USING TEMPORALLY LIMITED WIND DATA IN THE WIND EROSION PREDICTION SYSTEM

S. J. van Donk, C. Liao, E. L. Skidmore

ABSTRACT. *The Wind Erosion Prediction System (WEPS) is a computer model for the simulation of windblown sediment loss from a field. The model is used to evaluate the effect of alternative cropping systems and management scenarios on wind erosion. WEPS requires hourly wind data, which for many locations are unavailable. Therefore, the objective of our research was to investigate whether wind speed and direction can be simulated adequately from temporally limited data and to determine suitable times of the day to take measurements if only a few measurements per day can be made. For three locations (La Junta, Colorado; Sidney, Nebraska; and Pendleton, Oregon), two statistical datasets were created to be used with the WEPS stochastic wind generator. The first was based on the full dataset with 24 hourly observations per day, and the second was based on a subset of four observations per day: at 0200, 0800, 1400, and 2000 hours local standard time (LT). Erosive wind power densities (WPD), calculated from both datasets, agreed well with each other. On an annual basis, the discrepancy was greatest for La Junta, with a difference of 0.8 W m^{-2} (6%). For the five most erosive months, the mean absolute WPD difference was less than 10% for all three locations. Prevailing wind erosion direction and WEPS-simulated soil loss also showed good agreement between the two data sets. Many other subsets of two, three, and four measurements per day performed as well or better than the 0200, 0800, 1400, 2000 LT subset. In spite of temporally limited wind data, it is possible to use WEPS to estimate wind erosion risks and the effectiveness of various conservation practices. The results of this study allow researchers to evaluate whether limited data, measured at certain times of the day, are suitable for use in WEPS. For a new station, if only a few measurements per day are going to be made, the results of this study may be used as a guide to choose the times of the day to take these measurements.*

Keywords. *Erosive wind power density, Wind direction, Wind erosion simulation, Wind speed.*

Wind erosion is a serious problem in many parts of the world, with the most severe effects in arid and semiarid regions. To better cope with the ravages of wind erosion, the USDA Agricultural Research Service (USDA-ARS) has developed a process-based Wind Erosion Prediction System (WEPS) (Hagen, 1991; Wagner, 2001). WEPS is a computer model for the simulation of windblown sediment loss from a field. It is used primarily for soil conservation and environmental planning. The model can be used to evaluate the effect of alternative cropping systems and management scenarios on wind erosion. It keeps track of eroded sediment amounts in three size classes: creep/saltation (particle diameter >100 µm), suspension (<100 µm), and particulate matter with an aerodynamic diameter <10 µm (PM_{10}). WEPS has been designated to replace the more empirical Wind Erosion Equation (WEQ) currently used by the USDA Natural Resources Conservation Service (USDA-NRCS).

Wind is the principal driver of WEPS. However, it is generally not practical to use measured historical wind data with WEPS, because many multi-year wind records have missing data. Researchers may also want to simulate wind erosion for a longer period than the length of the measured data record, e.g., for 60 years, which is a typical WEPS simulation run. In addition, the measured data require much more computer disk space than wind summary statistics combined with a stochastic wind generator. Therefore, a stochastic wind generator is often more appropriate for use with WEPS than using the measured data directly (Skidmore and Tatarko, 1990; van Donk et al., 2005).

WEPS generates wind speeds by month and by wind direction because wind speed varies with time of the year and wind direction. Wind speed by month is important because a field may be protected against wind erosion in one month, but not in another. For instance, most winter wheat fields in the U.S. Great Plains are better protected with biomass in May when wheat is actively growing than in February when wheat is dormant. Wind speed by direction is important for determining distances to non-erodible field boundaries. The longer this distance, the more a wind erosion avalanche effect can be expected. Wind direction relative to the direction of tillage operations and row crops is also important for wind erosion. Ridges and rows offer more protection if they are perpendicular to the wind than if they are parallel with the wind (Arm-

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brust et al., 1964; Hagen and Armbrust, 1992). In addition, the proper placement of wind barriers depends on wind direction (Skidmore and Hagen, 1977; Hagen et al., 1981).

At a WEPS workshop in China (Institute of Soil and Water Conservation; Yangling, Shaannxi, China; 12-18 May 2005), it was recognized that at many locations where wind erosion is a problem, only limited wind data are available. For example, at Yulin, China, wind data have been recorded at only four times a day: at 0200, 0800, 1400, and 2000 hours local standard time (LT). WEPS requires 24 hourly wind speed observations per day.

The time of measurement is important if one can only make a few measurements per day. In the middle of the day, the atmosphere is typically more unstable than during the night, due to heating of the earth's surface, resulting in enhanced vertical air mixing and consequently greater wind speeds closer to the earth's surface (Rosenberg et al., 1983; Campbell and Norman, 1998). Thus, daytime wind speeds alone would overestimate the 24-hour wind resource. But a mix of daytime and nighttime wind speeds, such as that at Yulin, may more accurately estimate it.

Several researchers have studied diurnal wind speed distributions. Ephrath et al. (1996) developed a method to calculate diurnal wind speed patterns from daily data. Molla et al. (2001) characterized diurnal and seasonal wind speed patterns using a two-dimensional Fourier transformation. Weggel (1999) related maximum daily wind gusts to mean daily wind speed. The objective of our research was to investigate whether the WEPS stochastic wind generator can adequately simulate wind speed and direction from temporally limited data and to determine suitable times of the day to take measurements if only a few measurements per day can be made.

Methods

A quality-controlled hourly wind data set (TD-6421, version 1.1) was obtained from the U.S. National Climatic Data Center (NCDC). The hourly data are samples taken at the top of every hour. One sample (observation) is a 1 or 2 min average and represents an entire hour. Wind speeds refer to a height of 10 m. Three stations were selected from the NCDC data set for this study: La Junta, Colorado; Sidney, Nebraska; and Pendleton, Oregon. La Junta and Sidney represent the windy, and wind-erosion prone, Great Plains region of the central U.S. The dust bowl of the 1930s occurred in this region. Pendleton lies in the very different climatic region of the northwestern U.S., which is also known for problems with wind erosion. La Junta had 16 years of data, while Sidney had 22, and Pendleton 52.

For each of the three locations, two statistical datasets were created to be used with the WEPS stochastic wind generator (van Donk et al., 2005): one based on the full NCDC data set with 24 hourly observations per day, and a second one using only a subset of four observations per day (at 0200, 0800, 1400, and 2000 LT, to mimic data availability such as that of Yulin, China).

Erosive wind power density (WPD) was chosen to evaluate how well the two data sets agreed with each other, because WPD is proportional to sediment transport by wind (Bagnold, 1941; Skidmore, 1998). WPD was calculated using the WEPS definition (Hagen et al., 1999):

$$\begin{aligned} \text{WPD} &= 0.5\rho(u-u_t)u^2 \qquad u > u_t \\ \text{WPD} &= 0 \qquad\qquad\qquad\quad u \le u_t \end{aligned} \tag{1}$$

where WPD is erosive wind power density (W m^{-2}), ρ is air density (kg m^{-3}), u is wind speed (m s^{-1}) at 10 m height, and u_t is the threshold wind speed (m s^{-1}) above which sediment starts to move. A threshold of 8 m s^{-1} is often thought of as a minimum threshold (Hagen, 1995), but for less erodible fields, u_t may be 10 or 12 m s^{-1} or even higher. In this study, a threshold of 10 m s^{-1} was used. Air density is a function of station elevation and air temperature:

$$\begin{aligned} \rho = 348.56 \Big[&(1.013 - 0.1183(EL/1000) \\ &+ 0.0048(EL/1000)^2\Big] \div (T + 273.1) \end{aligned} \tag{2}$$

where EL is station elevation above sea level (m), and T is air temperature (°C).

The NCDC data set that we worked with included only wind data, so we were not in a position to calculate air density and WPD using actual temperatures. Hence, we used a constant T of 20°C. Fortunately, for our study, it is not important to use actual temperatures, since the objective is to compare, for the same station, WPD calculated from the full data set with WPD calculated from a limited data set. Therefore, the absolute values of ρ and WPD are not critical here. We confirmed this assertion using a data set for North Platte, Nebraska, which included both hourly wind and temperature data. WPD differences between the full and limited data sets, calculated using a constant temperature of 20°C, were very similar to those calculated using actual temperatures. The largest discrepancy of 0.4 W m^{-2} was for January, for which the WPD difference was 4.9 W m^{-2} using the assumption of a constant temperature of 20°C and 5.3 W m^{-2} using actual temperatures. For all the other months, the discrepancy was 0.1 W m^{-2} or less.

The WEPS statistical data base has a wind speed probability distribution for each combination of 12 months and 16 wind directions (van Donk et al., 2005). For each of these combinations, the average WPD was calculated:

$$\text{WPD}_{m,d} = \int_{u_t}^{u_{\max}} p_{m,d}(u)\ \text{WPD}(u)\ du \tag{3}$$

where WPD$_{m,d}$ is the average WPD for month m and direction d (W m^{-2}), $u_{\max}$ is the maximum wind speed (m s^{-1}), and $p_{m,d}(u)$ is the wind speed probability for month m and direction d. Equation 3 was integrated numerically. Monthly average erosive wind power density was calculated as the weighted average of the 16 wind directions:

$$\text{WPD}_m = \sum_{d=1}^{16} \text{WPD}_{m,d}\ \text{DF}_{m,d} \tag{4}$$

where WPD$_m$ is the average WPD for month m (W m^{-2}), and DF$_{m,d}$ is the wind direction frequency for month m and direction d (fraction). Annual average erosive wind power density was calculated as the average of the 12 monthly values.

In addition, the prevailing wind erosion direction (PWED) was calculated using concepts from Skidmore (1965). First, a "wind erosion force" was calculated for each month-direction combination:

$$f_{m,d} = DF_{m,d} \int_{u_t}^{u_{\max}} p_{m,d}(u)\ u^3\ du \qquad (5)$$

where $f_{m,d}$ is the wind erosion force for month m and direction d. Equation 5 was integrated numerically. Next, combining contributions from all 16 cardinal wind directions, the wind erosion force from direction θ was calculated for θ = 0° to 359° with a step of 1°:

$$F_m = \sum_{d=1}^{16} f_{m,d} \cos[22.5(d-1) - \theta] \qquad (6)$$

where F_m is the wind erosion force from wind direction θ for month m. Negative values of cos[22.5(d - 1) - θ] were set to 0 in equation 6. PWED is the direction θ for which F_m is greatest.

Monthly and annual WPD and PWED were calculated from both the 24-hour and the four-hour wind data sets. In addition, WEPS simulations were conducted for winter wheat – fallow rotations on a square (805 × 805 m) field, using both wind data sets, for both conventional tillage and reduced tillage. Simulated wind erosion was used in addition to WPD and PWED to evaluate the adequacy of the limited data set.

The time of measurement is important if one can only make a few measurements per day. Daytime wind speeds overestimate WPD of the full 24-hour data set (WPD_{24}), and nighttime wind speeds underestimate it. Therefore, in addition to the analysis of the four-hour data set with measurements at 0200, 0800, 1400, and 2000 LT, many other combinations were investigated. These combinations were not only for cases with four measurements per day, but also for two and three measurements per day. Not all possible combinations were investigated, but only the ones that had the potential to accurately estimate WPD_{24}. For example, combinations of only daytime wind speeds would surely overestimate WPD_{24}, so these were not included in the analysis. Many combinations of daytime and nighttime wind speeds were included because they are more likely to accurately estimate WPD_{24}.

Results and Discussion

The erosive wind power density indicates that spring is the most erosive season for all three locations, with a secondary erosive season in the fall (table 1). The prevailing wind erosion direction at La Junta is between north and northwest and at Sidney northwest during the most erosive time of the year. At Pendleton, the prevailing wind erosion direction is west all year round.

Erosive wind power density calculated from the full 24-hour data set and that calculated from the four-hour data set (measurements at 0200, 0800, 1400, and 2000 LT) agreed well with each other for most months for the three locations (table 1). For the five most erosive months, the mean absolute WPD difference was less than 10% for all three locations. For the less erosive months, e.g., the summer months, the percent WPD difference was generally greater. At these lower WPD values, it is more likely to obtain large percentage differences. For example, the percent difference between 0.1 and 0.2 W m^{-2} is 100%, but that does not mean that this difference is important. The greater percent difference in WPD in the less erosive months is not so important, because not much wind erosion is expected during this time, provided the soil is not much more erodible than during more erosive times of the year.

Table 1. Erosive wind power density (WPD) and prevailing wind erosion direction (PWED)[a] based on the full wind data set with 24 hourly measurements per day (subscript 24) and based on a subset using only four measurements per day at 0200, 0800, 1400, and 2000 LT (subscript 4).

	WPD_{24} (W m^{-2})	WPD_4 (W m^{-2})	WPD Diff. (W m^{-2})	WPD Diff. (%)	$PWED_{24}$ (deg.)	$PWED_4$ (deg.)	PWED Diff. (deg.)
La Junta							
Jan.	7.2	8.1	-0.9	-13	322	303	19
Feb.	16.4	16.1	0.3	2	349	350	-1
Mar.	22.0	19.8	2.2	10	329	328	1
Apr.	24.8	23.4	1.4	6	351	331	20
May	22.2	19.6	2.6	12	10	11	-1
June	13.6	11.7	1.9	14	214	39	175
July	8.1	4.0	4.1	51	38	39	-1
Aug.	5.8	2.3	3.5	60	8	11	-3
Sept.	4.9	5.5	-0.6	-12	13	12	1
Oct.	10.4	10.0	0.4	4	9	5	4
Nov.	9.9	17.9	-8.0	-81	356	354	2
Dec.	7.5	4.7	2.8	37	343	332	11
Year	12.5	11.7	0.8	6			
Mean absolute WPD difference is 9% for the five most erosive months[b] and 25% for all twelve months.							
Sidney							
Jan.	14.4	14.4	0.0	0	314	311	3
Feb.	18.1	18.7	-0.6	-3	316	314	2
Mar.	17.4	14.8	2.6	15	319	320	-1
Apr.	19.2	19.2	0.0	0	320	319	1
May	13.3	14.8	-1.5	-11	324	322	2
June	4.7	5.1	-0.4	-9	308	304	4
July	3.8	1.4	2.4	63	167	159	8
Aug.	1.8	1.2	0.6	33	171	232	-61
Sept.	4.2	7.0	-2.8	-67	317	319	-2
Oct.	11.6	13.9	-2.3	-20	320	322	-2
Nov.	12.1	16.0	-3.9	-32	314	318	-4
Dec.	18.0	17.1	0.9	5	312	315	-3
Year	11.5	11.9	-0.4	-3			
Mean absolute WPD difference is 5% for the five most erosive months[b] and 21% for all twelve months.							
Pendleton							
Jan.	7.7	6.1	1.6	21	252	251	1
Feb.	8.4	7.8	0.6	7	256	255	1
Mar.	13.1	12.5	0.6	5	261	262	-1
Apr.	12.1	12.3	-0.2	-2	266	265	1
May	7.5	6.4	1.1	15	266	266	0
June	7.1	6.9	0.2	3	268	268	0
July	4.3	4.7	-0.4	-9	269	269	0
Aug.	3.1	2.6	0.5	16	268	267	1
Sept.	5.4	5.5	-0.1	-2	267	267	0
Oct.	4.1	4.6	-0.5	-12	259	257	2
Nov.	9.5	10.0	-0.5	-5	256	256	0
Dec.	10.4	9.2	1.2	12	251	249	2
Year	7.8	7.3	0.5	6			
Mean absolute WPD difference is 6% for the five most erosive months[b] and 9% for all twelve months.							

[a] PWED: 0° = north, 90° = east, 180° = south, and 270° = west

[b] Five most erosive months = five months with the greatest WPD_{24}.

However, the –81% difference for La Junta in November is a large difference in one of the more erosive months

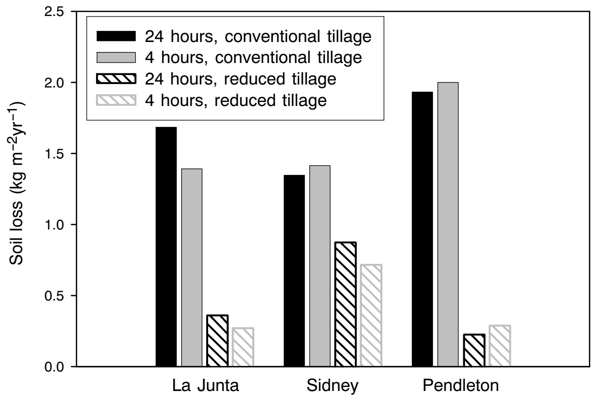

Figure 1. WEPS-simulated average annual field soil loss, based on the full NCDC wind data set with 24 hourly measurements per day (24 hours) and based on a subset using only four measurements per day: at 0200, 0800, 1400, and 2000 LT (4 hours) for winter wheat – fallow rotations with conventional tillage and reduced tillage.

(table 1). This was largely due to one single hourly data point in a data set of 16 years. The wind speed was 30.8 m s^{-1} on 25 November 1984 at 1400 LT. If this wind speed had occurred at 1300 instead of 1400 LT, WPD_{24} would still be the same 9.9 W m^{-2}, but WPD_4 would have dropped from 17.9 to 11.0 W m^{-2} and the difference would have been only −11%.

On an annual basis, the discrepancy in WPD was greatest for La Junta, with a difference of 0.8 W m^{-2} (6%). Prevailing wind erosion direction also showed good agreement between the two data sets, especially at Pendleton (table 1).

Generally, WEPS-simulated average annual soil loss also indicated good agreement between the two wind data sets, although differences were as great as 20% (fig. 1). When simulating reduced tillage, simulations with either wind data set showed marked reductions in soil loss. This indicates that WEPS can use limited wind data to assess the effect of alternative management practices on wind erosion.

At La Junta, more than 50% of WEPS-simulated wind-blown sediment left the square field over the southern border (table 2), which corresponds with the prevailing wind erosion direction being from the north and northwest during the most erosive seasons (table 1). Perhaps surprisingly, more than 30% of wind-blown sediment left the field over the northern border at Sidney. This does not seem to agree with the prevailing wind erosion direction being from the northwest during the most erosive seasons (winter and spring). However, the most vulnerable (erodible) period did not coincide with the most erosive times of the year. It occurred at the end of the fallow cycle, during summer and early fall, just before and after wheat planting, when residue cover was the lowest and wheat plants were still very small. During the summer, the prevailing wind erosion direction is from the south at Sidney (table 1), explaining the significant amount of soil crossing the northern border. It is not surprising to see that about 90% of wind-blown sediment left the field over the eastern border at Pendleton, where winds are very dominant from the west all year long. WEPS-simulated wind-blown sediment crossed field borders approximately in the same direction between the two wind data sets (table 2), which supports the hypothesis that WEPS can run adequately with this limited data set of only four measurements per day.

At Sidney, the average wind speed during the daytime is approximately 20% greater than during the night (fig. 2). At La Junta and Pendleton, similar differences were observed. However, wind erosion is not driven by average wind speed. Only high wind speeds are of interest. Thus, for wind erosion, erosive wind power density and the percentage of wind speeds greater than a certain threshold (e.g., 10 m s^{-1}) are more interesting variables than average wind speed. These variables show a much more pronounced difference between daytime and nighttime than average wind speed does. At Sidney, the percentage of wind speeds greater than 10 m s^{-1} based only on wind speeds measured at 14 hours was about two times greater than that based on the full 24-hour data set (fig. 2) and more than four times greater than that based on nighttime measurements. WPD based only on wind speeds measured at 14 hours was about two times greater than WPD_{24} (fig. 3).

If only one wind speed measurement per day were feasible, then 1900 or 2100 LT would be the best time of the day to take a measurement at La Junta, since WPD calculated from data measured at these times approximates WPD_{24} the best (fig. 3). Other times that would be good at La Junta are 1000 and 2200 LT. At Sidney, 1700 LT would be the best time, with 0900 and 1800 LT being good alternatives. At Pendleton, 1000, 2000, 2100, and 2200 LT would be good times to measure wind speed.

If two measurements per day were feasible, then 0200 and 1100, 0200 and 1200, 0200 and 1300, 0800 and 1800, and 0900 and 1900 LT would be among the best combinations of times of the day to take measurements at La Junta (fig. 4). At Sidney, 0200 and 1000, 0200 and 1600, 0300 and 1600, 0800 and 1700, 0900 and 1800, and 0900 and 1900 LT would be among the best combinations. At Pendleton, 0200 and 1200, 0200 and 1700, 0300 and 1200, 0800 and 1700, 0900 and 1800, and 0900 and 1900 LT would be among the best combinations of times of the day to take measurements if two measurements per day were feasible (fig. 4).

There are many good combinations of times of the day to take measurements if three (fig. 5) or four (fig. 6) measurements per day were feasible. The combination of hours used for the first part of this study (0200, 0800, 1400, and 2000 LT) underestimates WPD_{24} somewhat at La Junta and Pendleton

Table 2. Percent of WEPS-simulated wind-blown sediment crossing the borders of a square field, based on the full wind data set with 24 hourly measurements per day (24 h) and based on a subset using only four measurements per day (4 h) at 0200, 0800, 1400, and 2000 LT.

	La Junta			Sidney			Pendleton		
Field Boundary	24 h (%)	4 h (%)	Diff. (%)	24 h (%)	4 h (%)	Diff. (%)	24 h (%)	4 h (%)	Diff. (%)
Southern	52.6	62.5	-9.9	15.3	23.2	-7.9	3.2	0.4	2.8
Western	12.9	6.3	6.7	11.4	5.2	6.2	1.7	0.1	1.6
Northern	18.5	5.7	12.8	38.5	31.9	6.6	5.0	11.7	-6.7
Eastern	16.0	25.6	-9.6	34.8	39.7	-4.9	90.1	87.8	2.3
Total	100.0	100.0	0.0	100.0	100.0	0.0	100.0	100.0	0.0

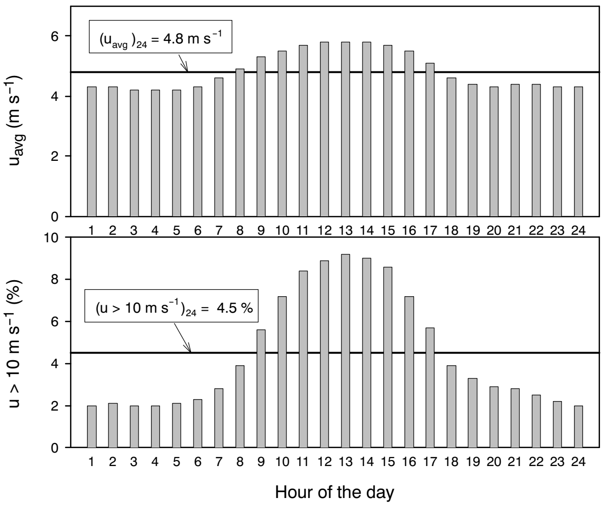

Figure 2. Average wind speed (u_{avg}) and percentage of wind speeds greater than 10 m s^{-1} (u > 10 m s^{-1}) for Sidney, Nebraska, based on one wind speed measurement per day (0000 LT, 0100 LT, 0200 LT, etc.). These two variables based on all 24 hourly measurements per day (subscript 24) are also shown.

and overestimates it at Sidney (fig. 6). This combination does not give the best performance of all possible combinations, but it is certainly reasonable. Apparently, these hours are a good mix of daytime and nighttime wind speeds.

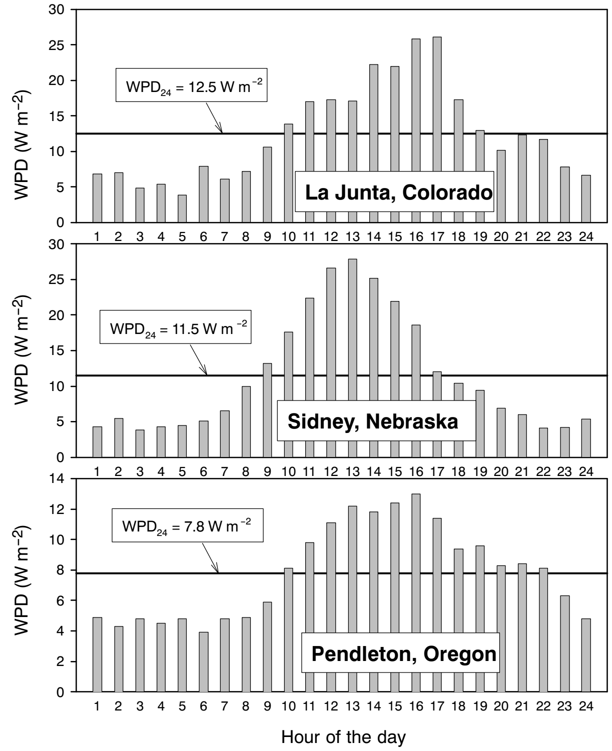

Figure 3. Erosive wind power density (WPD) for three locations, based on one wind speed measurement per day (0000 LT, 0100 LT, 0200 LT, etc.). WPD based on all 24 hourly measurements per day (WPD_{24}) is also shown.

CONCLUSIONS

Wind power density calculated from the full 24-hour data set and that calculated from a four-hour subset (measurements at 0200, 0800, 1400, and 2000 LT) agreed well with each other for the three locations. On an annual basis, the discrepancy was greatest for La Junta, with a difference of 0.8 W m^{-2} (6%). For the five most erosive months, the mean absolute WPD difference was less than 10% for all three locations. Prevailing wind erosion direction also showed good agreement between the two data sets.

WEPS simulations showed that wind-blown sediment crossed field boundaries approximately in the same direction using either wind data set. WEPS-simulated average annual soil loss also corresponded well between the two data sets. This shows that WEPS can use limited wind data to assess the effect of alternative management practices on wind erosion. Many other subsets of two, three, and four measurements per day performed as well or better than the 0200, 0800, 1400, 2000 LT subset. In spite of temporally limited wind data, it is possible to use WEPS to estimate wind erosion hazards and the effectiveness of various conservation practices.

The results of this study allow researchers to evaluate whether limited data, measured at certain times of the day, are suitable for use in WEPS. For example, based on the results of this study, we can be confident that we can apply WEPS using the limited data of Yulin, China, with measurements at 0200, 0800, 1400, and 2000 LT. We could be even more confident if a station in the proximity of Yulin, with 24 hourly measurements per day, were available for this type of analysis, since the best combination of hours varies from location to location and from region to region. For a new station, where only a few measurements per day are going to be made,

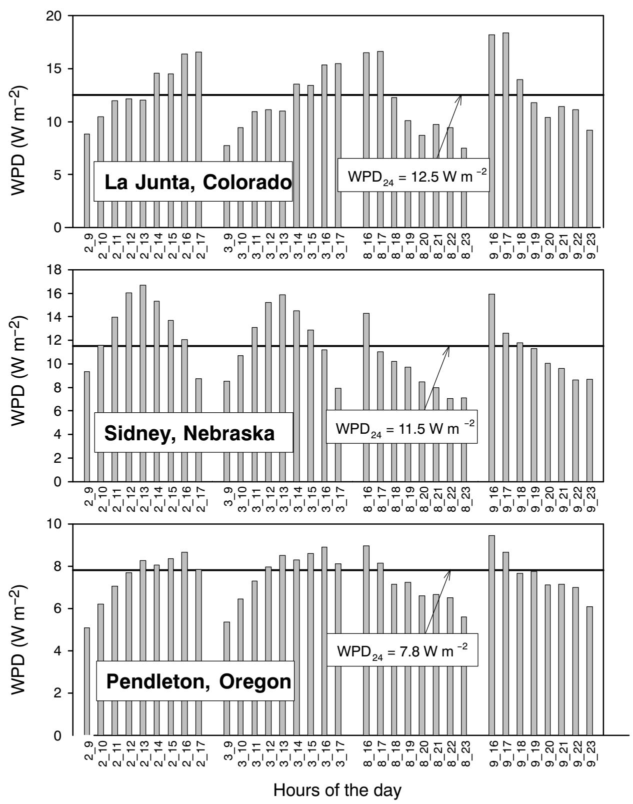

Figure 4. As figure 3, but based on <u>two</u> wind speed measurements per day (0200 and 0900 LT, 0200 and 1000 LT, etc.).

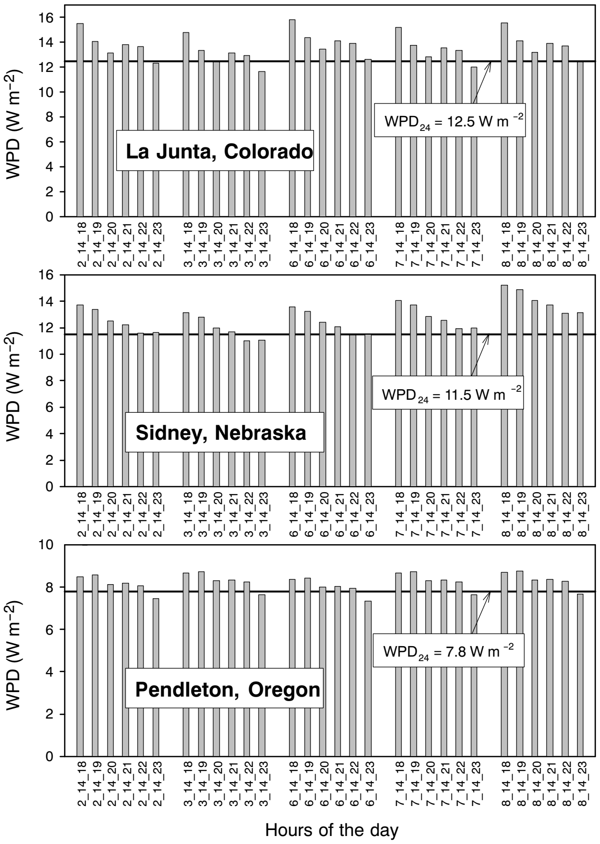

Figure 5. As figure 3, but based on __three__ wind speed measurements per day (0200, 1400, and 1800 LT; 0200, 1400, and 1900 LT; etc.).

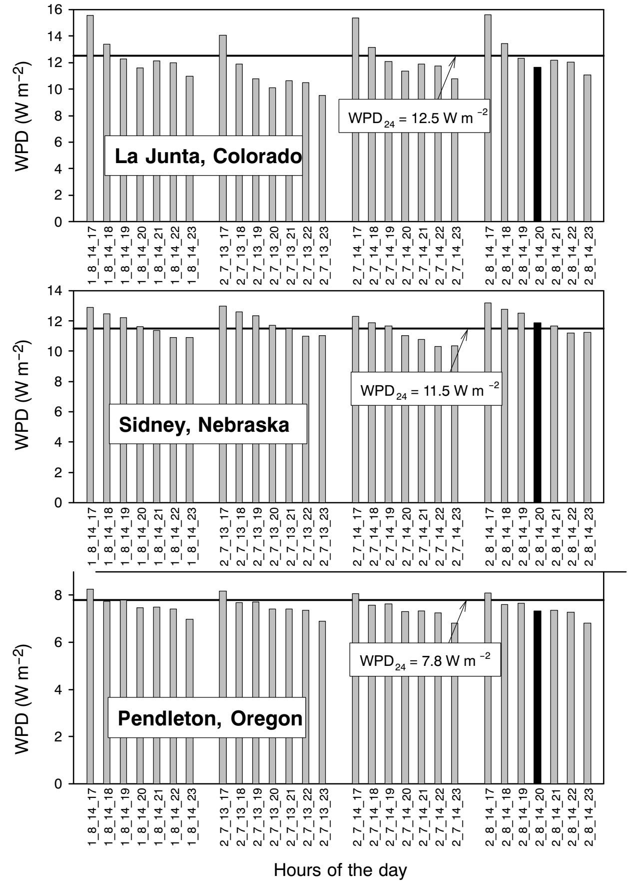

Figure 6. As figure 3, but based on __four__ wind speed measurements per day (0100, 0800, 1400, and 1700 LT; 0100, 0800, 1400, and 1800 LT; etc.). The highlighted combination (0200, 0800, 1400, and 2000 LT) was used for the first part of this study.

the results of this study may be used as a guide to choose the times of the day to take these measurements.

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