Detailed Measurements on the Effects of Trees on Wind Speed, Energy, Vertical Shear and Turbulence

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DETAILED MEASUREMENTS ON THE EFFECTS OF TREES ON WIND SPEED, ENERGY, VERTICAL SHEAR AND TURBULENCE

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ABSTRACT

A case study of the effects of trees on the wind resource, including wind speed, turbulence intensity and vertical shear profile is presented. The purpose of the study was to determine the economic benefits of tree removal vs. varying the turbine hub-height at a potential windfarm site. Three 32m meteorological towers separated by roughly one km were installed on a ridgeline covered with trees typically 12m tall. Hourly means and standard deviations of wind speed, direction and vertical velocity were collected for a two-year period. During the first year, the trees were left standing. At the beginning of the second year, trees surrounding the middle tower were clear-cut for a radius of ten tree-heights. No trees were removed at the other two towers, one of which served as the primary reference tower.

Comparisons were made among the data collected before and after the trees were removed. The change in speed ratios between the middle tower and the reference tower was analyzed to determine the relative increase in wind speed and wind power. Relative changes in turbulence intensity and vertical shear were also examined. These analyses were performed for summer and winter seasons separately, because the forest is mostly deciduous. The third tower was used as a control to evaluate the statistical "noise level" of the experiment.

Wind speeds increased at all four levels of the middle tower, with the largest increase at the lowest level, as expected. Large changes in vertical shear were measured, due to the unequal increase in wind speeds with height. Decreases in turbulence intensity were also measured in similar proportion. Two surprising findings were the lack of any changes in the turbulence intensity at the 40m level and the large (50%) decrease in vertical velocity at the 32m level.

METHODOLOGY

Three towers were instrumented with calibrated wind speed sensors on a 900m high ridge in New England. At Site 1, a 30.5m tower, Maximum #40 wind speed and NRG direction sensors were installed at 21 and 30.5 meters above ground level. (Sensor levels in this report are always referenced to ground level.) The trees are about 12 m tall at this site; thus the sensors were 9 and 18.5 m above tree level. An R. M. Young vertical velocity sensor was also installed at the 30.5m level. A thermometer was installed near the base of the tower.

The towers at Sites 2 and 3 were both 32m tall and were instrumented at 22 and 32 m. Site 2 had the same instrumentation as Site 1. During the middle of the study, two additional levels were added to this tower. A speed and direction sensor were installed at 13m, (tree-top level). In addition, the tower was temporarily extended to 40m and speed and direction sensors were installed at that level. Site 3, the control tower had instrumentation at 22 and 32m AGL.

Data were collected at these three sites for two years. After the first year all trees within a 10 tree height radius were removed around the middle tower, Site 2. Some of the logging debris was left at the site and the pile of debris was approximately 1.5 m high. Data continued to be collected for another year. Thus a year of data was available before and after the trees were cut down. Comparisons were made between these two one-year data sets.

To help determine statistical "noise", Site 3 was used as a control tower. Speed ratios were calculated between this tower and Site 1 before and after the logging. Since trees were not removed at these two sites, any changes in ratios can be considered noise. The change in speed ratios were all within +/-1%, from which it is concluded that the statistical noise level is about 1% for speed ratios.

SITE 2 SPEED, ENERGY AND POWER INCREASES

There were four measurement levels at Site 2. Logging induced increases in wind speed and energy were highest at the lowest (tree-top) level and almost negligible at the 40m level. The 32m level had the most complete data recovery so it will be examined first. The other levels will be discussed in the order of decreasing data recovery: 22m, 13m and 40m.

Due to the high data recovery at the 32m level, it was possible to analyze the changes in speed and theoretical electrical energy by several screening variables. The changes in theoretical energy are based on a 33m rotor diameter, 330-kW power curve. Analysis using other curves yields very similar results to these. Table 1 lists the changes in speed and theoretical energy ratios for eight most frequent 30-degree wind direction sectors and three speed ranges. The change in ratios is listed in percent and is defined as: [Ratio after/ratio before].

TABLE 1
CHANGE IN SPEED AND THEORETICAL ENERGY RATIOS: 32m LEVEL

Direction Band	Speed	Energy	
0 - 30 deg	5.8%	22.9%	
60 - 90	5.0	10.6	
180 - 210	3.1	9.6	
210 - 240	2.6	6.0	
240 - 270	2.3	6.3	
270 - 300	4.7	8.5	(modal wind band)
300 - 330	2.1	6.5	
330 - 360	1.2	11.1	
Wind Speed Range			
0 - 5 mps	2.1	-	
5 - 8.5	3.0	-	
8.5- 27	3.5	-	

The table shows that the speed-ups are above the noise level (1%) for nearly all wind directions. Maximum speed-up is from the north-northeast sector, which has the flattest upwind terrain. This suggests that logging at flat, potential windfarm sites should yield even more energy increases and economic benefits, than on ridgelines. The speed-ups range from 1-6% and the increase in theoretical energy ranges from 6-23%. Table one shows that the speed-ups are a function of wind speed, and increase in higher winds. Table 2 below lists the changes in speed, theoretical energy and wind power (watts/sq. m) by season and time-of-day. The table also lists the changes for all available data.

TABLE 2
CHANGE IN SPEED, ENERGY AND WIND POWER: SITE 2, 32m LEVEL

Condition	Speed	Energy	Power
Summer	3.4%	11.3%	9.8%
Winter	2.4	6.2	11.6
Daytime	2.7	6.3	13.8
Nighttime	2.9	8.1	9.3
All data	**2.9**	**7.3**	**11.2**

At the 32m level the overall speed-up was about 3% and the energy increase was about 7%. The increases in speed and energy were higher in the summer, apparently due to thicker foliage. This finding is expected and is interesting in light of the higher increase in speed ratios for high winds. The speed-ups were slightly higher in high winds, which are likely to occur more frequently in winter, than summer. The full extent of the summer increases may therefore have been partially masked, i.e. offset by the lower speed-ups in the lower summer winds.

The correlation coefficient between Site 1 and Site 2 at the 32m level was 0.96. Using a Student's t test, the observed change in speed ratio of 2.9% is statistically significant at the .001 level.

Table 3 below lists the changes in ratios for annual and seasonal periods at the 22m level of Site 2. The low wind speed bin is 0-6.9 mps and the high wind speed bin is 6.9 mps and above.

TABLE 3
CHANGE IN SPEED, ENERGY AND WIND POWER: SITE 2, 22m LEVEL

Condition	Speed	Energy	Power
Summer	-0.1%	13.3%	12.0%
Winter	5.7	22.2	17.8
Daytime	3.6	17.4	20.4
Nighttime	4.0	19.6	15.2
Low winds	0.9	-	-
High winds	6.2	-	-
Summer, high	4.6	-	-
All data	**3.8**	**18.6**	**17.1**

Table 3 shows a curious -0.1% speed ratio (i.e., decrease) for the summer period. Mean speeds do not reflect wind speed distributions, and the energy and wind power ratios show large increases for the summer period. There was no significant change in ratios in the low wind speed class, for the whole year. The lack of change in the summer speed ratio is probably due to the low winds. This is shown by the special case analysis (line 7) of summer, winds of 4.5 mps or greater. The increase in the speed ratio was 4.6% for this case.

There was no significant difference in speed ratios between day and night. The increases were higher in strong winds. This is the same pattern as the 32m level. The 22m level had larger speed and energy increases than the 32m level, except for the summer speed ratio. The theoretical energy increase at 22m is more than double the energy increase at the 32m level.

The 13m level sensors were at the tree-top level before the logging occurred. Due to the enormous tree-induced friction we would expect large increases at this level. The increases in speed, theoretical energy and wind power were 33.2%, 365% and 250%, respectively. Additional analyses showed no significant differences between daytime and nighttime. There were slightly greater increases in speed ratios in higher winds. This is similar to findings at the 32m and 22m levels. Although turbine hub-heights are never considered for the 13m level, the speed-ups are important because the bottom of the rotor could be very near this height.

The 40m level operated for a short period; roughly five months. The change in speed, energy and wind power ratios at the 40m level were 1.8%, 4.3% and 1.6%, respectively. These results are consistent with the other levels, i.e., we would expect smaller increases further above ground, but the results may not be statistically significant. Recall that the 'noise level' for speed ratios at Site 3 was about one percent.

SUMMARY - SITE 2 SPEED, ENERGY AND POWER INCREASES

Table 4 below lists the percent changes at all four levels of the tower.

TABLE 4
SITE 2 SUMMARY TABLE - INCREASES AT ALL LEVELS (%)

Level	Speed	Energy	Power
13m	33.2	365	250
22m	3.8	18.6	17.1
32m	2.9	7.3	11.2
40m	1.8	4.3	1.6

The table shows the dramatic increases at the lowest level, with decreasing impact at increasing heights above the trees. At 40 m, which is roughly 3 tree-heights, the increase is quite small. The data in table 4 are also plotted on figure 1 which can be found in the conclusion of this paper.

Research by D. Elliott and J. Barnard (1989, "Detailed Analysis of the Wake and Free-Flow Characteristics at the Goodnoe Hills MOD-2 Site", Richland, WA.) suggests that velocity deficits from groves of trees may extend much further downwind than ten tree-heights. The speed and energy increases measured at site 2 might have been even greater if the area of tree removal had been larger than 10 tree-heights.

VERTICAL SHEAR

A rule-of-thumb for calculating shear exponents (alpha) among trees is to assume the effective ground height to be 3/4 the tree height. In other words, if there are 20m trees, the effective ground level is 15 m. A 25m sensor level above 20m trees is 10 m above this effective ground level. Using this convention, the vertical shear exponent (alpha) has been calculated between all combinations of levels, before and after tree removal. Recall that after the trees were removed, there was approximately 1.5 m of rubble on the ground, which is treated as 1.5m trees in these calculations. Table 5 lists the shear exponents at Site 2 before and after logging.

TABLE 5
SITE 2 VERTICAL SHEAR EXPONENT (ALPHA AS DEFINED ABOVE)

	40m	40	40	32	32	22m above ground level
Period	32m	22	13	22	13	13m
Summer:						
no trees	.22	.21	.35	.21	.38	.49
trees	.21	.17	.35	.15	.38	.49
Winter:						
no trees	NA	NA	NA	.20	.32	.41
trees	NA	NA	NA	.19	.34	.41

Table 5 shows that the calculated shear exponents (alpha) are nearly identical in many cases, before and after trees were removed. This is consistent with the rule-of-thumb. The table shows higher vertical shear values in summer than winter. This is probably due to a combination of the summer foliage and lighter summer winds. The table also shows that the vertical shear between the top three levels is fairly consistent; about .20. On the other hand, the shear between the 13m level and the upper levels is about twice as high; about .40. This suggests that shear measured immediately above tree-top level is not representative of shear at two tree-heights. Therefore it is recommended that if one uses multi-level towers to measure vertical shear above trees, the placement of the lowest measurement level should be twice tree height, to be above the strongest frictional effects of the trees.

Although the changes in the shear exponents were consistent with the rule-of-thumb, its use is not appropriate in certain situations. It should not be used to predict speed-up factors due to tree removal. For instance, the rule-of thumb predicts a 5% speed-up at the 40m level, but the measured speed-up was just below 2%. The rule overpredicts speed-up factors at all four levels.

Vertical shear expressed as an absolute speed difference has also been analyzed between the three lowest levels of the tower. The calculations are based on hourly means. Maximum instantaneous shears would be much higher than the hourly maximum values discussed below. Table 6 lists the mean and maximum hourly wind shear measured between these levels, before and after tree removal.

TABLE 6
SITE 2 HOURLY MEAN AND MAXIMUM WIND SHEAR (mps)

Sensor	Trees Present		No trees present	
Levels	Mean	Max	Mean	Max
32, 22m	0.8 mps	4.4 mps	0.8 mps	3.3 mps
32, 13m	2.9	9.1	2.1	8.4
22, 13m	2.2	6.7	1.4	6.0

The table shows that there is a drop of about one mps in both the mean shear and maximum hourly shear after the trees were removed, except for the mean shear between the 22m and 32m levels. The 1-mps drop corresponds to a 27% decrease in mean shear between the 32 and 13 m levels, and a 38% decrease between the 22 and 13 m levels. These decreases would result in lower loads on the turbine blades, i.e. longer life expectancy.

VERTICAL WIND SPEED

The vertical component of wind speed was measured at the 30.5m level at site 1 and the 32m level at site 2. The percent changes in vertical velocity ("W") were larger than the changes in any other parameter. Table 7 lists the mean vertical velocity at site 2 with and without trees. The data presented in table 7 are for all wind speeds and directions.

TABLE 7
SITE 2 MEAN VERTICAL VELOCITY (cm/sec) AND ANGLE OF ATTACK (deg)

Season	Trees Present	Trees Removed
Summer	41.9 cm/sec	20.9 cm/sec
Winter	92.2	54.4
Annual	65.4	32.2
Mean angle of Attack	4.5 deg	2.1 deg

The table shows that there was a decrease of roughly 50% in the vertical component of wind speed at Site 2. (There was no decrease at Site 1.) The decrease at Site 2 corresponds to a reduction in mean angle of attack from 4.5 degrees to 2.1 degrees. The change in angle of attack might be explained by the following hypothesis. The wind generally blows parallel to the ground. Since the ground is rising towards the meteorological tower in the prevailing flow direction, the winds will be coming uphill and will have a positive vertical component. When the trees were removed, upwind of the tower, the terrain still rises, but because there is a "depression" where the trees were removed, the effective slope up to the meteorological tower is less steep. Since the effective upslope is less steep, there is a decrease in angle of attack and a decrease in W.

Although there was a large decrease in W, there was only a moderate decrease in the standard deviation of W, referred to as sigma w. Sigma w is the vertical component of turbulence intensity. Sigma w decreased from 69 cm/sec with trees to 59 cm/sec with trees removed, which is about a 15% decrease.

TURBULENCE

Levels of turbulence have been compared before and after tree removal. Turbulence intensity is defined here as the hourly standard deviation of the wind speed divided by the mean speed, in wind speeds of 4.5 mps and above. Crosswind turbulence is defined here as the standard deviation of wind direction, in wind speeds of 4.5 mps and above. Table 8 lists the turbulence intensity before and after tree removal at the four levels.

TABLE 8
SITE 2 TURBULENCE INTENSITY

Level	Trees Present	Trees Removed	Change(%)
40m	.162	.172	+6.2%
32m	.193	.183	-5.2
22m	.222	.201	-9.5
13m	.360	.247	-31.4

Table 8 shows that mean turbulence levels decrease with increasing height above ground. The table shows that there were decreases in turbulence intensity at three levels, but an increase in turbulence at the 40m level. This is not an expected result, but the data period at this level was quite short. Turbulence intensity decreased more significantly at the lowest levels of the tower, as expected.

Crosswind or directional turbulence was also examined and the results were slightly different. Table 9 lists the changes in both turbulence intensity and crosswind turbulence.

TABLE 9
SITE 2 TURBULENCE SUMMARY - PERCENT CHANGE

Sensor Level	Crosswind Turbulence	Turbulence Intensity
40m	-2.7%	+6.2%
32m	0.0	-5.2
22m	-14.3	-9.5
13m	-22.4	-31.4

The table shows that crosswind turbulence decreased at three levels, but that there was no change at the 32m level. There was a slight decrease in crosswind turbulence at the 40m level, in spite of the increase in turbulence intensity.

Based on these mixed results, it is difficult to say that there were significant decreases in turbulence above the 22m level. The lowest two levels of the tower clearly show decreases in turbulence. The turbulence measured at the upper two levels is probably due more to atmospheric conditions than the effects of the trees. It is possible that decreases in turbulence at all levels could have been greater if the area of tree removal had been larger and if the debris had been removed.

CONCLUSIONS

Wind speed and other data collected at three meteorological towers have been analyzed to determine the effects of trees on the wind resource. Data were available from four levels on a tower, in an area with ~12m tall trees. Results obtained from this study should be transferable to other sites with the following caveats:
1. Similar terrain shape, i.e. ridgeline. In steeper upslope areas, a smaller radius of clear-cutting might be adequate. In flat areas, benefits should be greater.
2. More dramatic improvement might take place with a larger tree removal radius and if all debris are removed, so that the resulting surface is smoother.
3. Increases in theoretical energy were calculated from four distinct sensor levels. Actual energy improvements might vary from the values in table 10.

Wind speeds increased at all four levels, with the most significant increases in speed and theoretical energy at the bottom of the tower. At the 32m level (2.6 tree-heights) the speed increase was 3% and the theoretical energy increase, assuming a 33m rotor, 330-kW wind turbine, was 7%. At the 40m level (3.25 tree-heights) the speed increase was only 2% and the energy increase was 4%. The speed increases probably do not extend much further up than 4 tree-heights. If turbines with hub-heights at this level are being considered, it may not be economical to remove the trees. The only benefit that would occur is a decrease in wind shear at the bottom of the blade and reduced blade loads. Table 10, lists the energy increases that could be expected at four typical hub-heights. These numbers are based on linear interpolation of the increases listed in table 4. The speed and energy increases are displayed on figure 1 below.

TABLE 10

ENERGY INCREASES (%) FOR VARIOUS HUB-HEIGHTS FROM CLEAR CUTTING

Hub-Height	Tree Heights	Energy Increase
24m	2.0	15.9%
30	2.5	9.0
37	3.0	5.5
43	3.5	3.1

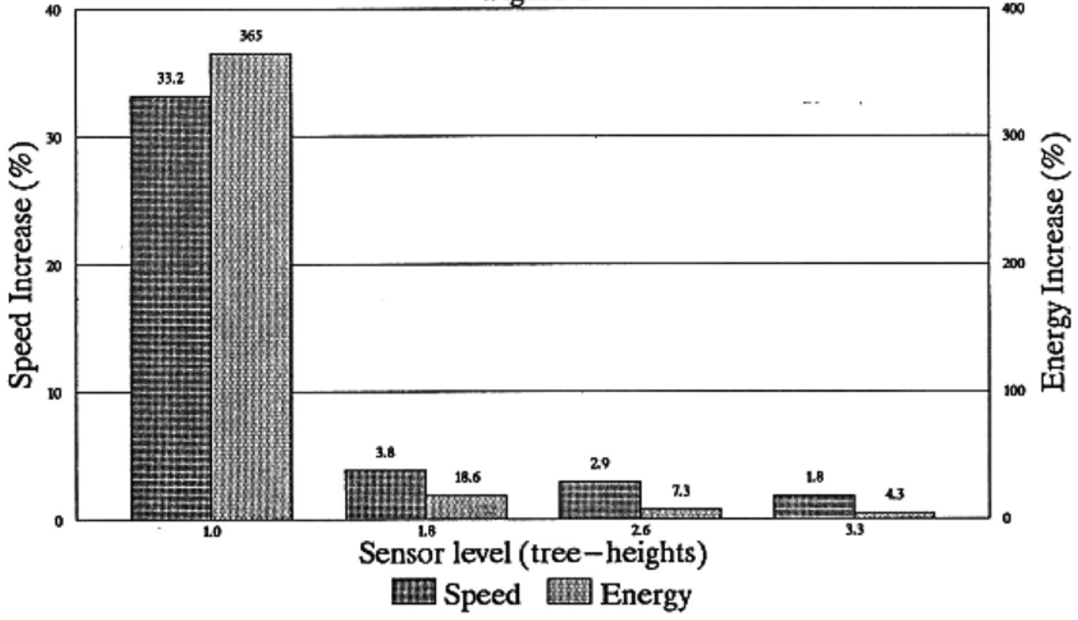
Vertical shear decreased by 30% to 40% due to the unequal increases in wind speed at different tower heights. The largest change was at the bottom of the tower where the mean shear decreased by 1 mps, or 38% between the 13m and 22m levels.

The rule-of-thumb, that the effective ground height is 3/4 tree height was validated. However, this rule should not be used to estimate speed-up factors associated with tree removal.

Vertical velocity at the 32m level decreased by about 50%. This decrease in vertical velocity was probably due to the change in the effective angle of the slope upwind of the meteorological tower. The change in vertical velocity is very dependent on upstream terrain and the same results should not be expected in flat areas.

Turbulence decreased significantly at the 13 and 22m levels, but only slightly at higher levels. Apparently the turbulent effects of the trees only extend up to about two tree-heights. Above that level, ambient turbulence is more significant than the turbulence induced by the trees. Results might have been different with a larger radius of tree removal and if the stumps and debris had been removed.

Figure 1



SPEED AND ENERGY INCREASES (%) AFTER REMOVAL OF TREES