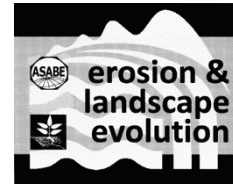


SPATIAL APPLICATION OF WEPS FOR ESTIMATING WIND EROSION IN THE PACIFIC NORTHWEST

J. Gao, L. E. Wagner, F. Fox, S. H. Chung, J. K. Vaughan, B. K. Lamb



ABSTRACT. *The Wind Erosion Prediction System (WEPS) is used to simulate soil erosion by wind on cropland and was originally designed to run simulations on a field scale. This study extended WEPS to run on multiple fields (grid cells) independently to cover a large region and conducted an initial investigation to assess how well WEPS performed in that environment by comparing simulations for two historical dust events with field observations and satellite images in the Columbia Plateau region of Washington. We modified the WEPS source code to allow it not only to run on multiple grid cells but also to save the state of the simulation so that it can be re-initiated from that state in future runs, allowing the model to be started and then stepped through time incrementally under various future climate or forecast weather scenarios. We initially ran WEPS on the entire state of Washington, with the entire Pacific Northwest region as our ultimate target area, to provide PM₁₀ and eventually PM_{2.5} emissions from wind erosion events as input to the chemical transport model CMAQ, which is used by the AIRPACT regional air quality modeling system for the Pacific Northwest. Three principal inputs to WEPS are meteorological data, soil data, and crop management practices. These data, at a 1 km × 1 km grid cell resolution, are the basic input data for running the spatially distributed model. The climatic data from a three-year period were stochastically generated based on statistical representations of past meteorological measurements from stations in the region and were used for initializing WEPS, and then a three-day set of meteorological data corresponding with historical dust storm events were selected for simulation by WEPS of wind erosion of cropland in the state of Washington. The crop management data were selected based on the land use and USDA Natural Resources Conservation Service (NRCS) crop management zones, and the soil data were derived from the NRCS SSURGO database. We aggregated the outputs from 1 km × 1 km grid cells into 12 km × 12 km grid cells for easier visualization and then mapped the total surface soil erosion, suspension, and PM₁₀ emissions for each 12 km × 12 km grid cell. This study shows that WEPS can be successfully extended to run from one field grid cell to multiple field grid cells, and the model can identify regions with high potential for soil erosion by wind. It also demonstrates that WEPS can be used for real-time monitoring of soil erosion and air quality in a large region if actual and forecast weather inputs are available.*

Keywords. *Air quality, GIS, model, WEPS, wind erosion.*

Soil erosion by wind is a serious problem worldwide, especially in arid and semi-arid regions. It not only removes the most fertile component of the surface soil but also becomes a particularly serious environmental problem that affects day-to-day air quality. For example, from 22 to 24 September 2009, a dust storm swept across the Australian states of New South Wales and

Queensland. The dust plume was more than 500 km in width and 1000 km in length (ABC News, 2009). During the storm's peak, the Australian continent was estimated to lose 75,000 tons of dust per hour off New South Wales (ADS, 2009). Another region often affected by dust storms is northern China. In March 2010, a large dust storm originating in China was reported to severely affect air quality in eastern Asia, including Korea, Japan, Taiwan, and extended all the way to the west coast of the U.S. (Bodeen, 2010). Therefore, simulating dust storm initiation and estimating soil loss from emission sources is necessary for conservation planning and natural resource protection, and predicting atmospheric transport of dust storms is essential for air quality monitoring and estimating potential adverse health and safety (reduced visibility) effects.

The prediction of wind erosion is a complex process. The USDA Agricultural Research Service (ARS) has taken the lead in developing wind erosion models in the U.S. The ARS started wind erosion research in the 1940s and introduced the first wind erosion model widely applied in the U.S., the Wind Erosion Equation (WEQ), in the 1960s (Woodruff and Siddoway, 1965). The WEQ model has been modified and improved by ARS scientists with more than

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20 years of field and laboratory studies (Hagen, 1991). As an empirical model, though, WEQ had many limitations with respect to prediction accuracy under untested conditions and can estimate only long-term average annual erosion rates. With advances in wind erosion science and computer technology, the USDA Natural Resources Conservation Service (NRCS) requested the ARS to develop a replacement for WEQ in the 1980s (Hagen, 1991). The Wind Erosion Prediction System (WEPS) was the result of those discussions and is now the WEQ replacement used for wind erosion assessments of cropland by the NRCS. WEPS development involved an ARS-led national, multidisciplinary team of scientists. Several U.S. federal agencies have assisted or contributed funding in the development of the model, including the ARS, NRCS, and U.S. Forest Service, along with the U.S. Environmental Protection Agency, U.S. Army Corps of Engineers, and Bureau of Land Management.

WEPS is a physical process-based daily simulation model that simulates weather, field surface conditions, and erosion (Wagner, 1996). An interface was also developed to allow users to select input variables and view output results easily. WEPS has a modular structure that consists of a user interface, a main controlling routine for the science model, six science submodels, and five databases (fig. 1). This structure facilitates model maintenance, upgrades, and new applications. The weather is the primary driver for natural surface physical processes. The hydrology submodel simulates soil energy dynamic changes, including soil temperature and water content within soil layers. User-initiated practices, including tillage, planting, harvesting, and irrigation, are simulated in the management submodel. The soil submodel simulates soil physical and chemical changes in soil layers and the surface due to weathering processes between management events. The growth of crops is simulated in the plant growth submodel, and plant

decomposition is accounted for in the decomposition submodel. If the surface threshold friction velocity is less than the actual friction velocity computed from the hourly wind speed and current surface aerodynamic roughness, then the erosion submodel will simulate erosion processes. The output of the WEPS model includes total erosion, suspension, and PM₁₀ (particulate matter with aerodynamic diameter less than 10 μm) emission into the atmosphere for a single field.

WEPS can be used to simulate temporal variability of field conditions and soil loss/deposition within a field over time. The advantage of the model is its dynamic simulation for short periods, even a single dust storm. As a stand-alone erosion tool, WEPS is currently limited to simulating a region (field) represented by a single soil type, with a crop management sequence applied to the entire field, driven by weather from a single location. To allow for simulations on a much larger scale, we extended WEPS to deal with multiple homogeneous fields. There are no erosion process interactions from one field or grid cell to an adjacent one at this time, but that limitation is not considered critical for our intended use of WEPS within a regional air quality dispersion model. However, modifications are currently being made to WEPS to eventually allow it to simulate more complex fields that consist of more than one soil type and/or crop management sequence.

The objectives of this research were to: (1) modify WEPS to allow users to save and restore the internal state of the model, enabling it to be run in an “initialize and then run in an incremental time step” mode rather than a typical “initialize and run for multiple years” mode; (2) enable WEPS to run on multiple grid cells for simulating a larger region with spatial soil, climate, and management variability; (3) develop a preliminary database of regionally spatial inputs (soil, climate, and management) to allow the spatial WEPS model to simulate soil erosion by wind, including PM₁₀ emissions, on a sub-daily time step, which could be used as an input to a regional air quality model; and (4) conduct an initial qualitative evaluation of the modified WEPS model in a regional environment.

In this research, we ran the modified WEPS model on the state of Washington. However, the ultimate target area is the entire Pacific Northwest region, to provide PM₁₀ and eventually PM_{2.5} emissions as input to the chemical transport model Community Multiscale Air Quality (CMAQ; Byun and Schere, 2006), which is used by the Air Indicator Report for Public Awareness and Community Tracking (AIRPACT), a regional air quality modeling system for the Pacific Northwest (<http://lar.wsu.edu/airpact>; Chen et al., 2008; Herron-Thorpe et al., 2012).

METHODS

DATA INPUT

The research was initially applied to the state of Washington with a final goal to incorporate WEPS into the AIRPACT-3 air quality modeling system for the Pacific Northwest (Chen et al., 2008). The AIRPACT-3 domain includes the states of Washington, Oregon, and Idaho, and

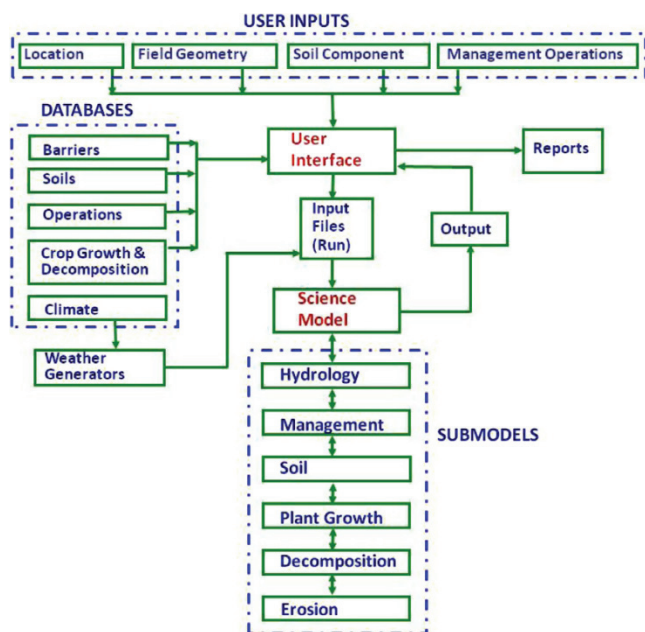


Figure 1. WEPS modular structure with user interface, user inputs and databases, and science model consisting of six submodels.

parts of neighboring states and Canada. In regional air quality applications, the domain is divided into grid cells. The standard grid cells for AIRPACT-3 are 12 km × 12 km in size. For simplicity, we will refer to this domain as a “12 km grid” and the individual 12 km × 12 km cells as “12 km cells.” Grids and cells of other sizes are denoted similarly. Three principal datasets are required to run WEPS: meteorology, crop management practices, and soil data. To incorporate WEPS into the AIRPACT-3 regional modeling framework, we subdivided each 12 km cell into 144 one-kilometer cells to better reflect the preferred WEPS spatial scale of a “typical field size” of 260 ha (2.6 km²) or less. Thus, the 1 km cell values were either summed or averaged and mapped into the appropriate 12 km cells.

Meteorological Data

The meteorological data used in WEPS include daily weather and hourly wind information. In the stand-alone version of WEPS, the daily weather data are usually generated with the CLIGEN generator via simulation using monthly statistical station parameters derived from measured meteorological data. The weather data include daily precipitation, maximum and minimum temperature, solar radiation, and dew point temperature (Hagen, 1991). Hourly wind data are usually generated with the WINDGEN generator through the historical statistical meteorological variables (van Donk et al., 2005). The wind data include hourly wind speed and daily wind direction.

A representative CLIGEN station and a WINDGEN station were assigned to each 12 km grid cell. We used Delaunay triangulation to generate a distance-weighted interpolated county record (Voronoi diagram) for each WINDGEN station (Guibas et al., 1992) and used the nearest station for CLIGEN, and then converted the CLIGEN and WINDGEN station polygons to a raster format at a 12 km grid size based on the area majority algorithm. We used the same CLIGEN and WINDGEN data for each 1 km cell within a 12 km cell. We used a total of 48 climate stations and 46 wind stations in the state of Washington to generate the CLIGEN and WINDGEN climate files, respectively, for initializing WEPS.

Since WEPS currently starts a simulation on 1 January with default initial soil, surface, and water content conditions, and no residue or actively growing crops, it is typically expected to be run in an initialization mode for a time before erosion estimates are computed. As many crop management practices have multi-year rotation cycles, a multiple of the crop rotation cycle being used is typically specified to better initialize the model. This initializing process allows WEPS to acquire a better estimate of the initial simulation values for all internal variables, such as soil layer water content, plant height, residue cover, etc., for the region under simulation.

This initialization process was first conducted with the modified spatial WEPS. We generated sufficient daily weather and hourly wind data for each CLIGEN and WINDGEN station, respectively, within the state of Washington, and used data from a three-year period to initialize WEPS for the storm simulations. The internal

WEPS data from the initialization run were then saved prior to the dust storm dates to be evaluated (22 Sept. and 3 Oct.). The WEPS simulation was then restarted by restoring the saved internal data and run with modified WRF meteorology fields for the two dust storm dates (23 Sept. 1999 and 4 Oct. 2009).

Two historical dust storms were used to evaluate the WEPS simulations. One was a dust storm with a southwesterly wind direction on 23-25 September 1999. The duration of hourly wind speeds greater than 8 m s⁻¹, which is the default minimum wind speed threshold for erosion to be computed within WEPS, lasted more than 10 h on 23 September 1999. The other was a strong dust storm with a northeasterly wind direction on 4-5 October 2009, with wind speeds greater than 8 m s⁻¹ lasting 8 h. The meteorological fields for the two events were acquired from simulation by Weather Research and Forecasting (WRF; Skamarock et al., 2008; www.wrf-model.org), an operational weather forecasting model widely applied for scientific research. The hourly wind speeds from the WRF model are spatial instance events at multiple heights above ground (WEPS uses the 10 m height values) and are used as the meteorological input for the AIRPACT-3 air quality modeling framework (Chung et al., 2013). In this study, the WRF hourly surface meteorological fields (10 m height wind speeds and 2 m height temperatures) at 12 km spatial resolution for the Pacific Northwest (www.atmos.washington.edu/mm5rt) were provided as input to the spatial WEPS model to simulate the storm events.

Crop Management Practices

The crop management files were downloaded from the NRCS nationwide list of crop management zone (CMZ) files. The CMZ files were developed by the NRCS based on typical crops and management practices employed on the farms within each zone. The state of Washington contains ten NRCS CMZs. For these preliminary simulations, only one file was selected from the crop management files available in each zone for each grid cell, which included single-year and multi-year rotation sequences. Even though the CMZ files are divided into different categories based on the tillage activity, such as conventional till and no-till, we selected a single representative rotation for a given crop from the conventionally tilled practices for these simulations. Selecting a representative management file for each grid cell was a challenge because of the variety of crops grown and the range of management practices applied within the simulation region.

For land use data, we used the USDA National Agricultural Statistics Service (NASS) Cropland Data Layer (CDL) (www.nass.usda.gov/research/Cropland/SARS1a.htm). The CDL is raster, geo-referenced, land cover data with a ground resolution of 56 m and is generated using multiple satellite imageries, including the Indian RESOURCESAT-1 AWUFS, Landsat 5 TM, and MODIS, collected during the 2008 and 2009 growing seasons. Individual crops were identified with seasonal images with an overall accuracy exceeding 90% for dominant crops such as corn, soybeans, wheat, and rice (www.

Table 1. Partial list of crop management files selected by integrating crop management zone (CMZ) and land use type.

Index	CMZ Code ^[a]	CMZ	Land Use Type	Land Use ID	CMZ File Name
1	821	8	Barley	21	Barley, spring, conv, cm8.man
2	823	8	Spring wheat	23	Wheat, spring, MT, cm8.man
3	824	8	Winter wheat	24	Wheat, winter, conv, cm8.man
4	828	8	Oats	28	Oats, spring, conv, cm8.man
5	4621	46	Barley	21	Barley, spring, conv, fplow, Z46.man
6	4631	46	Canola	31	Oats, spring, conv, fplow, Z46.man
7	4661	46	Fallow	61	Wheat, winter, mtfallow, CMZ46.man
...
117	7101	71	Corn	01	Corn, silage, clean till, fall mbplow, Z71.man

^[a] The CMZ code is a combination code of the CMZ and land use type. The first one or two digits represent the crop management zone (CMZ), and the last two digits represent the crop type determined by the land use data set.

nass.usda.gov/research/Cropland/docs/JohnsonPE&RS_Nov_2010.pdf). The land use data reflected the crop type in the 2009 growing season but could not completely provide the land use in fall 2009, which could lead to the selection of incorrect crop management files.

Crop management files were selected based on a combination of land use and CMZ by overlapping the two spatial datasets. An index was created by combining the crop identifier (ID) of land use and the zone number of CMZ. The index was linked with a table to select the appropriate crop management files (table 1). A total of 117 indices were generated for the state of Washington with a combination of land use and CMZ. We selected a single crop management file as required for WEPS for each 1 km cell for these simulations. A typical crop may have multiple management files in each zone due to the variety of tillage practices applied in the region. For this study, though, we selected conventional tillage management, typically the most erosive practice, since we did not have the time or resources to determine the most representative practices in use over the entire domain for these preliminary simulations. It is expected that this choice would likely overpredict the erosion and PM₁₀ emissions for these simulation runs. If the land use type was fallow or idle during the period of simulation, then we selected a crop management file that contained a fallow cycle from the multi-year rotation folders.

Soil Data

The soil data were obtained from the NRCS SSURGO soil database and downloaded via SOAP protocols from the NRCS Soil Data Mart website (NRCS, 2010). We downloaded the soil data for counties that included spatial files and tabular data. All spatial files in the state of Washington were merged and converted from polygon feature to 1 km raster format. One soil map unit was assigned to each 1 km cell according to the majority algorithm of multiple map units in each polygon for these simulations. The map unit with the highest area percentage was assigned to each grid cell.

A map unit may contain one or more components and normally has up to three components. Only the component with the highest percentage was selected to represent the map unit. If two or more components had the same percentage, we took the first one alphabetically for that map unit. We used the map unit as an index to generate the spatial soil coverage.

WEPS uses up to 29 soil attributes for wind erosion

simulation. All of the required attributes were acquired or derived from the tabular SSURGO data. We generated two final tables from the database. One was the component table, which included nine attributes derived from the component and map unit tables of the SSURGO database. The other was the layer attribute table, which included 20 attributes generated from the horizon, component, and map unit tables. The spatial coverage and the component table were linked by map unit ID (fig. 2); the component table and layer table were connected by the common key, horizon ID. When WEPS called for the soil data, the map unit identifier was found from the soil spatial coverage, which then acquired the soil attributes from the component and layer tables based on their common keys.

MODIFICATION OF WEPS SOURCE CODE

Having a modular structure, WEPS was relatively easy to modify for spatially distributed regional simulations. We added new variables and modified the existing variables of the model to handle spatial analysis for multiple grid cells. The main program (the routine driver) was rewritten for the requirement of multi-cell simulation. We did not modify the WEPS user interface, as it was not required for use in this simulation study.

We added a “save state” routine to store the state of the system (all internal variable values) and a “restore state” routine to facilitate initializing the model and then repeatedly running it from a predetermined (previously run) initial condition. After reading the input data, including CLIGEN, WINDGEN, soil, and crop management data, we ran the WEPS science model to initialize the system to the state prior to the desired evaluation date. The “save state” routine then saved all the values for the many temporal internal variables within the model into a text file. The model could then be run for any period of time starting at the saved state by reading in the initialized variables from a previous “save state” file. If users want to advance in time from the saved state, they can start from a previous saved state, run with the additional weather or climate data, and then save the state again. By using a combination of historical climate data and forecast meteorological data, this procedure can be used to forecast soil erosion by wind on a continuous basis.

CONFIGURING THE SIMULATIONS FOR WEPS

The current WEPS model uses a single, uniform simulation region, and that region is limited to a rectangular area. The uniform region is assumed to have only one soil type (uniform soil properties) and a single crop

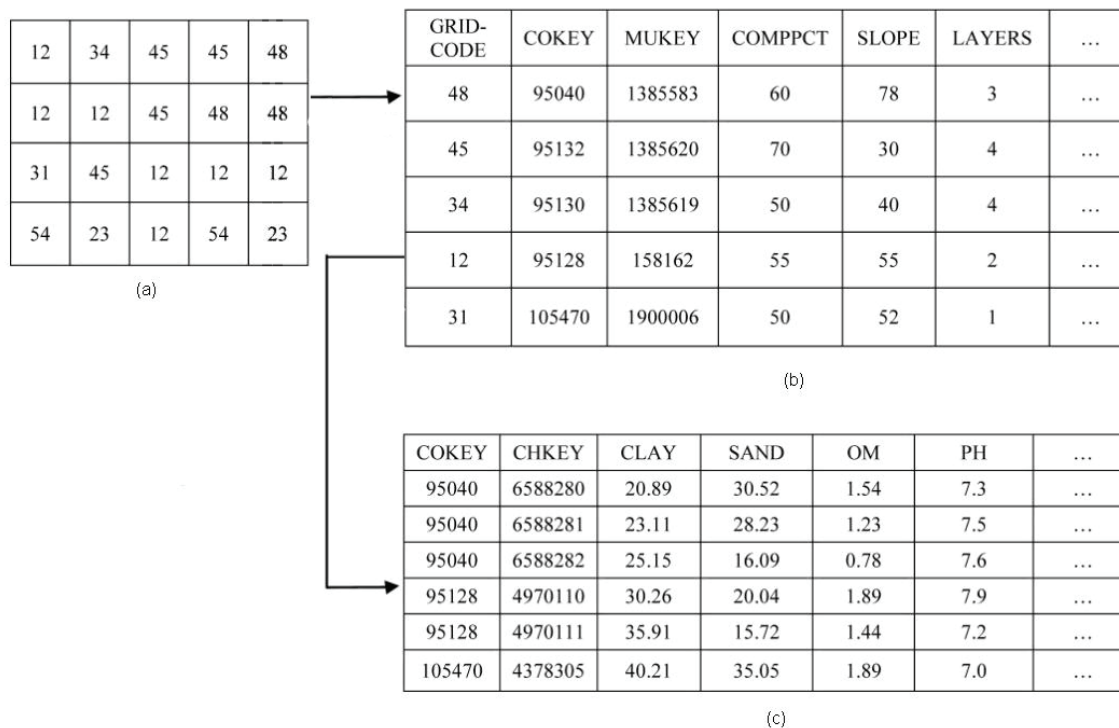


Figure 2. Linkage among soil spatial attributes, component table, and layer attribute tables: (a) the soil map unit identifier numbers (IDs) assigned to each 1 km grid cell; (b) the soil component table, which includes the soil component attributes and a map unit key (GRID-CODE) from the soil map unit; and (c) the soil layer with soil texture composition and other attributes, including a component key (COKEY) from the soil component table. The three tables are connected through their common keys.

management practice applied over the entire region. In a large region, variations in soil, management practices, and even weather exist. To address this problem, we used a hierarchical structure to divide the large simulation region into smaller regions (12 km × 12 km cells), and then each of these regions was further divided into smaller subregions (1 km × 1 km cells) to achieve a spatial area small enough to meet the WEPS requirement for a “typical field size” of less than 260 ha (fig. 3). The smallest regions, 1 km cells, were assumed to have a uniform surface condition of applicable size to run WEPS.

We divided the entire state of Washington into 34 rows and 50 columns with a 12 km cell size that matched the standard grid cell size used by the AIRPACT-3 air quality modeling system of the Pacific Northwest (Chen et al., 2008). As indicated earlier, each 12 km cell was further divided into 144 one-kilometer cells (fig. 3b). Each 1 km cell is the cell size assigned a single soil and crop management value for running WEPS (fig. 3c).

The WEPS model was run for the domain in two loops. We ran the outer loop over the 12 km grid (34 rows by 50 columns) to cover the state of Washington. Within each 12 km cell, we ran an inner loop for each 1 km cell. The total erosion, suspension, and PM₁₀ emission for each 12 km cell were generated after running the WEPS model for all constituent 1 km cells. To eliminate unnecessary WEPS runs, we created a temporary array and a flag to mark completed cell runs. If an upcoming 1 km cell had the same soil, land use, and crop management within the same 12 km cell as a flagged 1 km cell (guaranteeing that the same climate would also be used), then we retrieved the

output from the temporary array without running that WEPS simulation again. For reporting purposes, the total erosion, suspension, and PM₁₀ emission for each 12 km cell were obtained by summing and averaging the values for the 144 constituent 1 km cells. The total erosion, suspension, and PM₁₀ emission values for the 12 km grid cells were saved as a text file, which was then converted to raster grid format for further visualization.

TWO WEPS SIMULATION CASES

Two dust storms that occurred in eastern Washington were used to initially evaluate WEPS simulations of soil erosion by wind over the regional domain. One storm occurred on 23 September 1999, and the other occurred on 4 October 2009. In each case, WEPS was first initialized with three years of simulated meteorological data using WINDGEN and CLIGEN and stopped a day before the dust storm event occurred, saving the state of the system. The meteorological simulations from WRF for the storm event days were then used as input to WEPS for simulation after reloading the previous “save state” file. Daily and hourly outputs of total erosion (saltation/creep and suspension), suspension, and PM₁₀ emissions were generated and recorded for each 1 km cell and then aggregated to, and reported for, the 12 km cells. Because PM₁₀ is a fractional part of the suspended soil for the WEPS output, PM₁₀ and total suspension both have the same distribution and are generally similar to the total erosion distribution. We discuss only the spatial distribution of PM₁₀ in the state of Washington for these simulations because that is the particle size of interest for air quality, as it can be carried great

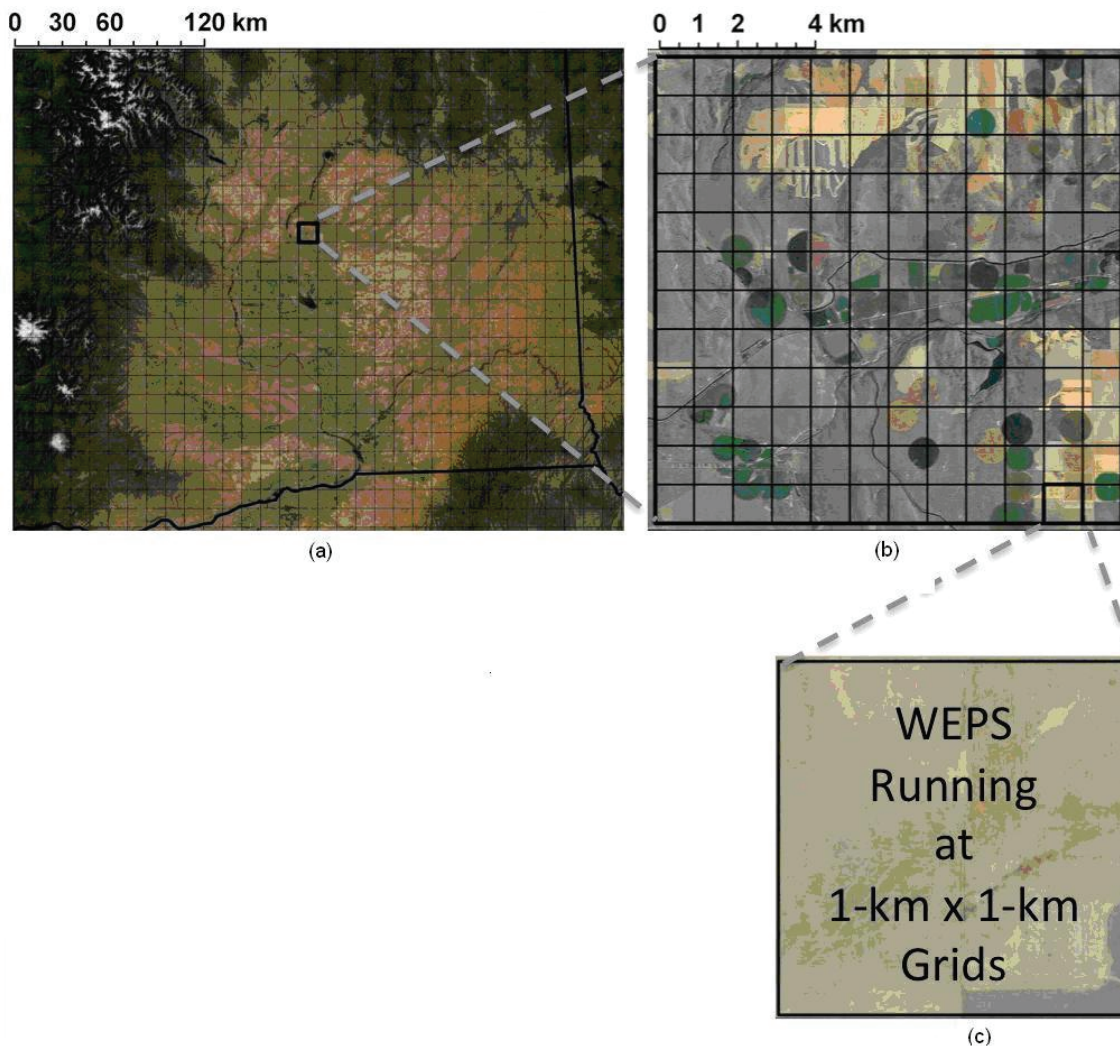


Figure 3. Hierarchical structure used to run WEPS in a large region: (a) large region with 12 km cells, (b) 12 km subregion with 1 km cells, and (c) 1 km cell size used to run WEPS.

distances from the source; PM_{10} emissions will eventually be used as input to the AIRPACT-3 modeling system.

RESULTS AND DISCUSSION

DUST STORM ON 23 SEPTEMBER 1999

Figure 4 shows the spatial distribution of total daily PM_{10} emissions for the WEPS simulation using WRF meteorology for the dust storm on 23 September 1999. An obvious erosion region was located in eastern Washington, with higher erosion rates in the southern part than in the northern part. The highest erosion occurred in Benton County, with a daily PM_{10} emission rate ranging from 90 to 136 $kg\ ha^{-1}$. Sustained erosive winds were an important factor for the significant soil loss estimates. The highest modeled wind speed was greater than 10 $m\ s^{-1}$, with wind speeds greater than 8 $m\ s^{-1}$ lasting more than 7 h in southern Benton County (8 $m\ s^{-1}$ is the minimum threshold wind speed to initiate WEPS erosion computations). The lesser erosion in the northern region was due to lower wind speeds in that region. The highest wind speed in northern Douglas and Lincoln counties was about 9 $m\ s^{-1}$, and winds

greater than 8 $m\ s^{-1}$ lasted only 1 to 2 h. Except for several grid cells in Grant County with a PM_{10} emission rate greater than 90 $kg\ ha^{-1}$, the general PM_{10} emission rates in the northern region were less than 50 $kg\ ha^{-1}$.

Land use, along with the associated crop management practices, are one explanation for the high soil erosion estimates. All grid cells showing erosion are located in crop management zones 49 and 50 (fig. 4). From the overlap of land use coverage and the CMZ map, we found that winter wheat was the dominant crop, and significant fallow or idle land was present. Therefore, conventional winter wheat/summer fallow rotation management files were selected for the WEPS simulation. This contributed significantly to the six 12 km grid cells with the highest erosion rates in the southern region. The land use for these six cells was dominated by fallow and winter wheat. The newly tilled cropland is probably a key factor contributing to soil erosion in this region. In contrast, soil erosion was less in the northern region, where the land use consisted of a higher percentage of alfalfa and grassland, two types of land use usually well protected from wind erosion, even though the wind speeds were almost identical in the

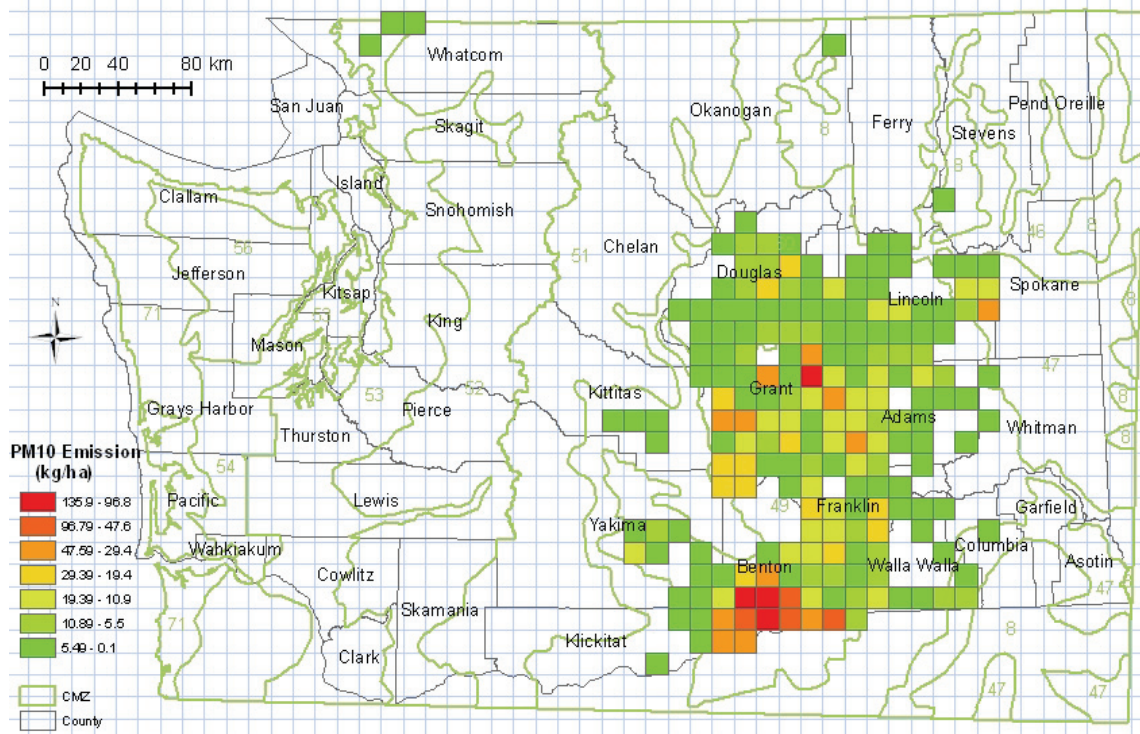


Figure 4. PM₁₀ emissions (kg ha⁻¹) from WEPS simulation with WRF-modeled wind speeds for the dust storm on 23 September 1999.

Table 2. Observed and WRF-simulated wind statistics for four wind stations during the two dust storms, along with the simulated PM₁₀ emissions from an average of five 12 km grid cells that used the measured wind station data.^[a]

Wind Station Location	Wind Speed Statistics ^[b]	23 September 1999			4 October 2009		
		Measured	WRF	Measured:WRF Ratio	Measured	WRF	Measured:WRF Ratio
TRI-Cities	Minimum (m s ⁻¹)	4.0	1.3	3.1	1.5	1.1	1.3
	Maximum (m s ⁻¹)	16.1	9.8	1.7	10.8	10.0	1.1
	Average (m s ⁻¹)	9.3	5.5	1.7	5.3	6.3	0.8
	Hours >8 m s ⁻¹	17	7	2.5	8	6	1.3
	PM ₁₀ (kg ha ⁻¹)	308.3	42.9	7.2	44.1	40.6	1.1
Moises	Minimum (m s ⁻¹)	3.1	3.0	1.0	6.7	4.8	1.4
	Maximum (m s ⁻¹)	13.9	9.1	1.5	13.4	9.8	1.4
	Average (m s ⁻¹)	8.4	6.2	1.4	10.0	7.1	1.7
	Hours >8 m s ⁻¹	15	7	2.1	20	5	4.0
	PM ₁₀ (kg ha ⁻¹)	49.9	21.4	2.3	161.0	35.6	4.5
Fairchild	Minimum (m s ⁻¹)	2.7	3.1	0.9	8.1	6.3	1.3
	Maximum (m s ⁻¹)	11.6	9.4	1.2	12.9	9.5	1.4
	Average (m s ⁻¹)	7.9	6.4	1.2	10.9	8.3	1.3
	Hours >8 m s ⁻¹	11	7	1.6	24	15	1.6
	PM ₁₀ (kg ha ⁻¹)	14.8	9.2	1.8	92.6	4.6	20.1
Hanford	Minimum (m s ⁻¹)	1.3	1.1	1.2	4.1	0.8	5.4
	Maximum (m s ⁻¹)	11.6	6.5	1.8	13.4	9.4	1.4
	Average (m s ⁻¹)	4.2	3.4	1.2	8.2	4.7	2.4
	Hours >8 m s ⁻¹	4	0	-	10	5	2.0
	PM ₁₀ (kg ha ⁻¹)	6.7	2.6	2.6	29.2	4.0	7.2

[a] Measured wind speeds are from recorded station data, and WRF is simulated spatial 10 m wind data for the locations and dates indicated.

[b] Minimum, maximum, and average of daily hourly wind speeds (m s⁻¹). Hours >8 m s⁻¹ is the number of hours that wind speed exceeded the WEPS minimum threshold. PM₁₀ (kg ha⁻¹) is the simulated emissions from WEPS for all 12 km cells within a 25 km radius of the wind station.

northern and southern regions (table 2).

DUST STORM ON 4 OCTOBER 2009

The erosive winds of the dust storm on 4 October 2009 extended over most of eastern Washington. Comparing the emissions on a grid cell basis, the extent and magnitude of emissions on 4 October 2009 were generally lower than for the storm simulation on 23 September 1999. The maximum PM₁₀ emissions on 4 October 2009 were only 55 kg ha⁻¹

and were located near the border between Lincoln and Spokane counties (fig. 5), compared to a maximum for 23 September 1999 of 136 kg ha⁻¹ in Benton County (fig. 4). The WRF-simulated wind speeds during this storm were slightly higher than during the storm of 23 September 1999 (table 2). However, the magnitude of PM₁₀ emissions on 4 October 2009 was less than during the dust storm on 23 September 1999. This implies that the surfaces were probably less erodible, reflecting higher threshold friction

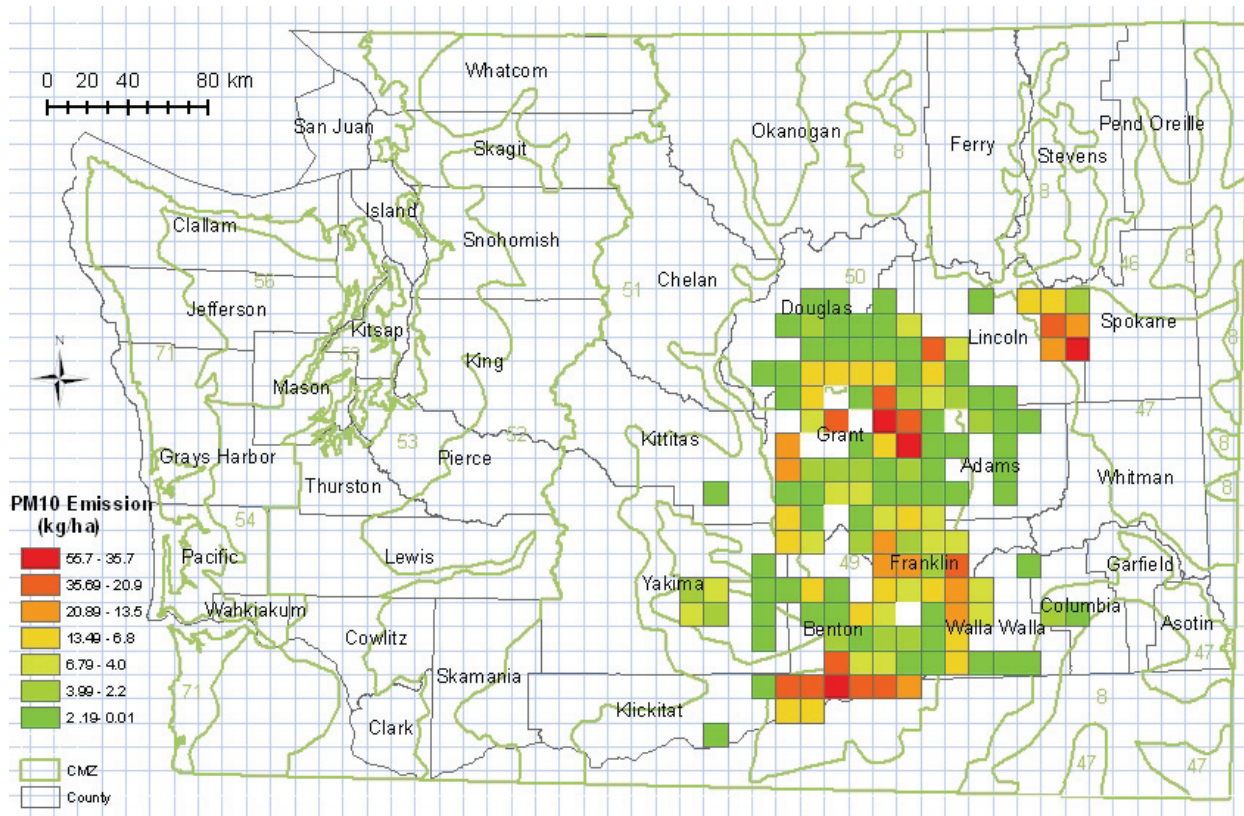


Figure 5. PM₁₀ emissions (kg ha⁻¹) from WEPS simulation with WRF-modeled wind speeds for the dust storm on 4 October 2009.

velocities for the 4 October 2009 simulation. For example, the maximum hourly wind speed in Lincoln County was greater than 10 m s⁻¹, and winds exceeding 8 m s⁻¹ lasted as long as 15 h in this area. Wind speeds greater than 8 m s⁻¹ and their longer duration were the direct reasons for the erosion emissions simulated in northeastern Lincoln County. For similar wind speeds and durations, the PM₁₀ emissions from the storm on 23 September 1999 were twice that of the simulated dust storm on 4 October 2009. This is likely due to better vegetative cover simulated for 4 October 2009, probably from improved surface protection due to the additional ten days growth of the winter wheat.

For the storm on 4 October 2009, three more regions with high emissions could easily be identified (southern Benton County, central Grant County, and Franklin County), where winter wheat, spring wheat, and fallow/idle were the most common land uses. The grid cells in southern Benton County with high PM₁₀ emissions in 1999 had slightly lower emissions during the storm on 4 October 2009. The hourly wind speeds ranged from 4.5 to 7.7 m s⁻¹, but speeds greater than 8 m s⁻¹ lasted from 2 to 6 h, with a maximum hourly wind speed greater than 11 m s⁻¹. A conventional winter wheat/fallow practice was assumed to be the primary practice in this region. Winter wheat was the dominant land use in this region, and the green vegetation could be detected in the western part of Grant County from a MODIS satellite image (fig. 6). The surface covered with winter wheat played a protective role against excessive soil erosion and presumably PM₁₀ emissions. However, several grid cells in western Adams County and several grid cells in eastern Grant County also generated higher PM₁₀

emissions in the region; the daily PM₁₀ emissions ranged from 90 to 136 kg ha⁻¹ during the event. For cells with higher wind speeds, crop management was the decisive factor in whether or not the cell was susceptible to wind-generated PM₁₀ emissions.

The modeled emission source pattern can be visually verified from the MODIS dust plume image on 4 October 2009 (fig. 6). The MODIS image from the Terra satellite (overpass time shortly after 11:00 a.m. PST) caught the dust storm on 4 October 2009 in eastern Washington, and the image indicates that the dust plume originated from wind erosion in central Lincoln County, western Adams County, and eastern Grant County. The dust plume traveled from northeast to southwest, consistent with the modeled wind direction from WRF. While the model results also indicate wind erosion emissions in Benton County, this cannot be definitively verified by the satellite image because the dust plume in the air over Benton County obscured the surface in Benton County. According to the model, some cells in northern Grant County and Douglas County experienced erosion, with PM₁₀ emissions ranging from 2 to 14 kg ha⁻¹, but the MODIS image did not show any dust in this region. One possible reason is that the MODIS sensors may not detect the dust plume when PM₁₀ concentrations are less than 300 µg m⁻³ (Chung et al., 2013). The discrepancy could also result from incorrect identification of crop management or land use for those grid cells. For western Grant County, the model assumed that the land use was fallow, based on the crop data layer, which was based on Landsat images taken during the growing season of 2008 and 2009. We selected a winter wheat-fallow

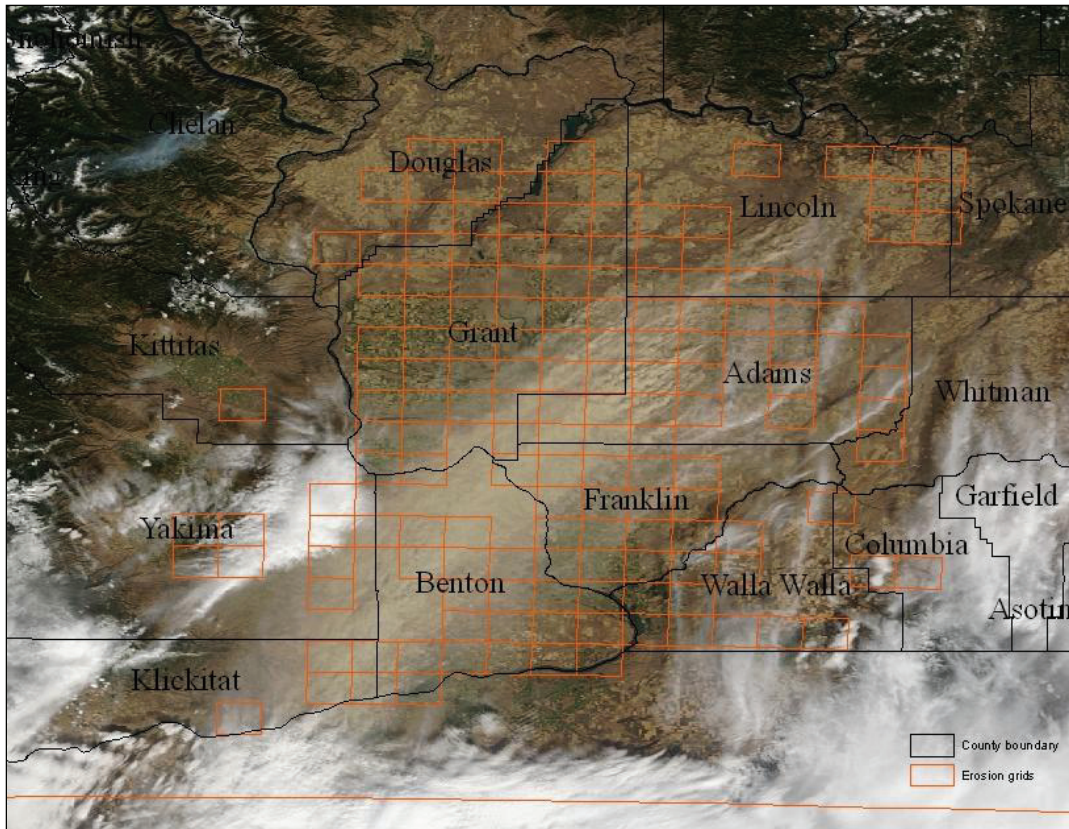


Figure 6. Grid cells emitting PM_{10} in the WEPS simulation and a MODIS image of 4 October 2009.

rotation as the crop management in the fallow land, but winter wheat was apparently planted, as suggested by the green color seen in the MODIS imagery. If this was indeed the case, then we should adjust the crop cycle sequence so that we use a fallow-winter wheat rotation based on the current land use, in effect reversing the rotation. The discrepancy between the modeled results and MODIS imagery for Douglas County could also be attributed to the model overestimating wind speeds, or alternatively, to erosion having taken place at a time missed by the satellite overpass. The Aqua satellite passes over the Pacific Northwest at $\sim 1:00$ p.m. local time, while the Terra satellite passes over the Pacific Northwest at $\sim 11:00$ a.m. local time.

COMPARISON OF WRF-SIMULATED WIND DATA WITH MEASURED WIND SPEEDS

Wind speed is a critical factor affecting soil emissions by wind. The WRF-simulated wind speeds were significantly different from the historical measured values. Soil erosion occurs if the friction velocity exceeds the surface threshold value, and the emission rates are proportional to the cube of the increasing wind speed. Doubling the wind speed can cause an eight-fold increase in erosion potential (Skidmore, 1965). To compare the WRF simulations with observation data from weather stations, we downloaded the measured hourly wind speeds for several locations from the National Climate Data Center (www.ncdc.noaa.gov/oa/ncdc.html). The station locations are identified in figures 8 and 9. Some station wind statistics are reported in figure 7 and table 2, where wind

data are compared at four station locations in Spokane, Franklin, Grant, and Benton counties. The WRF-simulated wind speeds were generally lower, and in some cases significantly lower, than the measured wind speeds (fig. 7). The WRF winds were close to the measured winds at only one weather station close to the Pasco/Tri-Cities area in Franklin County (fig. 7a). The WRF wind speeds at the other stations were much lower than the measured winds, and the number of hours simulated with winds above the WEPS minimum threshold of 8 m s^{-1} was less than the observation. Therefore, the WEPS simulation was significantly affected by the underestimation of wind speeds by WRF. Clearly, the WRF wind simulation will need to be adjusted through some type of calibration procedure to correct for this underestimation in order for WEPS to accurately simulate wind-induced PM_{10} emissions.

WEPS SIMULATION OF DUST STORMS WITH MEASURED WIND SPEEDS

Due to the large differences between WRF-simulated and measured wind speeds, we performed additional simulations using the measured wind speeds to compare the results between the two wind data sources. There are 32 wind stations available in the state of Washington, but only 14 are located in the eastern part of the state. Due to the sparse distribution of measured wind data locations, we could only substitute measured wind data for a limited area within the simulation region. The WRF data were replaced with measured wind data within a radius of 25 km around each station, i.e., a 5×5 grid of 12 km cells centered on the

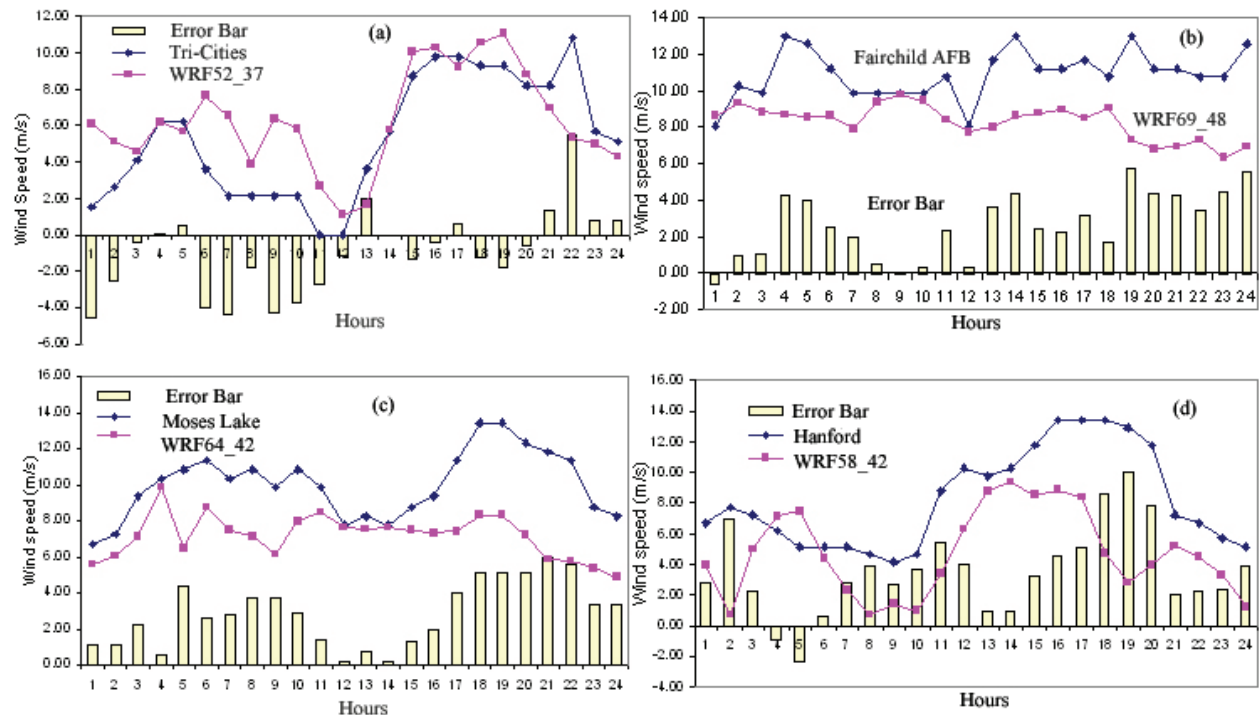


Figure 7. Comparison of surface wind speeds between WRF results (magenta) and observations (blue) at the closest meteorological stations at (a) Tri-Cities (46° 16' N, 119° 7' W), (b) Fairchild AFB (47° 37' N, 117° 24' W), (c) Moses Lake (47° 12' N, 119° 11' W), and (d) Hanford (46° 12' N, 119° 35' W) on 4 October 2009. Error bars indicate differences between observation and WRF-simulated wind speeds for each station.

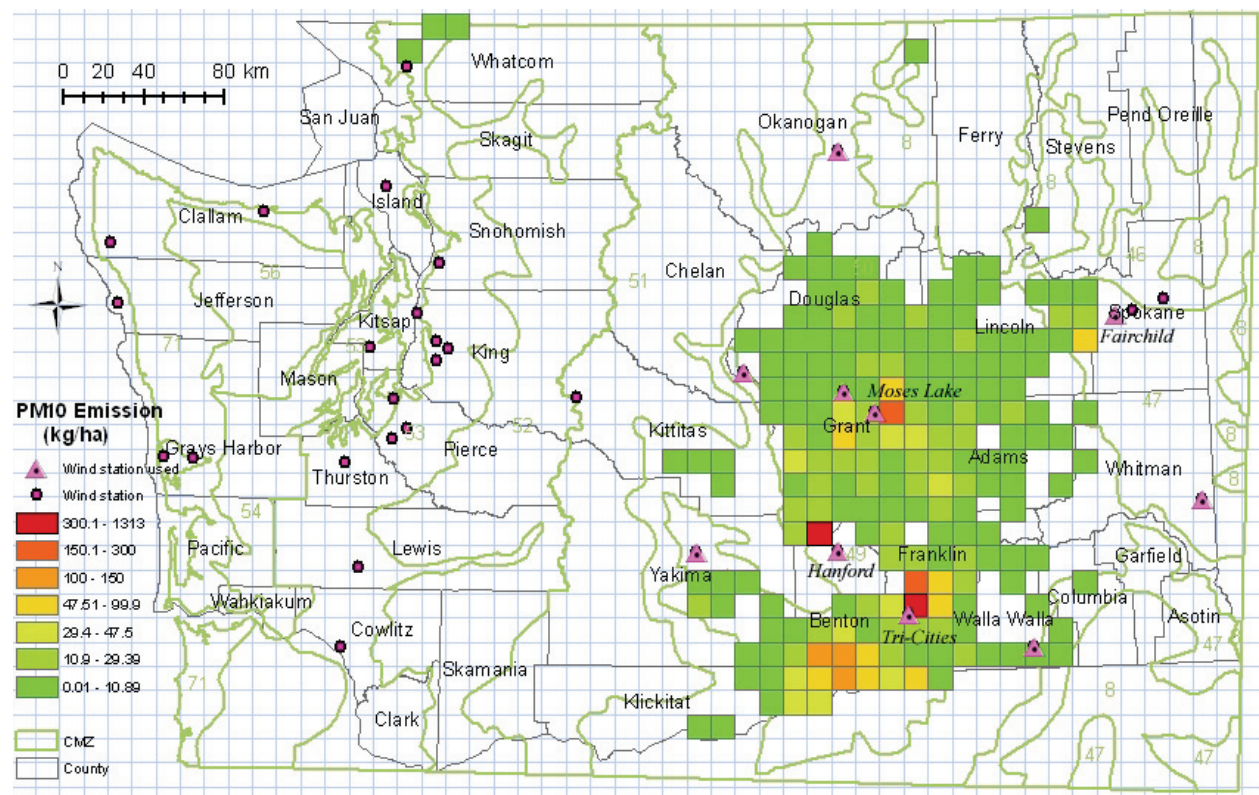


Figure 8. PM₁₀ emissions (kg ha⁻¹) from WEPS simulation of the dust storm on 23 September 1999, along with wind stations, indicating which stations were used for the simulation.

station location had their WRF wind data substituted. The grid cells outside these regions kept their WRF wind data. Figures 8 and 9 shows the surface emissions from the

WEPS simulation of the 23 September 1999 and 4 October 2009 dust storms along with the wind stations, indicating which stations were used for the simulation. The surface

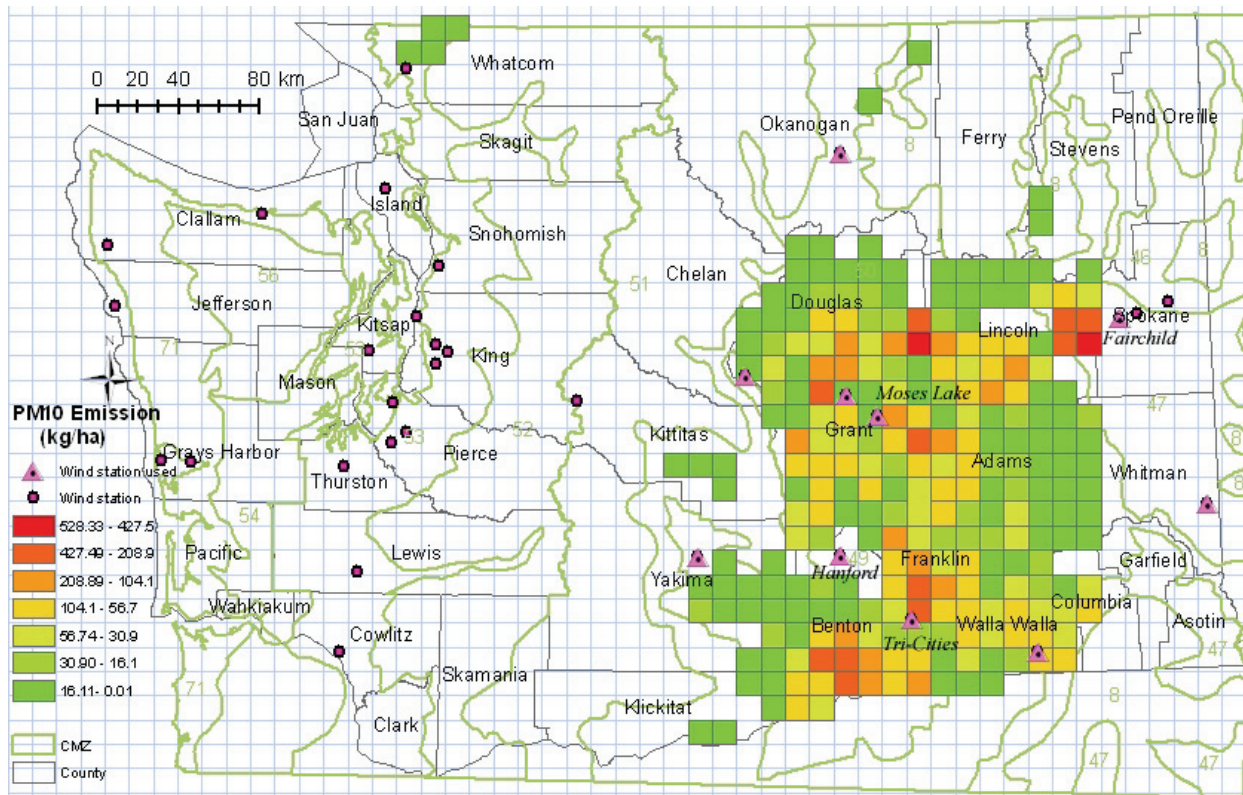


Figure 9. PM₁₀ emissions (kg ha⁻¹) from WEPS simulation of the dust storm on 4 October 2009, along with wind stations, indicating which stations were used for the simulation.

emissions of PM₁₀ from the two dust storms for the 12 km cells based on the measured winds were much greater, typically 2 to 10 times greater, than emissions based on the WRF wind data (table 2). In particular, the maximum PM₁₀ emissions were 20 times greater than the original WRF simulation around the Fairchild station for the 4 October 2009 storm.

CONCLUSIONS

The WEPS model was modified for regional-scale applications. A hierarchical structure was implemented to recursively divide a large region into many grid cells. The modified WEPS model was configured to run on a basic unit of a 1 km cell size, which was assumed to have a uniform surface represented by a single soil component, crop management practice, and meteorological conditions. The 1 km cell results were then combined to report emissions at the AIRPACT-3 regional dispersion model's 12 km cell grid size. WEPS was also modified so that its internal state could be saved and later reloaded in subsequent runs to eliminate repeated long initialization sequences for short-duration simulations. The necessary WEPS inputs for crop management practices were then determined for the entire state of Washington, for each 1 km cell, using satellite-generated maps to identify the matching land use within the NRCS Crop Management Zone database. In addition, the spatial soil data needed for WEPS were obtained from the NRCS national SSURGO database. The modified WEPS model was then applied to

the entire state of Washington with the corresponding spatial input variables. We first initialized the modified WEPS model on this regional domain using available CLIGEN and WINDGEN generated climate data. We then ran simulations of two historical wind erosion events (23 Sept. 1999 and 4 Oct. 2009) using WRF meteorological data. The results indicated that the WEPS modeling system can be extended for spatial analysis of windblown PM₁₀ emission on a regional scale with multiple soil components, varying meteorological conditions, and diverse crop management practices. However, analysis of simulations with measured wind data substituted for WRF data near the weather station locations showed that the WRF 10 m hourly winds are not adequate for WEPS simulations. The WRF wind speeds were consistently lower than the historical wind speeds measured during the wind erosion events on 23 September 1999 and 4 October 2009. A local adjustment is likely required for the WRF-simulated winds so that WEPS can more accurately predict PM₁₀ emissions on a regional scale.

Based upon our simulations of PM₁₀ emission for the two dust storms (23 Sept. 1999 and 4 Oct. 2009), we conclude that, if the wind speeds used are reasonably accurate, then the WEPS model can effectively identify dust emissions regions and can estimate PM₁₀ emissions. WEPS-generated PM₁₀ emissions could be then be used as an input to the AIRPACT-3 regional air quality dispersion modeling system to evaluate the impact of dust storms on air quality in the Pacific Northwest (Chung et al., 2013).

Soil surface erosion is strongly affected by a

combination of soil characteristics, cropping practice management, and weather conditions. A complete validation of the modified WEPS simulation at the field scale (1 km grid cell) would be a difficult task. The goal of this exercise was to modify WEPS for use on a regional scale and to address the issues of obtaining the initial spatial inputs required for WEPS, e.g., determination of soil and crop management practices at a 1 km cell scale for the state of Washington. The spatial pattern of the WEPS-simulated PM₁₀ emissions was evaluated visually with a single satellite image of the concentration plume. This superficial comparison indicated that the spatial pattern of the WEPS simulations qualitatively matched the distribution of wind erosion in the region. The modeling results can be improved with more accurate inputs for the WEPS model, including meteorological conditions, crop management practices, and land use and land cover data. An initial analysis was conducted to evaluate the impact of the WRF wind data used, which uncovered a general underestimation of WRF hourly wind speeds during the two historical wind erosion events simulated. No quantitative validation of the regional WEPS simulations has yet been attempted. However, WEPS has been validated with wind tunnel experiments for soils selected in U.S. locations (Hagen, 2004).

Since individual field data are not available for the region evaluated, the most feasible approach to evaluating WEPS PM₁₀ emissions is to complete the integration into the AIRPACT-3 regional air quality dispersion model and see if the simulated historical dust storms match the ambient PM₁₀ concentration measurements taken during the events, similar to what Chung et al. (2013) have done using SWEEP (the stand-alone wind erosion submodel for WEPS). The addition of PM₁₀ flux measurements along with ambient meteorological and PM₁₀ concentration measurements will provide a comprehensive data suite for evaluating the regional application of the WEPS model.

Future application of this method should focus on obtaining spatial representation of the actual combinations of crop, management practice, and soil type applied in the region for use in WEPS simulations. One step in this direction would be to ensure that the correct percentages of conventional till, reduced till, and no-till practices are applied on a county-by-county basis. A lack of exact information might mean additional simulations of 1 km cells for the different management practices applied, with a weighted average of those multiple runs for an estimate for those 1 km cells. An evaluation of the different soil types within a 1 km cell could be conducted in a similar manner. The differences in the PM₁₀ emissions should also be evaluated against the increased run time for the regional simulation.

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