WIND-TUNNEL MODELING OF HILL AND VEGETATION INFLUENCE ON WIND POWER AVAILABILITY

David E. Neff [(1)] and Robert N. Meroney [(1)]

[(1)]Civil Engineering Department, Colorado State University
Fort Collins, CO 80523, United States

Presented at

2nd European & African Conference on Wind Engineering (2EACWE)
Genova, Italy
June 22-26, 1997

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ABSTRACT. Forested hills and ridges pose a number of significant technical and environmental issues for siting wind turbines. The change in the wind profile across the top of the hill due to the presence or absence of trees and differences in roughness characteristics must be understood in order to develop accurate energy estimates. A three phase research program was undertaken to examine wind flow over tree covered hills and ridges. The first phase of this work was a review of the known effects on wind flow due to individual trees, forest stands, and forest clearings. The second phase of the work involved wind tunnel measurements of hill-top wind speed profiles as a function of surface roughness, hill shape, and hill slope. The third phase examined the behavior of wind floor over a scale model of a proposed wind energy site in the United States New England region.

INTRODUCTION

Vegetation and hill shape are known to influence the magnitude and profile of wind velocities and turbulence in the atmospheric shear layer immediately adjacent to the ground. Such influences can enhance or decrease the performance of wind turbines due to changes in wind energy availability and induced stresses on wind turbine rotors [1,2]. Mountainous ridges fully or partially covered by high-roughness vegetation can influence wind speeds in the atmospheric boundary layer. Removal of the forest over ridge tops can substantially increase crest wind speeds, reduce turbulence, and inhibit flow separation. Consequently wind energy availability can also be modified substantially by forest clear cut operations. This paper reviews the behavior of flow over vegetated complex terrain and consolidates recent information concerning the amplification (or reduction) of wind speed and turbulence due to the presence of hills and vegetation covered terrain

WIND TUNNEL EVALUATION OF AIRFLOW OVER TWO-DIMENSIONAL HILLS COVERED WITH SIMULATED VEGETATION

The parametric effects of hill shape, vegetation density, and clearing size on hill-top wind speed and turbulence were measured through a series of wind-tunnel measurements performed over idealized two-dimensional hill shapes, different model forest heights, and various sizes of clear-cut area [1, 3, 4] .

Two-dimensional sinusoidal and triangular ridge shapes 61 m high at a model scale of 1:1000 were selected. Measurements of wind speed profiles at 12, 24, 37, 49, 61, 91, 129, 183, 244, and 305 meters were obtained for each model run. Four slopes were specified for each ridge shape: 1:2, 1:3, 1:5, and 1:10.

The effects of three different tree heights, 6.1, 12.2, and 18.3 meters, and four different forest configurations were included in the modeling. . The four different forest clearings included 1) no tree removal, 2) The highest tree top being level with hill top ground level, 3) highest tree top being 30.5 m lower than the hill top ground level, and 4) all trees completely removed to the base of the hill. The combination of 2-D ridges, ridge slopes, tree heights, and forest clearings resulted in a total of 96 different run conditions. Additional measurements were also made to assure approach flow Reynolds number invariance, lateral uniformity, and longitudinal uniformity.

Experimental Setup

The experiments were performed in the Meteorological Wind Tunnel facility at Colorado State University's Fluid Dynamics and Diffusion Laboratory (CSU FDDL). The wind tunnel has a speed range of 0 to 40 m/s, a test section length of 26.8 m, and a square test section area of 3.34 m^2. The test section length upwind (~20 meters) of the model site area had sufficient fetch for the natural development of simulated atmospheric boundary layer winds. The model ridges, both sinusoidal and triangular, were always 6.1 cm tall; hence the wind tunnel flow blockage ratio was approximately 3 percent (See Figure 1). The initial twelve meters of the test section floor was covered with thin carpet type roughness, this was followed by six meters of commercial grade Astroturf with a bristle height of ~12 mm. The sections of ground roughness were present during all test measurements. Following these fixed conditions, two tree height specific roughness mats 1830 mm wide by 1520 mm long were placed end to end on the tunnel floor. The different model ridges were placed underneath and centered in-between these two mats (See Figure 2). The placement of the model ridge and the downwind mat was adjusted dependent on the specific tree clearing on the ridge top being tested. Vegetation on the hills was simulated using an Astroturf™ artificial grass product with bristles 6, 12, and 18 mm tall (See Figure 3).

Single-hot film anemometer measurements were used to document the longitudinal mean velocities and the longitudinal turbulence levels for all velocity profiles in the test program. Pitot-static probes were used as a velocity standard during calibration of the hot-film measurement system and to provide reference measurement points. The Pitot-static probes measurements have an absolute accuracy to within ±2% of the actual velocity. Normalized hot film measurements agreed with pitot-static calibrations within ±1%; hence the total error is estimated to be less than ±2.9% for the majority of the data values with outliers of 3.8%. Due to the cubic expressions used in calculating wind energy, this implied errors in power of ±8.7 and ±11.4 %, respectively.

Test Program Results

Hill and vegetation perturbations were evaluated in terms of normalized velocity profiles, fractional speed up factors, and percent power decrease due to increased vegetation interference. As anticipated the effect of vegetation is generally limited to the region immediately above the ground except when its presence (or absence) induces flow separation (Figure 4). Wind speeds near the

ground increased substantially for even small clear cut operations at the crest, but over the steeper hills, clear cutting provides only marginal power improvement. Hill shape affects surface winds more for the shallower hill slopes.

Turbulent intensities are primarily a function of the upwind tree height. In general, the percent fractional speed-up values show their greatest increase from the "no cut" to the "-30.5 m" option while the change from the "-30.5 m" to the " full cut" situation is small (Figure 4). Figure 5 displays the model ridge percent power decrease observed for an equivalent 12.2 m (40 ft) measurement height. Note that in for the steeper slope cases maximum clear cuts actually produce less power availability than minor tree removal.

WIND TUNNEL EVALUATION OF THE PROPOSED KIBBY MOUNTAIN, MAINE, WIND ENERGY FARM SITE

Subsequently, an actual complex terrain area proposed for a wind-energy farm in the north-eastern United States (Kibby Mountain area, Maine) was simulated with a variety of clear-cut options. The three-dimensional and irregular nature of the terrain led to non-linear interactions which perturbed the conclusions obtained during the earlier two-dimensional study. Results are presented in terms of reduction in wind speed and percent power decrease from a reference unvegetated situation.

Measurements of wind speed at different heights above the topographical model were obtained for 65 different run conditions including two wind directions, one tree height 9 m tall, sixteen measurement locations, three, hill/ridge top forest clearing conditions of no tree removal, highest tree top level with hill top ground level, and highest tree top being 30.5 m lower than hill top ground level, and two below hill/ridge top forest clearings of no tree removal and tree removed to a 183 m radius.

Experimental Setup

A model scale of 1:2000 was chosen to be representative of the atmospheric boundary layer winds (Figure 6). The model as inserted in the Environmental Wind Tunnel (EWT) of the FDDL measured about 4.84 m by 6.05 m) which had a field size of 9.7 km by 12.1 km. The model was precisely modeled on 24 model topography boards from laminated layers of Minicell™ Foam using a three-dimensional computer controlled routing system designed and constructed at CSU.

Tree cover was simulated with an artificial grass product consisting of bristles 4.5 mm tall, connected to a flexible matting 1 mm thick. At a length scale ratio of 1:2000 these 4.5 mm tall bristles are representative of the 30 foot tall trees. This artificial grass carpet was cut and glued to all 24 model topography boards. Significant landmarks, such as roads, rivers and mountain names were designated on the model. Modeling of the effect of tree removal was accomplished by using dog hair clippers to shave (clear cut) the artificial grass (trees) from the designated areas.

Test Program Results

Results were again presented in terms of normalized velocity profiles, and percent power increase comparisons. Flow over the isolated ridges mirrored earlier measurements over the generic 2-D ridges, and speed up over three dimensional hills were lower than that produced by equivalent slope

and shape 2-D ridges (Figure 7). When another hill or ridge existed directly upwind of a measurement site, there appeared to be non-linear flow interactions induced which resulted in deviations from the 2-D experience. Finally, it was concluded that a "crew cut" type approach to tree cutting and removal is an adequate strategy for most forested ridges and hills if higher wind speeds are sought for wind energy development.

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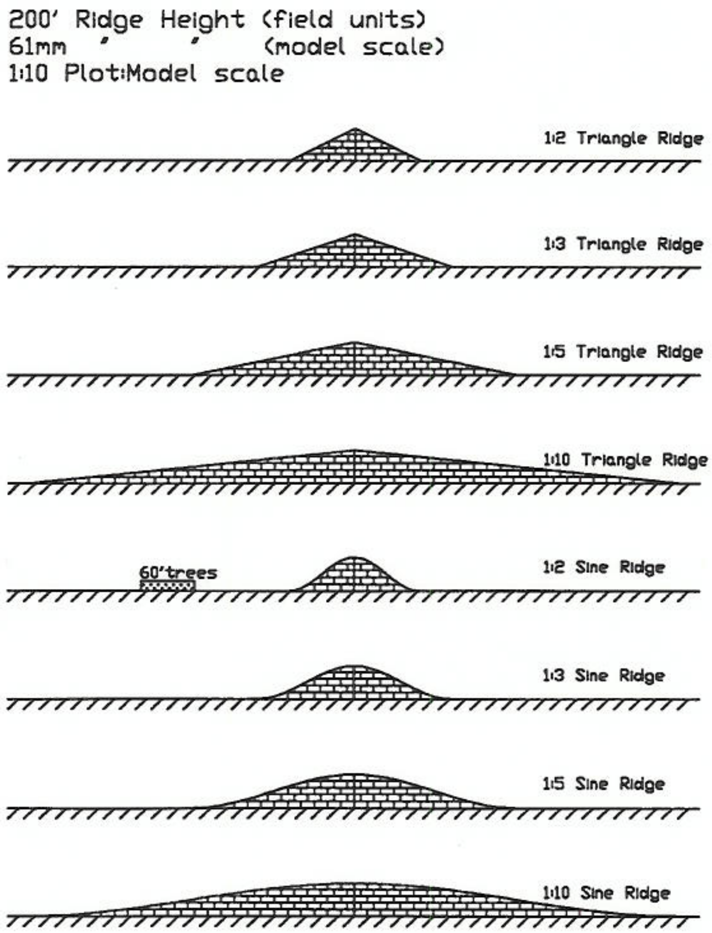

Figure 1: Model ridge cross sectional profiles

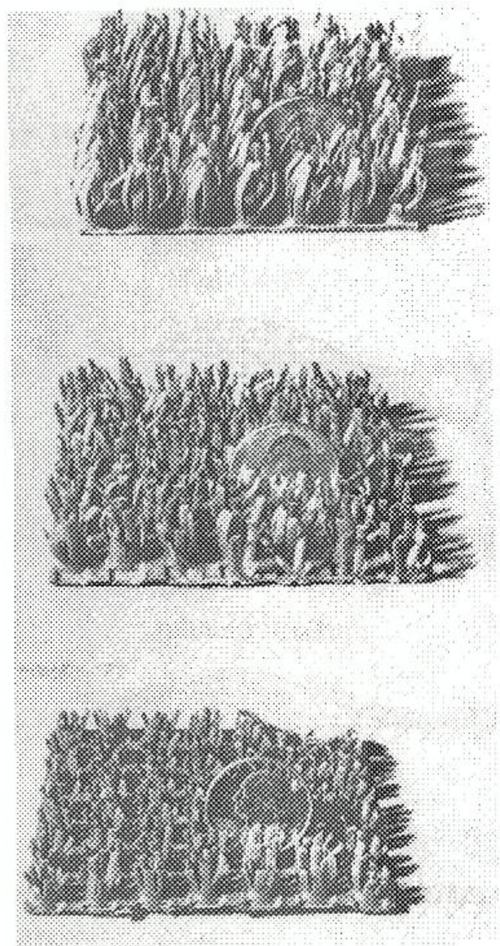

Figure 2: Model forest matting for 60, 40 and 20 foot high trees.

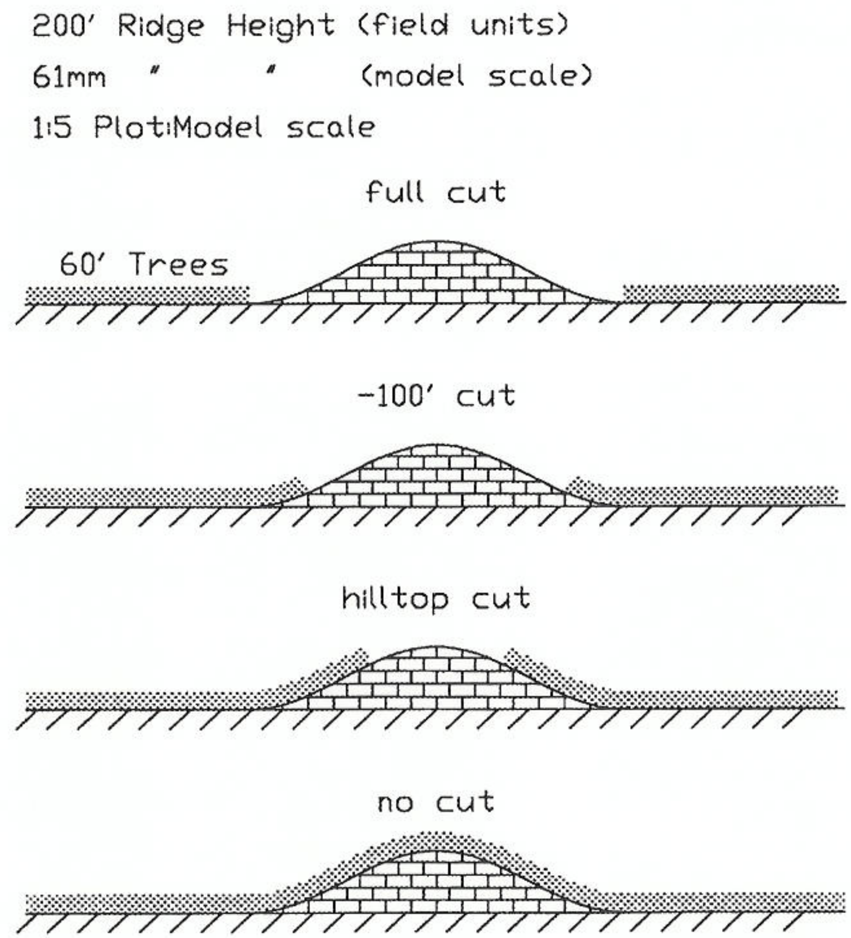

Figure 3: Model forest clearings for 60 foot trees On 1:3 slope sinusoidal ridge.

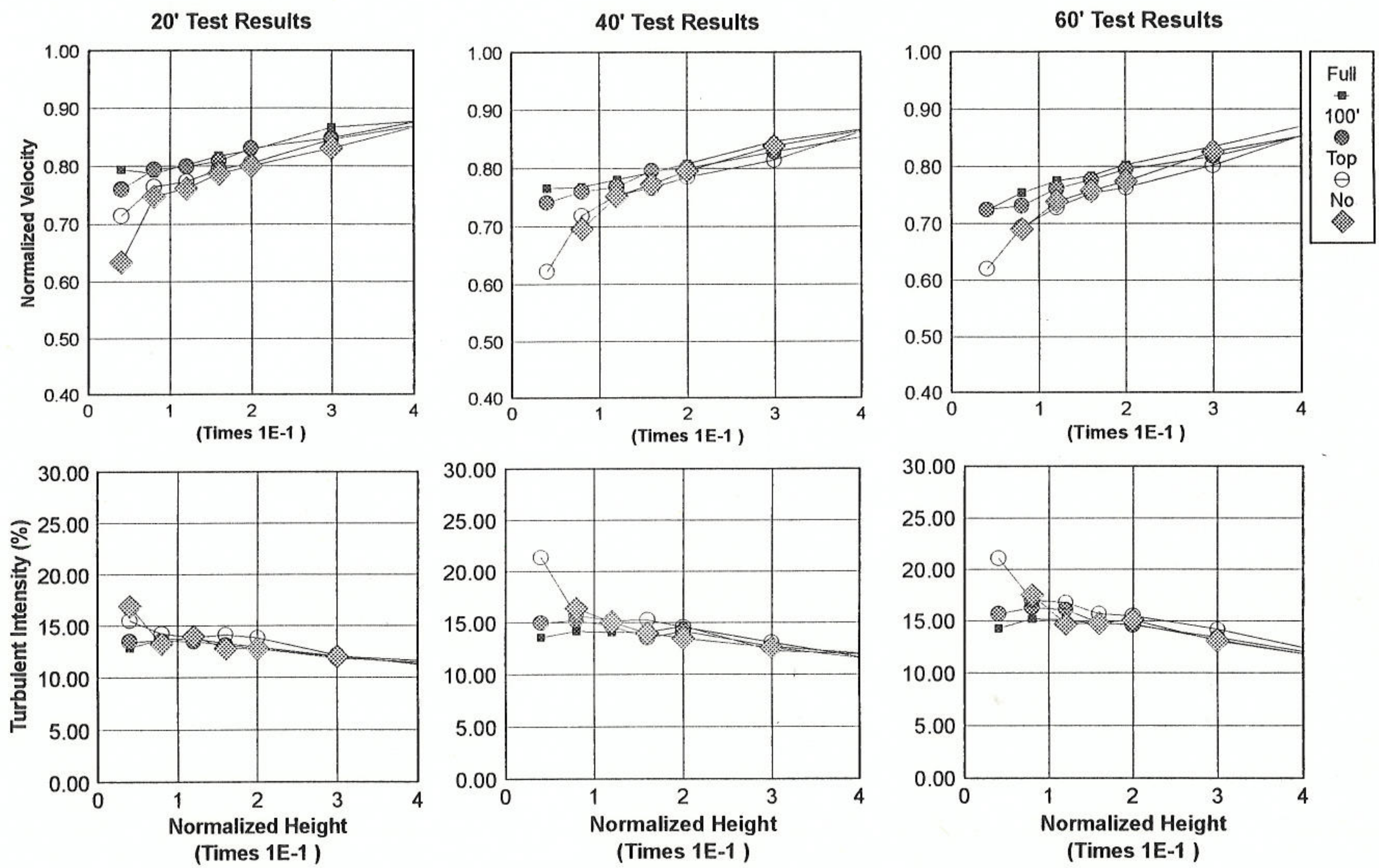

Figure 4: Model Ridge Velocity and Turbulence Profile Test Results; Trinagular Shape, 1:5 Slope.

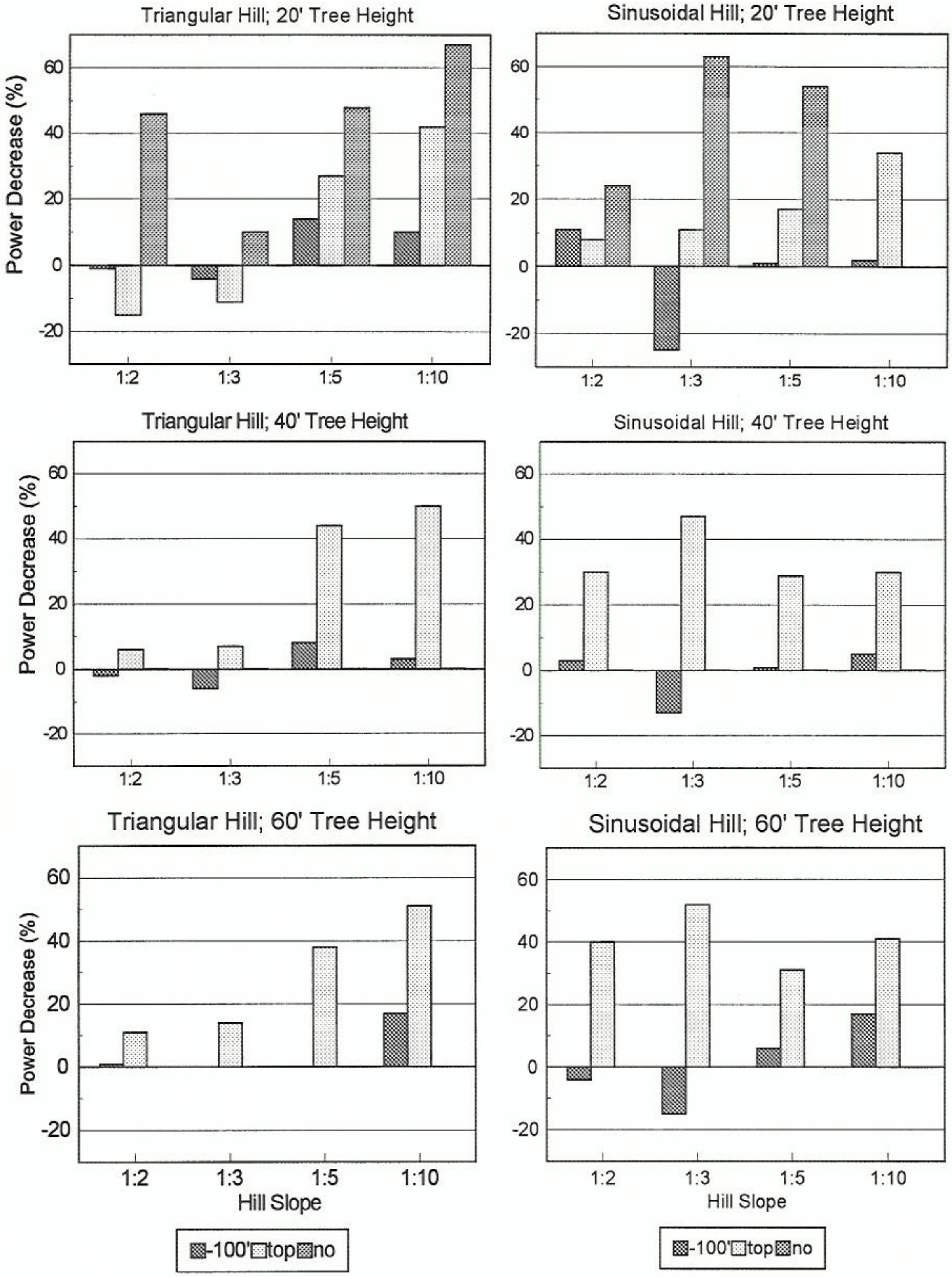

Figure 5: Model ridge percent power decrease over full clearcut option test results; 40' measurement height

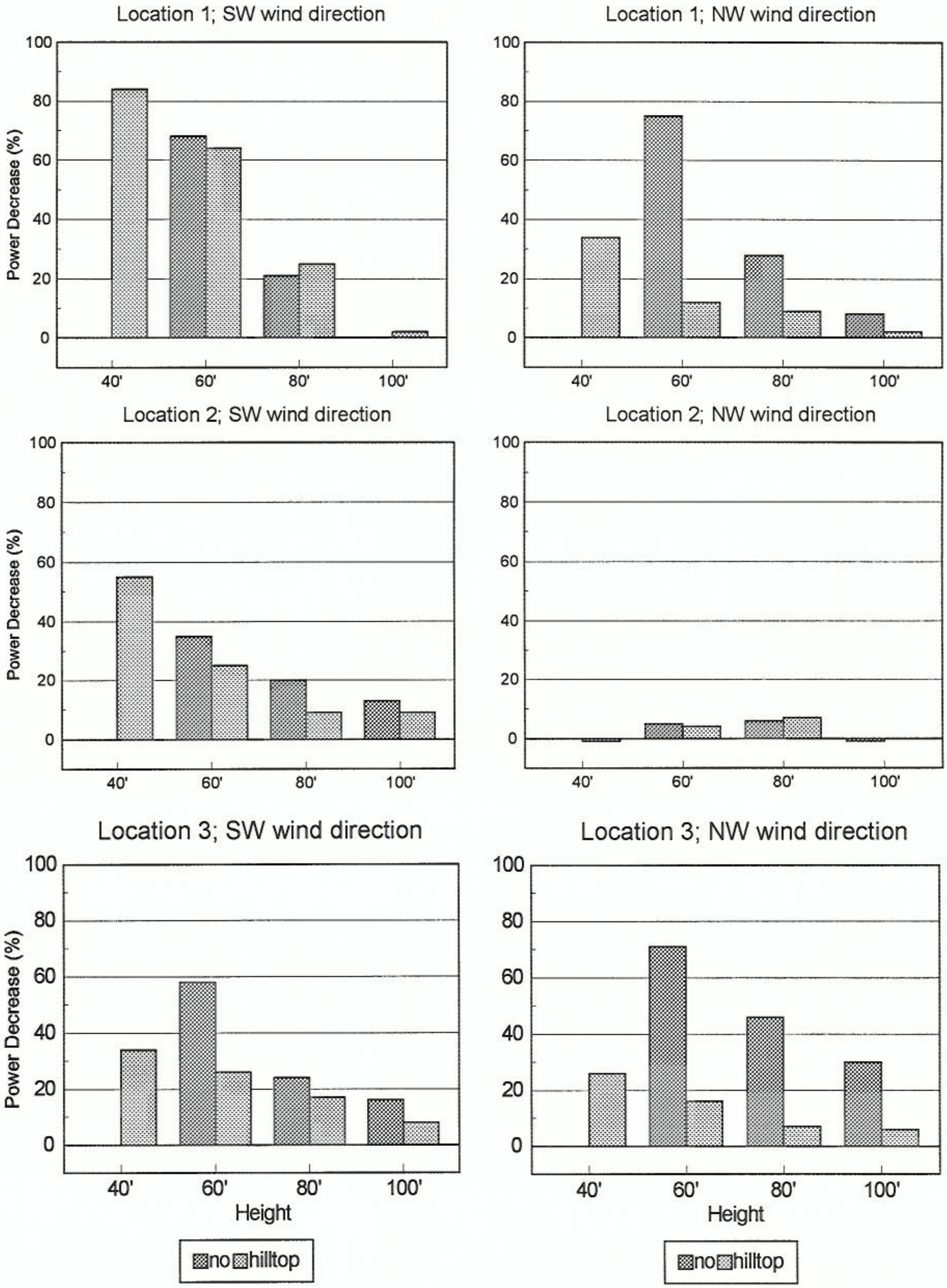

Figure 6: Kibby Mountain Model Tests, Percent power decrease over largest clearcut option test results; 40' measurement height