-diurnal through decades. The elements of the simulation system are a set of remote sensing/GIS routines that build a landscape hierarchy and parameterize a set of process modules operational at the different levels (Fig. 1). The model solves a local water, carbon and nutrient mass balance at each grid cell, or patch, in the watershed, grows the canopy, including leaf, stem and roots (coarse and fine root components), and solves for forest floor litter and soil water, carbon and nutrient stores, transformations and fluxes. Multiple canopy layers and species can be incorporated, with competition for light, water and nutrients explicitly simulated, with resulting differential growth of canopy components. Canopy conductivity is computed on the basis of total leaf area, absorbed photosynthetically active radiation (PAR), temperature, vapor pressure deficit and available soil water. This links transpiration and photosynthetic rates to microclimate and hydrologic flowpath positions. Hwang et al. (2009) have shown canopy structure responds by evolving specific patterns over the landscape. Community composition, mortality and succession are not included in this model, but may be prescribed, as can specific disturbance events.

In this paper we extend ecohydrologic modeling to include impacts on geomorphic processes emphasizing spatial and temporal patterns of coupled water and carbon cycling in forest ecosystems, and interaction of forest structure with slope stability. We make use of the RHESSys distributed ecohydrological framework with simple data assimilation to derive transient simulations of carbon and water cycling over short to long time periods. Specifically, we use as a case study a subcatchment in the Coweeta watershed in western North Carolina during extreme rainfalls to retrospectively model distributed meteorological conditions, above and below ground forest components, and the feedback on soil strength and pore pressure. We use the results of this retrospective analysis to illustrate how coupled geomorphic and ecohydrologic modeling can forecast the potential of landslide prediction and produce long term hazard assessment as part of a linked system serving as the production function for ecosystem services.

2. Methods

2.1. Study area description

Our study site is the Coweeta Hydrological Laboratory, a Forest Service experimental watershed since the 1930s, in the southern

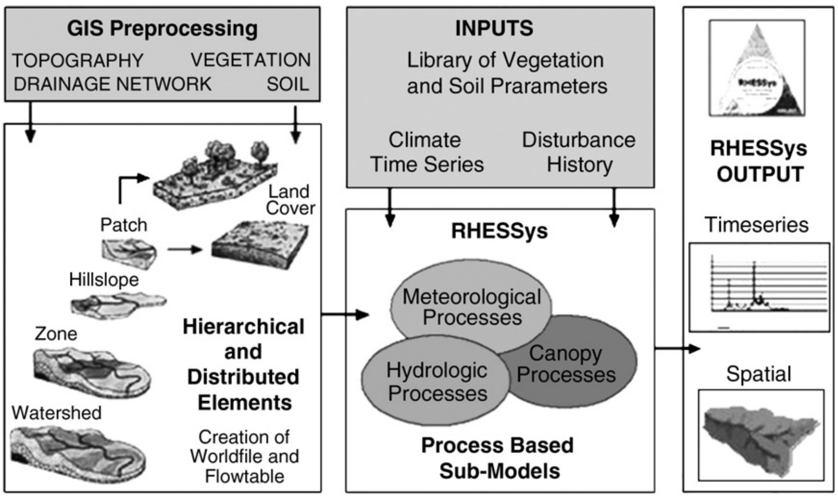

Fig. 1. The RHESSys simulation structure combines distributed hydrology, canopy and soil ecosystem processes and microclimate modules. Processes are computed over a hierarchy of land objects from patches, through hillslopes and basins. The model can accept prescribed inputs of canopy information, or can calculate canopy variables internally. Disturbance or land use change can be prescribed within the simulations, and outputs include time series and spatial distributions of key ecohydrological variables. Details and downloads are available from http://wiki.icess.ucsb.edu/rhessys/RHESSys.

Appalachian Mountains. The watershed has been a National Science Foundation funded Long Term Ecological Research (LTER) site since 1980 and has comprehensive hydrological, meteorological and ecosystem field data available (Douglass and Hoover, 1988). We focus initially on this site to take advantage of the rich, long term data sets, with subsequent analysis planned for regional watersheds. The Coweeta watershed includes fifteen actively gaged subwatersheds with historical information for other catchments dating back to the 1930s. Elevations range from ~700 m to ~1600 m, with the upper catchments positioned along the prominent Nantahala Escarpment that dominates the higher elevations (Fig. 2). Surface slope tends to increase with elevation, with the steepest topography along the escarpment. Mean annual precipitation ranges from 1800 mm at the base meteorological station, to 2300 mm along the escarpment. Soils are described as sandy loam inceptisols and ultisols, typically of colluvial origin, and soil depth is generally inversely proportional to slope. Significant accumulations of colluvial deposits below the Nantahala Escarpment are deep and can be organic rich as mineral and organic debris is shed from above. Bedrock is typically folded schist and gneiss.

Southern Appalachian forests are among the most biodiverse and productive in the temperate world. Species composition is influenced strongly by topographic position and disturbance history (Day et al., 1988). Significant changes in the ecological disturbance regime over the past two centuries have included fire suppression, chestnut blight, logging and a current die-off of hemlock because of an invasive insect, the hemlock woolly adelgid (Elliott and Hewitt, 1997, Ellison et al., 2005). The cumulative impact of past and recent change in forest composition and disturbance appears to have led to an expansion of evergreen species, including rhododendron (*Rhododendron maximum*) (Dobbs and Parker 2004). Rhododendron is characterized by shallow, weak root systems (Hales et al., 2009), low transpiration rates, and suppresses germination and recruitment of deeper rooted overstory species (Clinton and Vose, 1996; Lei et al., 2002; Nilsen et al., 1999). Expansion of this species may result in an increase in landslide hazards throughout the mountains.

2.2. Modeling framework and a case study: 2004 landslides in Coweeta WS37

A combination of human development pressure on steep slopes, the dynamics of forest ecosystems and potential climate change contribute to an increase in landslide hazards in this region. Large

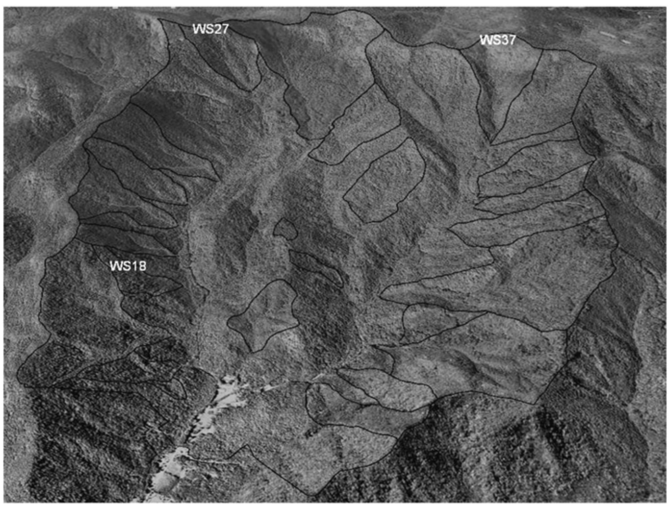

Fig. 2. Coweeta watershed with gaged catchments outlined. Watersheds 18 (13 ha), 27 (39 ha) and 37 (44 ha) are labeled. WS37, along the Nantahala Escarpment, experienced a set of small landslides in September 2004.

landslides associated with tropical storm precipitation are relatively common throughout recorded Appalachian history (Clark, 1987; Eaton et al., 2003; Hack and Goodlett, 1960; Wieczorek et al., 2004, Witt, 2005). Recent events in September 2004 were related to two closely-spaced hurricanes, Frances and Ivan. The financial and human impact of these storms on southern Appalachian communities has led to an effort to map historic landslides and to analyze landslide hazards for all mountainous North Carolina counties, including Macon County within which is the Coweeta Basin (Wooten et al., 2007). This more extensive project makes use of SINMAP (Pack et al., 1998), which is based on steady state hydrology. SINMAP is particularly useful for large area landslide risk assessment, but may not localize landslide risk to specific terrain, soils and vegetation conditions as it uses more generalized distributions of key model parameters. In this paper, the RHESSys model is used in the data rich environment of the Coweeta LTER to explore the dynamics and feedbacks in ecohydrological and geomorphic processes with specific spatial patterns of the model parameters. The Coweeta watershed has comprehensive, interdisciplinary datasets that characterize spatially distributed ecosystem, hydrologic and geomorphic form and processes.

2.2.1. Framework for coupled ecohydrological-geomorphic modeling

RHESSys can be operated as a real-time, retrospective or future scenario watershed modeling framework. Information to develop landslide hazards in real time or over long retrospective or forecast time periods are provided by assimilating or simulating foliar and root biomass to estimate the contribution of root cohesion to soil strength, and transient simulation of saturation levels of soils to compute pore water pressures. For the present study we operate the model with historical meteorological data in retrospective mode, and use canopy information estimated with field measurement and remote sensing methods, and root distributions as described by Hwang et al. (2009) and Hales et al. (2009) to closely reproduce ecosystem conditions corresponding to the major storm events in 2004.

Estimation of forest cover and soil and root depth and strength are given below. Daily meteorological data were derived from the main climate and rain gage stations at Coweeta (CS01/RG06). Simulations for Coweeta subwatershed 37 (WS37) were used to develop and explore the linkage between RHESSys and planar slope stability models. WS37, a high elevation catchment backing onto the Nantahala Escarpment, was clear cut in 1963, but with no wood removed. Canopy regrowth and closure were rapid, but periodic small planar landslides are evident. Whereas more extensive and larger landslides during Hurricanes Ivan and Frances were experienced elsewhere outside of Coweeta in the Little Tennessee watershed, failures along the long, steep slopes of WS37 (Fig. 2) provide a test case for model development and application. Soil water and pore pressure patterns, runoff production and carbon cycling are simulated, and the pore pressure patterns are used to contribute to the calculation of transient hillslope stability using an infinite slope model.

2.2.2. Slope stability dynamics

Whereas different forms of mass movement processes are active in the area, including soil creep and deep rotational slides, we concentrated on planar debris avalanches which have been extensively studied and discussed over the last several decades (e.g. Hack and Goodlett 1960, Wieczorek et al., 2004). The infinite slope model (e.g. Carson and Kirkby, 1972), coupled to distributed or quasi-distributed hydrologic models has become a widely used method to evaluate the distribution of landslide susceptibility within watersheds (e.g. Dietrich and Montgomery, 1998; Gorsevski et al., 2006; Montgomery and Dietrich, 1994; Pack et al., 1998; Wu and Sidle, 1995). The more advanced of these incorporates transient dynamics of water balance and vegetation. The typical lack of detailed knowledge of vegetation state, including canopy contributions to water balance and root cohesive strength, soil mechanical properties and precipitation patterns in complex terrain, however, has led to the development of Monte Carlo methods to incorporate uncertainty by specifying simple distribution functions of key model parameters (Gorsevski et al., 2006, Pack et al., 1998). In most cases, landscape zonation of key driving factors other than topography are not incorporated, which is a potential source of bias as the specific combinations of canopy, soils, topographic and microclimate conditions produce landslide susceptibility. The Monte Carlo methods, while acknowledging the uncertainty of key model parameters, typically specify independent probability distribution functions and, therefore, do not capture the effects of covariance in these components. An effect of this approach may be to underestimate the spatial variability of slope stability hazards, and to reduce the ability to specify specific locations most likely to experience slope failure.

The infinite slope model compares a ratio of the resisting with driving forces, based on static resolution of gravitational forces, soil strength, and dynamic pore pressures derived from the depth of saturation within a soil mass. This ratio is given as a safety factor (e.g. Carson and Kirkby, 1972):

$$SF = \frac{C_t + \left(\gamma - m\gamma_w\right) z \cos\beta \cos\beta \tan\phi}{\gamma z \sin\beta \cos\beta} \quad (1)$$

where β is the slope angle, ϕ is the soil angle of internal friction, γ is the unit weight of soil, γ_w is the unit weight of water, z is the soil depth, m is the saturated fraction of soil depth, and c_t is the total cohesion, consisting of the sum of c_s, the soil cohesion, and c_r, the root cohesion. In most of the colluvial soils in the area c_s is small, and c_r provides most of the cohesion. Soil pore pressures develop in response to seasonal and storm dynamics variation in m in response to precipitation intensity and duration, flowpath drainage and convergence, and forest evapotranspiration, whereas the root cohesion varies in space and time with seasonal and longer term ecosystem dynamics. *SF* values greater than one indicate stable slopes (resisting forces > driving forces) whereas *SF* values less than one indicate unstable slopes.

The North Carolina lidar digital elevation data are available statewide at a resolution of ~6 m (20 ft) and can be obtained from (http://www.ncdot.org/it/gis/DataDistribution/ContourElevationData/). The lidar data are used to derive β, the flowpath structure contributing to the pattern of pore pressures, and information required to distribute local meteorological information by elevation, slope and aspect in RHESSys. The spatial distribution of soil variables are approximated from empirical models of sampled root and soil depths as a function of measurable terrain and canopy information. RHESSys is used to derive the transient spatial and temporal patterns of soil moisture, saturation levels and pore pressures, as well as the key factors contributing to these variables (e.g. stomatal conductance, lateral throughflow, evapotranspiration, interception, drainage and runoff production).

2.2.3. Measurement of forest canopy cover

The peak leaf area of the forest was estimated by a combination of field measurements and remote sensing (Hwang et al., 2009). Plot scale estimation of leaf area with a combination of leaf litter (Bolstad et al., 2001), LAI-2000 measurements (LI-COR Inc., Lincoln, NE, USA) and hemispherical photography (analyzed with the Gap Light Analyzer Software, Institute for Ecosystem Studies, Millbrook, NY, USA) were carried out in June of 2007 to estimate the peak leaf area index (LAI). Hwang et al. (2009) used a June 2003 IKONOS image to produce a high resolution normalized difference vegetation index (NDVI) to develop nonlinear regression estimates of LAI. NDVI is a normalized ratio between red and near infrared bands of remote

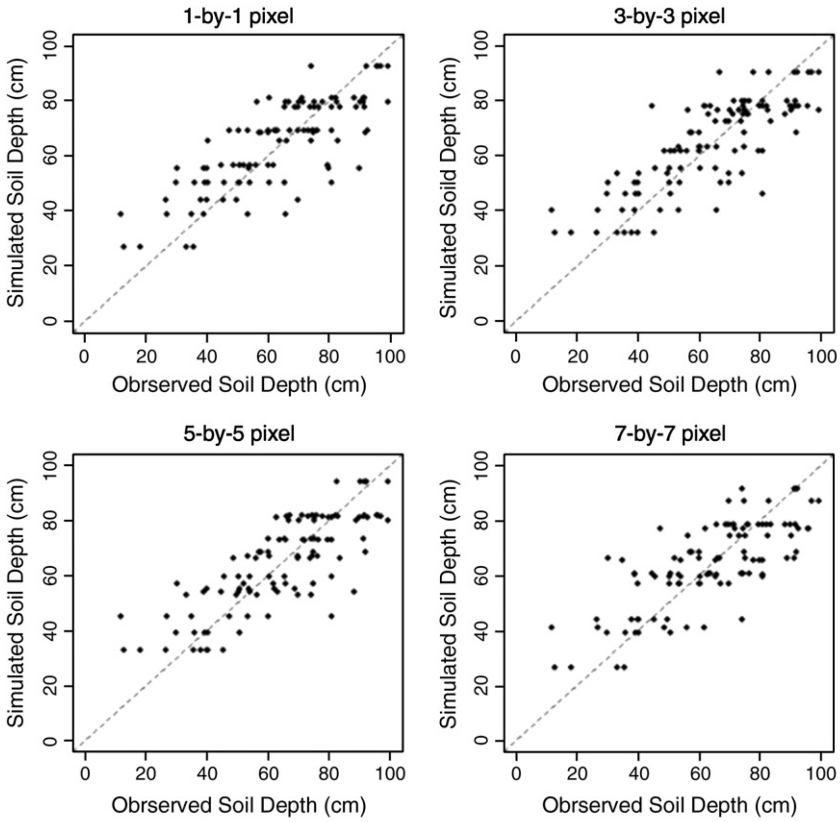

Fig. 3. Tree regression based estimates of soil depth to refusal computed with different raster window sizes for the independent terrain and canopy variables. A 3 × 3 window was chosen to develop empirical estimates of soil depth, shown in Fig. 4.

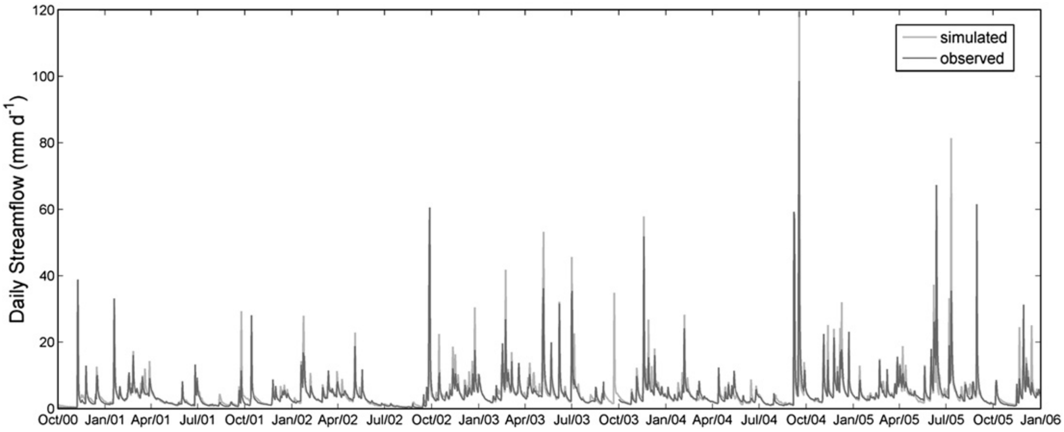

Fig. 4. Observed and predicted runoff production for a five year period for WS37. Note the two large runoff events in close succession in September 2004 from Hurricanes Ivan and Frances.

sensing images, related to various vegetation biophysical parameters (e.g. leaf area index, fraction of absorbed photosynthetically active radiation, canopy cover, and biomass) across different ecosystems (e.g. Sellers, 1985). NDVI was calculated at the same resolution as the topographic variables by resampling an early June, 2003 IKONOS image (4 m multispectral resolution) to represent the maximum canopy density. Although field measurements did not coincide with the collection of remote sensing imagery, the accuracy of the field and remote sensing estimates are within the interannual variation of LAI in the absence of major disturbance. Leaf phenology is incorporated by specifying average leaf-on and leaf-off onset dates and length.

2.2.4. Characterisation of root cohesion and soil depth

For this study we use a simple model that differentiates root cohesion based on topographic position between ridges, slopes and hollows, generated from root tensile strength estimates from sixteen pits excavated and presented by Hales et al. (2009), and a simple tree regression of soil depth estimates. Estimates of soil depth from depth to refusal measurements (Dean Urban, Duke University, personal communication) were made by manually driving 1 m probes into the soil to depth of refusal at 108 sites within the study area. At each site, measurements were repeated thirty times at points spaced 2-m apart along random transects and averaged. This method was designed to provide information on restricting layers within potential rooting zones. These results underestimate depths in deeper soils based on the probe length; however, reconnaissance in the study area suggests landslide trigger zones are typically not in deeper soils in hollows, but just above these areas where soil depths are moderate to shallow. For simplicity, we use a mean root depth of 0.75 m generated from the pit excavations because insufficient data exist to generate a spatially variable model.

Four topographic and one ecological variable were used in a tree regression model for soil depth within the study area; elevation, slope, aspect, topographic wetness index (Beven and Kirkby 1979) from the state lidar data, and normalized difference vegetation index (NDVI) from the IKONOS image. Aspect was transformed into a number ranging from −1 (for northeast-facing slopes) to 1 (for southwest-facing slopes) with a cosine function as a radiation load surrogate (Beers et al., 1966). Topographic wetness index was calculated from the D-infinity method (Tarboton 1997). Tree regression models were developed with the R package (version 2.7.1, The R Foundation for Statistical Computing) at different grid window averaging sizes to test the effect of terrain and canopy scale on prediction strength.

3. Results

Tree regressions for soil depth to refusal showed NDVI to enter the tree model for the first set of splits, with elevation, wetness index and slope entering in later branches. Observed and estimated soil depth (Fig. 3) showed some variability over the range of window sizes, and we chose the 3×3 grid averaging model to develop estimates of spatial soil depth. As discussed above, this is considered a minimum depth given the length of the probes, but most planar failures inspected in the area occur in shallow, steep soils.

Calibration of RHESSys in WS37 was restricted to the use of streamflow because long term soil moisture measurements were not available. Observed and simulated runoff for 2000 through 2005 (Fig. 4) includes Hurricanes Ivan and Frances in September of 2004. The model was able to follow the runoff time series well. For this time period, Nash Sutcliffe Efficiency of model streamflow was computed for log of discharge (to better emphasize low flows) at 0.85 and for discharge as 0.75.

The simulated distributions of pore pressures, combined with surface slope, soil depth, root cohesion (Fig. 5) and other soil mechanical properties were used to solve Eq. (1) for every grid cell in WS37 for each day. The method for estimating the distribution of root cohesion (Hales et al., 2009) emphasized hardwood overstory root tensile strength. In areas dominated by *R. maximum* this may overestimate root cohesion. Estimates of ϕ computed from triaxial tests on a set of samples from the pits constructed by Hales et al. (2009) show values ranging around 30°, with a few at higher levels, up to 38° (Wooten, personal communication). In the absence of more precise information, we set a uniform 30 degree value for ϕ and note that we may be underestimating this parameter for steeper, more skeletal soils. The potential overestimates of root cohesion and underestimates of the friction angle may offset each other in some locations. Additional research is ongoing to improve the covariance structure of these parameters, the extent of *R. maximum* understory, and better estimates of the landscape zonation of ϕ.

A set of safety factor (*SF*) distribution maps (Fig. 6) are shown for September 6, a day prior to the September 2004 hurricanes, for September 7 (Hurricane Frances) and September 17 (Hurricane Ivan). We show the results for one realization of the model parameters that maximizes explanation of streamflow, although the modeling structure allowed us to identify and incorporate multiple realizations, developed with model parameter sets that produce above threshold levels of fit to measured runoff (e.g. Beven and Binley, 1992), to better incorporate parameter uncertainty. The antecedent precipitation for the month prior to September 6 was 72 mm at the base Coweeta meteorological station, with precipitation of 1.5 mm on September 6, 120 mm or September 7, 50 mm on September 16, and 132 mm on September 17. *SF* values are well in excess of 1.0 over most of the landscape on September 6th, with lower values (less stable) on the steep slopes of the Nantahala Escarpment. However, this area has bedrock outcrops in the steepest zones where we are likely over-estimating soil depth. An expansion of areas with *SF* approaching 1.0

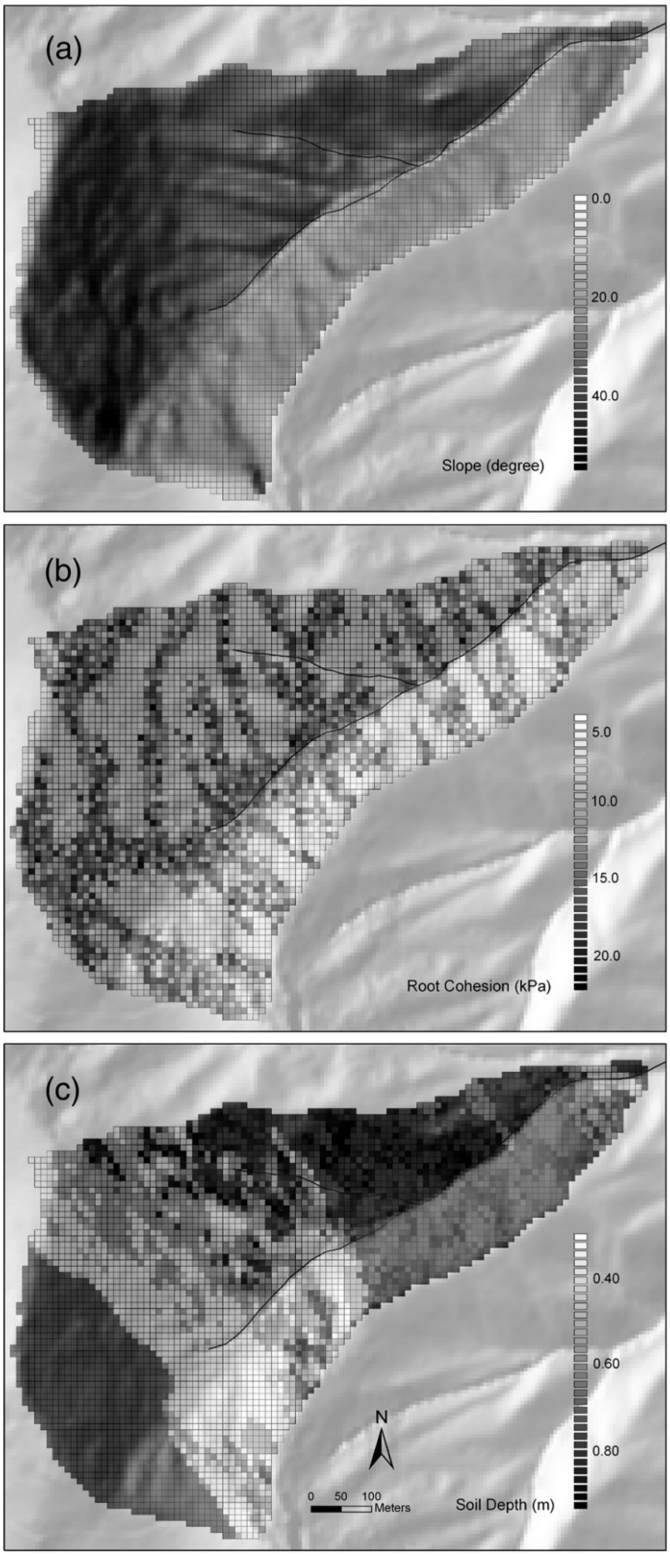

Fig. 5. Descriptions of spatially varying terrain, root cohesion and soil depth information required for Eq. (1) generated for Coweeta WS37: (a) Slope map developed from lidar elevation data, (b) root cohesion estimates generated from the method described in Hales et al. (2009) based on measured root strength, and (c) regression tree based estimate of soil depth.

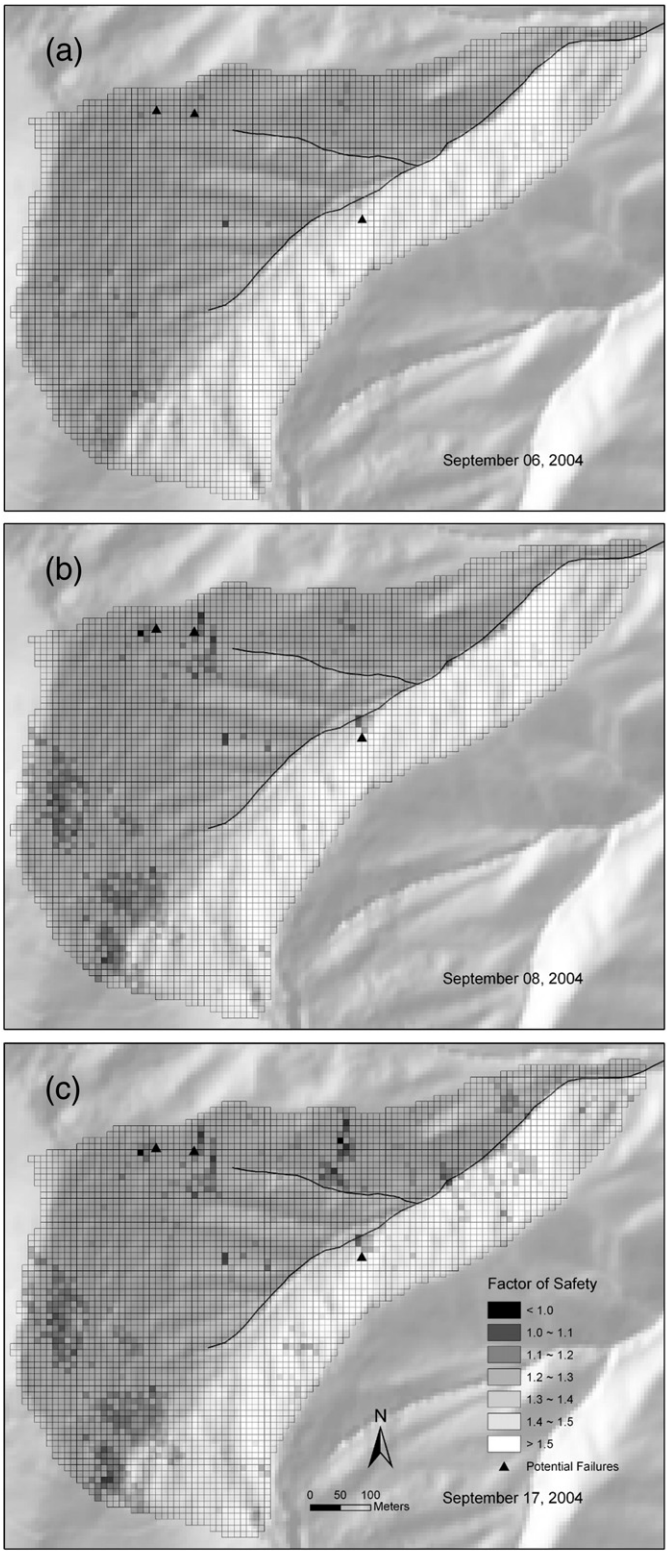

Fig. 6. Slope safety factor computed for September 6th, 8th and 17th for WS37 as Hurricanes Frances then Ivan passed through the area. Three areas with simulated *SF* close to or below 1.0 on September 17th, 2004 were inspected in 2010 and each had proximal features (triangles) corresponding with degraded scarp morphology.

occurs on the south facing (right side) slope in the middle elevations, especially during Hurricane Ivan on September 17. The simulations showed this region to record the lowest *SF*, with three small areas dropping to or slightly below 1.0 on September 16th and 17th, and remaining below 1.0 for a couple of days after as convergent throughflow maintained saturated conditions. Minimum values of *SF* reached within the catchment on these days were 1.32, 1.01, and

0.977 for September 6th, 7th and 17th, respectively supporting the threshold conditions for landsliding.

The simulations were carried out without knowledge of the specific location of previous failures which could be used for calibration or training of the landslide model. Fresh inspection of the area following the storms in 2004 was not carried out and no large failures were obvious on aerial photographs. Mapping the location of *SF* values less than or near one shows potential failure sites (Fig. 6). Field inspection in the summer of 2010 found features that appeared to be degraded landslide scars at locations proximal to all three of the simulated sites with *SF* close to or below 1.0. One site mapped with *SF* just above 1.0 (north slide slope of catchment) could not be located in thick rhododendron. Global Positioning System location of these features (estimated under full forest canopy) is known within ~10 m. Whereas it is difficult to identify these sites as corresponding specifically to the 2004 events, a number of other subtropical events occurred in the last few decades that initiated landslides in this area and the model appears to have localized areas of potential instability.

3.1. Discussion

We developed and presented a linked ecohydrological and slope stability model that produces estimates of a set of carbon budget, water budget and slope stability safety factors at a daily time step. Given potential errors in spatial input data, precipitation and model limitations, we attempt to locate specific sites of slope instability as the *SF* approaches (or drops below) 1.0. Sites with these minimum *SF* values appear to correspond with potential instability features in the landscape towards the head of swales. Observations in the area are consistent with the observation that initiation zones for debris avalanche are often at the very head of hollows where sufficient accumulation of soil, moderate topographic convergence, and steep slopes occur. An important working hypothesis is that soil mechanical failure occurs in this relatively limited hillslope area, with the soil mass mobilizing accumulated colluvium downslope. This is consistent with the location of the morphologic features found in the field near the simulated *SF* values close to or below 1.0. The nature of the initiation zone and the subcatchment area upslope are of primary interest in deriving potential instability and downslope hazards of debris slides and flows. The upslope topography, soil conditions and forest canopy properties need to be developed along with antecedent moisture and transient saturation conditions to evaluate the risk of landslides for each major storm.

A set of studies over the last two decades develop predictive models for soil properties based on topographic, geologic and botanical factors and reflect concepts in Jenny's (1980) classic model of soil evolution, using process based or fully empirical approaches (e.g. Catani et al., 2010, Dietrich et al., 1995, Gessler et al., 2000, Zhu et al., 1997). Catani et al. (2010) recently explored the sensitivity of slope stability to conceptual-empirical estimates of soil depth to bedrock patterns using an infinite slope model. Soil depth and composition remain amongst the most uncertain parameters for hydrologic and geomorphic modeling and analysis. The development and testing of shallow geophysical methods, remote sensing, process based simulations or other methods to estimate spatial patterns and covariance of soil, topographic and canopy variables should be given high priority.

In addition to spatial patterns of soil depth, the spatial distribution of root cohesive strength has important contributions to effective soil mechanical properties and to soil moisture flux and transient development of effective soil strength. The recognition of a systematic relationship between root cohesion and topography (Hales et al., 2009), in which relatively dry ridges and slopes have stronger roots distributed in the upper zones of the soil column, whereas wetter hollow locations had weaker roots distributed more evenly in the soil column, provides an important source of covariation between key components of the slope stability equation (Eq. (1)).

An interesting observation is that canopy NDVI tends to be an important contributor to the explanation of depth to refusal in the statistical models. Whereas we used an expected mean root depth in the current application, Hwang et al. (2009) found that root depth in Coweeta WS18 also correlated with leaf area. This reflects soil depth restrictions to root depth in shallow soils, and a physiologic adjustment of the root and leaf density within the canopy in providing the soil to atmospheric moisture transport, and hence a link between photosynthetic productivity and the available carbon stores to build leaf area and root biomass. Importantly, leaf area (and NDVI) are more readily estimated and mapped than root extent.

RHESSys was extensively tested in two other Coweeta catchments (WS18 and WS27) that have long term streamflow and soil moisture measurements (Hwang et al., 2009) and shown to perform well deriving time/space patterns of runoff production, soil moisture, and spatial patterns of LAI. The model also produced reasonable estimates of long term evapotranspiration and above ground net primary productivity as a measure of forest carbon assimilation and cycling. A significant result of Hwang et al. (2009) was that the spatial patterns of LAI and the rooting depths predicted by the model to maximize net primary productivity at the catchment level, also provide close approximations to observed LAI and root depth patterns. Whereas the current study used empirical estimates of LAI and rooting depth distributions, the research in the other catchments indicates that the canopy appears to adjust to a state that maximizes NPP at the catchment level, and that the model may be used to estimate root biomass and depth based on this principle.

3.2. Summary and conclusions

In this paper we present an approach to link a coupled ecohydrological model that simulates transient water, carbon and nutrient cycling in watersheds with the analysis of geomorphic slope stability. We use an infinite slope model in which we assimilate patterns of soil depth, root cohesion and soil mechanical properties from limited field measurements and remote sensing, with transient pore pressure distributions derived from a distributed ecohydrological model. Rather than assuming a steady state hydrologic system with simple treatment of forest water use, the ecohydrological model is fully transient and allows specific simulation of the build up of subsurface saturation levels and pore pressures along flow paths during storms. The effects of the species composition and structure of forests can be explicitly incorporated into this model through controls of water balance and root physiologic and strength differences. In addition, the effects of storm sequencing, as well as the length of interstorm periods and the rate of drainage and evapotranspiration as a function of microclimate, species and forest density within a patch and the upslope contributing area are also explicitly incorporated in generating pore pressures. Whereas we prescribe spatial patterns of canopy cover and summer peak leaf area, along with root depth and cohesion for this application, the model system has the ability to derive these ecological variables as spatial and temporal variables. Further research using the ecohydrological model and physiologically based statistical methods to produce patterns and covariance of root biomass, depth and cohesion that would reduce the need for local sampling is warranted.

Observations in the area and the results of simulation show that slope instability initiation sites tend to occur towards the head of hollows, in soils with shallow to medium depths where topographic curvature is moderate. Whereas areas further downslope with thicker soils and greater drainage areas (hollows or colluvial aprons) appear to have lower root cohesion, the lower slopes and higher LAI tend to produce greater slope stability. This suggests that initiation of landslides may occur in a relatively narrow topographic position (in the absence of major disturbance or vegetation change).

The approach we illustrate here has the potential to produce real-time updating of the spatial distribution of several ecosystem services and hazard production functions, as well as long term retrospective and future scenario developments. Incorporation of the spatial covariance between topographic, soils and canopy above and below ground information provides more specific mapping of the controls of ecosystem and geomorphic processes. The physiological covariance of canopy foliar and root biomass and the adjustment of root extent and root strength to topographic position provide important methods to estimate key model parameters in forest watersheds. Compared to Monte Carlo methods that specify independent distributions of major parameters, and are commonly seen to overestimate potential zones of landslide hazards without the ability to localize more specific hazard sites, the approach presented here may provide better estimates of site specific instability patterns. In addition, the specific locations of the potential sites of instability were closely mapped by the model with no prior knowledge of their location or existence or use of mapped landslides for calibration or model training. The approach has promise to achieve more spatially specific prediction of slope instability and will be further tested in watersheds with more numerous and larger landslides.

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