Aeolian Research 10 (2013) 9–24

Contents lists available at SciVerse ScienceDirect

Aeolian Research

journal homepage: www.elsevier.com/locate/aeolia

Review

A history of Wind Erosion Prediction Models in the United States Department of Agriculture: The Wind Erosion Prediction System (WEPS)

Larry E. Wagner*

USDA-ARS Engineering and Wind Erosion Research Unit, 1515 College Ave., Manhattan, KS 66502, USA

ARTICLE INFO

Article history:
Available online 7 November 2012

Keywords:
Wind erosion
Modeling
Climate generation
Wind erosion databases
Crop rotations
Wind erosion models

ABSTRACT

Development of the Wind Erosion Prediction System (WEPS) was officially inaugurated in 1985 by United States Department of Agriculture-Agricultural Research Service (USDA-ARS) scientists in response to customer requests, particularly those coming from the USDA Soil Conservation Service (SCS), for improved wind erosion prediction technology. WEPS was conceived to address deficiencies in the then-20-year-old, predominately empirical Wind Erosion Equation (WEQ) widely used by SCS, and it sparked an endeavor that relied on novel laboratory wind tunnel research as well as extensive field studies to adequately uncover the physical relationships between surface properties and their susceptibility to and influence on wind erosion. The result is that WEPS incorporates many process-based features and other capabilities not available in any other wind erosion simulation model today.

The USDA Natural Resource Conservation Service (NRCS) has now implemented WEPS as a replacement for WEQ within their agency. However, the road to achieve that replacement required years of close interaction between ARS and NRCS. NRCS had to ensure they had suitable national-scale WEPS databases before implementation. User input simplifications were required as well as modifications to the reports. Run-time concerns also arose during the lengthy testing and evaluation process. Many of these were strictly non-wind erosion science issues that had to be addressed before NRCS could officially implement and begin using WEPS within their agency. The history of the development of WEPS, its unique features and its solutions to selected critical issues encountered by NRCS prior to implementation are presented and discussed.

Contents

---

* Tel.: +1 785 537 5544; fax: +1 785 537 5507.
E-mail address: Larry.Wagner@ars.usda.gov

1875-9637/$ - see front matter Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.aeolia.2012.10.001

1. Introduction

Circa 1985, wind erosion modeling within the United States Department of Agriculture (USDA) had reached a ceiling in the level of maturity attainable with the empirical Wind Erosion Equation (WEQ) (Woodruff and Siddoway, 1965). The many weaknesses and limitations of the WEQ had already been recognized by wind erosion researchers and had been outlined in a number of publications (Skidmore, 1976; Cole et al., 1983; Cole, 1984a), despite the numerous enhancements obtained during its 20-year history (by 1985). Tatarko and Sporcic (2013) summarize the WEQ limitations while covering the early history of wind erosion modeling within the USDA. This manuscript completes the history of the Wind Erosion Prediction System (WEPS) era of wind erosion modeling within the USDA.

Due to the weaknesses of the WEQ, at one point, it became clear to the USDA wind erosion researchers that a new wind erosion model, including a more process-based, modular structure and a more extensive nature, would be needed to improve wind erosion predictions. The development of WEPS was thus initiated within the USDA by Agricultural Research Service (ARS) scientists and in response to customer requests; that is, WEPS was developed principally from the then USDA-Soil Conservation Service (SCS)[1] for an improvement in wind erosion prediction technology. WEPS was conceived to address deficiencies in the predominately empirical WEQ, which had been widely used at the time by the SCS. WEPS incorporates improved models for computing soil losses by wind from agricultural fields as well as for providing many new capabilities such as calculating suspension loss, estimating PM_{10} (particles with an aerodynamic diameter of 10 microns or less) emissions and specifying the direction in which soil leaves the field. WEPS was thus intended to be the future prediction tool of choice for those who plan soil conservation systems, who conduct environmental planning, or who assess offsite impacts caused by wind erosion (Hagen, 1991a). The official genesis of WEPS occurred in October of 1985 at an organizational meeting in Kansas City, Missouri, which was attended by ARS and SCS employees as well as by other government agency representatives, to discuss a replacement for the 20 year-old WEQ. Some noteworthy comments and observations were made at the meeting, as personally recorded by E.L. Skidmore: Dick Amerman, ARS National Program Leader, said, "*Develop a physically based model to replace WEQ…*"; Klaus Flack, SCS Chief Scientist, stated, "*We need erosion prediction, conservation planning, a tool to document and justify conservation programs, allocate resources…put some good science into the effort.*"; Rex Johnston, ARS Southern Plains Area Director, commented, "*Some of our basic concepts are faulty…let's put some good science into the effort.*"; and the Environmental Protection Agency (EPA) requested that the capability to predict PM_{10} be included in the new model.

An initial multi-disciplinary core group was soon formed, composed primarily of ARS and SCS scientists, to begin the development of a new Wind Erosion Model (WEM). Soon after, the term Wind Erosion Research Model (WERM) was used to describe the developing research model. The envisioned complete model to be delivered to customers, with national-scale databases and including a user interface, was to be called the Wind Erosion Prediction System (WEPS). Eventually, WERM was also dropped from the vocabulary in the model related development documents, with WEPS being the sole surviving acronym now used for all aspects of the project, from the developing science model to the fully released model, which includes the interface and the databases. The term WEPS will be used exclusively within this manuscript to describe the project unless explicitly mentioned otherwise within the cited documents.

The primary ARS scientists constituting the original core team were George Cole, Leon Lyles, Dean Armbrust, Larry Hagen and Ed Skidmore from the former ARS Wind Erosion Research Unit (WERU)[2] in Manhattan, KS and Bill Fryrear, J.D. Bilbro and Ted Zobeck from the Conservation and Production Systems Research Unit (CPSRU) in Big Spring, TX. The additional ARS core team members later participating during the development of WEPS were Larry Wagner, John Tatarko, D.J. Ding, Jeff Layton, Amare Retta, Abdu Durar, Naser Mirzamostafa, Fred Fox and Simon van Donk from WERU; John Stout, Ali Saleh and Scott van Pelt from CPSRU; Paul Unger, Jean Steiner and Harry Schomberg with the ARS Conservation and Production Research Laboratory (CPRL) in Bushland, TX; Ken Potter from the ARS Grassland, Soil and Water Research Lab (GSWRL) in Temple, TX; and Keith Saxton, Larry Stetler and David Chandler with the Hydrology and Remote Sensing Laboratory (HRSL) in Pullman, WA. Some prominent SCS, and later NRCS, employees who were involved with WEPS during its development were Klaus Flach, Bob Grossman, Scott Argabright, Ray Sinclair, Lorenz Sutherland, Henry Bogusch, Dave Lightle, Bruce Wight, Dave Schertz, Chuck Landers, Mike Hubbs, Norm Widman and, especially, NRCS' appointed liaisons with WERU such as Gary Tibke, Henry Bogusch, Arnold King and Mike Sporcic. Numerous collaborators outside the principle ARS research units were also involved in the field and laboratory research conducted for the development of WEPS. The collaborators consisted of soil scientists, agricultural engineers, agronomists and crop scientists from the ARS research field stations (Steve Merrill and Mike Lindstrom), SCS technical centers, and university researchers (John Lamb, Delbert Mokma, and Ronald Yoder) with a variety of backgrounds and expertise. Hence, the WEPS project was a truly multi-agency, multi-discipline project. Some major milestones and events during the developmental history of WEPS through the implementation of the model by NRCS are listed in Table 1.

The early work on WEPS consisted of identifying core team members, assigning research area leadership responsibilities, developing the initial framework for the model, and outlining the extensive field sampling and numerous laboratory studies needed to obtain the necessary data required for WEPS. Critical national funding was also pursued for WEPS in concert with its sister project, the Water Erosion Prediction Program (WEPP).

George Cole was selected as the original WEPS program leader due to his background in simulation modeling. Larry Hagen was assigned to lead the fundamental laboratory wind tunnel research necessary for the development of the WEPS erosion submodel. Ed Skidmore led the field research to obtain the range of the temporal soil properties relevant to wind erosion on Kansas soils, and Ted Zobeck coordinated the effort of many field collaborators to obtain similar data over a range of soil types across the U.S. Bill Fryrear was charged with obtaining the field site data for validation of the eventual WEPS erosion submodel (Table 2). J.D. Bilbro and Dean Armbrust were assigned to obtain the necessary physical plant characteristics relevant to wind erosion and to parameterize that data into a process-based plant growth model. Later additions to the core team assumed additional responsibilities: Abdu Durar – Hydrology submodel and development of an approach to adequately simulate the near surface water content at the air–soil interface; Amare Retta – Plant growth submodel and plant database development; Larry Wagner – Management submodel development and related field data collection; and Jean Steiner and

---

[1] The current Natural Resources Conservation Service (NRCS) was originally known as the Soil Conservation Service (SCS), but the name was changed in 1995 to better reflect the broadened scope of the agency's concerns. All references to SCS and NRCS are synonymous within this document, with the usage roughly correlating to the timeframe the names were in common use.

[2] The former Wind Erosion Research Unit (WERU) merged with the former Engineering Research Unit (ERU) in 2010 and are now known collectively as the Engineering and Wind Erosion Research Unit (EWERU).

Table 1
Important dates and milestones for the WEPS project.

Dates	Milestone event
October 1985	Organizational meeting in Kansas City, MO (genesis of WEPS)
1985	Initial core team meeting (George Cole selected as WEPS Project Leader)
December 17, 1985	First revision of WEPS User Requirements Specification (draft)
August 1986	Larry Hagen appointed as WEPS Project Leader
April 1991	Final revision of WEPS User Requirements (draft)
August 26–29, 1991	WEPS User Requirements meeting in Kansas City, MO
August 1995	First WEPS Technical Document published (draft)
September 1999	Larry Wagner appointed as WEPS Project Leader
April 4, 2005	WEPS formally delivered to NRCS for testing and evaluation
2005	NRCS requested "yield calibration" and "fixed yield:biomass" ratio features added to WEPS
2006	WEPS incorporates WEPP hydrology to meet NRCS runtime constraints
2006	Added irrigation monitoring processes to represent furrow, sprinkler and drip
February 2008	Simplified interface for NRCS (removed user-selectable "Project" level, etc.)
February 26, 2008	WEPS formally delivered to NRCS for training and database population
July 2009	Working interpolation system for Windgen stations added to WEPS
February 2010	WEPS accepted by NRCS for implementation
October 1, 2010	WEPS installed on 15,000 computers and operational in 2200 NRCS field offices (version 1.1.16)
December 7, 2010	Official "Notice of Implementation" by NRCS of WEPS use for soil erodibility system calculations in the Federal Registry (U.S. Gov., 2010)
February 2011	Updated WEPS databases provided to NRCS field office computers
October 1, 2011	Updated WEPS pushed to NRCS field office computers (version 1.2.9)
July 5, 2012	Updated WEPS databases pushed to NRCS field office computers

Table 2
WEPS field validation sites.

Location (city, state)	Erosion periods during years
Fresno, CA	1993–1995
Akron, CO	1988–1990
Eads, CO	1990–1992
Crown Point, IN	1990–1992
Elkhart, KS	1990–1993
Kennett, MO	1992–1994
Havre, MT	1992–1994
Lindsey, MT	1991–1992
Scobey, MT	1988–1990
Sidney, NE	1988–1991
Mabton, WA	1991
Prosser, WA	1991–1994
Big Spring, TX	1989–1997

Harry Schomberg – Decomposition submodel and associated field data collection.

Additionally, work on the WEPS User Requirements document with the assistance of SCS was initiated. Some core concepts identified in the first draft of that document by George Cole in 1985 covered how WEPS would perform or achieve the following: (a) be used, e.g., as a conservation planning tool as well as for inventory and assessment purposes by user agencies; (b) have a modular design with core submodel components; (c) include a list of required national databases; (d) observe conservation of mass principles, be process-based, climate driven, deterministic, robust, and validated; (e) be easy to use; (f) reflect impacts of applied management practices on wind erosion susceptibility; and (g) apply to all situations presently covered by WEQ. The concept of a "user interface" for the model was added in later drafts as a requirement under the "ease of use" directive.

One interesting requirement within the first draft was that the system would "*compute the frequency distribution of wind erosion at the rate of one management practice per 10 minutes*" and not take "*more than 30 minutes of user time (computer time can be longer) per farm, is to be required in the office to prepare and assemble needed information before going to the field.*" This was the estimated amount of time that it took a knowledgeable SCS field office employee to apply the paper (non-computerized) version of WEQ at that time. Later revisions of the user requirements document included additional constraints on the computational time and even specified particular computer hardware, including the use of a math coprocessor as a requirement, to meet the new runtimes. The final documented requirements for the runtime in the last draft authored by Hagen in 1991 were "*should compute…annual soil loss values…at the rate of two minutes for each year of the crop rotation*" and "*no more than 30 minutes of office time should be required to assemble the needed information before operating the program with a typical client.*" However, later discussions between WERU and the NRCS National Agronomist, circa 1993, resulted in a much tighter "*5 minutes to obtain and select inputs*" and "*less than 30 seconds per rotation year for a simulation*" requirement upon WEPS. The significance of this one requirement had profound implications both during the development of WEPS and on the final delivered model submitted to NRCS years later.

Multiple meetings with SCS were held over the coming years, with multiple updated drafts produced as a result. The "WEPS User Requirements" document was never officially signed off by SCS, nor formally published, due to a variety of external factors, although Hagen did publish a manuscript that covered a partial list of those user requirements (Hagen, 1991a). Regardless, the "WEPS User Requirements" document contained the blueprints faithfully followed throughout the development of WEPS. The last formal meeting with SCS regarding the user requirements for WEPS was held August 26–29, 1991 in Kansas City, MO.

Many other meetings, workshops, and training sessions were held, first by the core researchers and the field research collaborators and later with much more direct NRCS involvement, during the WEPS user interface and database development. A listing of such meetings held over the years is shown in Table 3. These meetings covered the basic laboratory and field research that had been conducted early on for WEPS during the "core team" meetings and later during the many "Quarterly ARS/NRCS Agreement" meetings (2002–2009) covering the specific modeling and user interface issues, the four NRCS WEPS testing meetings (2005), the development and population of databases, and eventually the NRCS "train the trainer" workshops.

It took approximately 10 years to conduct the basic research and field studies required for the WEPS erosion routines and its supporting submodels, to develop the core science model and to validate the erosion code. Then there was brief 2 year stint where the WEPS developers were asked to work on a Revised Wind Erosion Equation (RWEQ), but was later requested to return to working on WEPS. The latter 10-year period was primarily focused on

Table 3
WEPS core team, subgroup and NRCS/ARS Agreement meetings.

Dates	Location	Purpose
October, 1985	Kansas City, MO	Initial meeting formalizing WEPS project
November 3–5, 1987	Manhattan, KS	WEPS Core Team meeting
April 13–15, 1988	Big Spring, TX	WEPS Core Team meeting
October 28–30, 1988	Morris, MN	WEPS Core Team meeting
May 21–23, 1989	Ft. Worth, TX	WEPS Core Team meeting
September 19–21, 1989	Lincoln, NE	WEPS Core Team meeting
April 3–5, 1990	Bushland, TX	WEPS Core Team meeting
April 18–21, 1991	Manhattan, KS	WEPS Core Team meeting
August 26–29, 1991	Kansas City, MO	WEPS User Requirements meeting
November 19–21, 1991	Big Spring, TX	WEPS Core Team meeting
April 21–23, 1992	Manhattan, KS	WEPS Core Team meeting
October 28, 2002; February 3, 2003 April 24, 2003; July 22, 2003 March 2, 2004; June 3, 2004 November 5, 2004; April 5, 2005 August. 11, 2005; December 13, 2005 May 2, 2006; September 6, 2006 November 30, 2006; March 13, 2007 July 19, 2007; October 11, 2007 October 23, 2008; July 28, 2009	Manhattan, KS	Quarterly ARS/NRCS WEPS Agreement meetings
March 29–31, 2005 June 1–3, 2005 August 23–25, 2005 December 29–30, 2005 November 6–8, 2006 January 22–24, 2007 February 12–14, 2007 March 12–14, 2007 April 9–11, 2007	Various locations throughout the U.S. MO, KS, CO, NENM, ND, SC, IDMT, IA, NV, WA, etc.	NRCS WEPS Testing meetings

developing the interface and expanding the necessary databases for NRCS implementation. This does not mean there were no ongoing improvements, bug fixes and enhancements being made to the science model during the latter 10 years. Some specific major changes are identified in Table 1 during that time frame were the NRCS requested “yield calibration” feature and a “fixed yield:biomass” ratio for determining crop yields. In addition the WEPP hydrology code was incorporated to meet NRCS runtime constraints. The iterative process during the NRCS testing stages was crucial to the refinement of the WEPS science model, the maturation of the usability of the interface and to the ultimate successful conclusion of the implementation of WEPS within NRCS.

Initial completion dates were under-estimated at the beginning of the WEPS project. The program interfaces changed rapidly during this time, starting with the text-based menu systems and concluding with the highly graphical, mouse-based windowed systems. The level of support required by NRCS to develop national-level databases was not anticipated.

2. Model description

WEPS was constructed to be modular, unlike most models of that era, e.g., the Erosion Productivity Impact Calculator (EPIC) (Sharpley and Williams, 1990). Hence, the advantages of constructing a modular program were already evident. WEPS was also built to incorporate the conservation of mass and momentum principles within the derived relationships where possible and to have submodels capable of simulating changes in the relevant properties important to wind erosion on a daily basis.

However, the concepts embodied in WEPS were not determined quickly. The previous work by the ARS scientists formed the initial basis for WEPS: the conversion of WEQ to a daily time step model for inclusion into EPIC (Cole et al., 1983; Cole and Lyles, 1984); the concepts of outside influences changing the susceptibility of a surface to wind erosion, e.g., crop growth, temporal soil surface properties modified by climate, changes in soil aggregate status due to tillage, etc. (Lyles and Tatarko, 1986); the derivations of the mathematical basis for the physical processes required to compare the wind tunnel relationships to the field-scale erosion rates (Cole, 1984a); the expressions of the period or interval for erosion loss (Cole, 1984b); the introduction of the conservation of mass and momentum principles into the wind erosion processes (Cole, 1985); and the investigations of the probability requirements for the erosion outputs (Cole and Higgins, 1985).

WEPS now consists of several major components, which will be further referred to collectively as WEPS 1.0: (a) the WEPS science model; (b) the WEPS interface; and (c) the databases of soil, crops, operations, management rotations, wind barriers and climate. The science model is the core wind erosion model used to perform the simulation. The WEPS interface obtains the required inputs from the user and then packages them into the necessary science model input files, executes the science model and presents the output in a more user-friendly format than provided by the science model itself. The science model, through its respective submodels, estimates the soil/vegetation “surface state” on a daily basis with respect to the erodibility of the surface. If the wind speed is significant enough during the day to generate a friction velocity that exceeds the static threshold friction velocity of that surface, then the erosion submodel will simulate the degree of wind erosion that occurs on a sub-daily time step for that day. Fig. 1 shows the basic structure of WEPS 1.0, including the interface user inputs, the databases, and the submodels in the science code. The science model is coded in FORTRAN, which was the programming language initially understood by the majority of scientists at that time. The WEPS interface is coded in Java, as it is the only programming language that has cross-platform capability, including the graphical display elements, without requiring any modifications at the source code or binary level. The databases are of three types: the text-based proprietary (unique to the program/database) formatting for the older databases and records (CLIGEN, WINDGEN, soil,

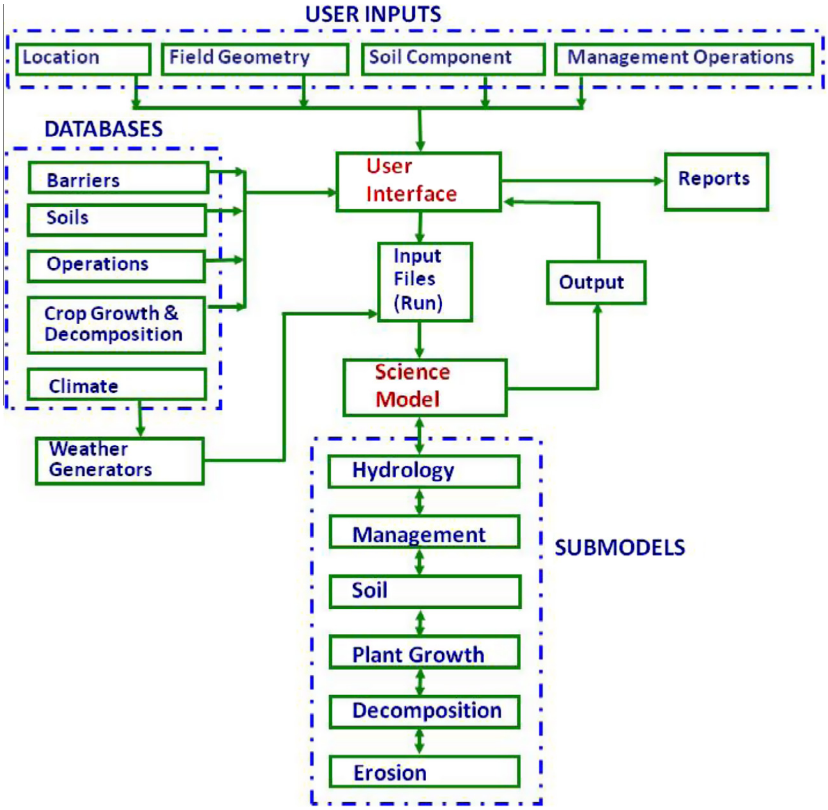


Fig. 1. WEPS 1.0 components, submodels and databases.

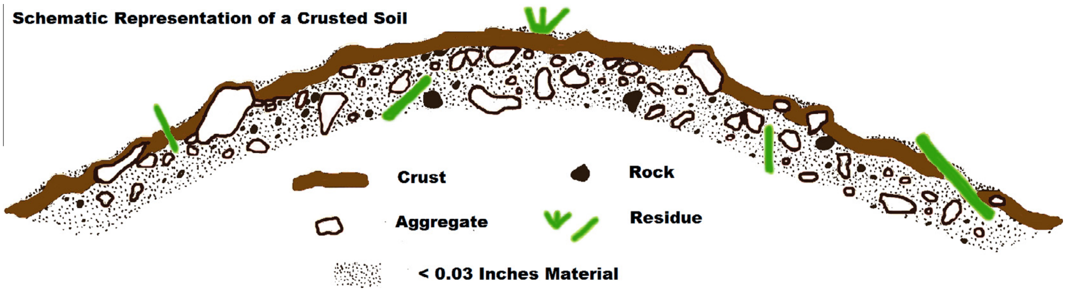


Fig. 2. Schematic representation of a crusted soil (Zobeck, 1991).

management and wind barriers), the XML-based for the crop and operation records accessed by the WEPS interface, and the GIS shape file-based for the climate record selection.

2.1. Science model

WEPS is unique as a wind erosion model because it seeks to determine the "surface state" on a daily and sub-daily basis with respect to the surface's susceptibility to wind erosion; no other wind erosion model is capable of this. WEPS simulates many of the physical processes known to occur as a result of wind erosion on cropland. The basic erodibility of the bare soil is determined from the aggregate size distribution on the surface as well as from the density and the dry stability of the aggregates. If the surface is either partially or fully consolidated (e.g., if it is crusted), then the fraction of crusted surface is taken into account along with the crust thickness, its dry stability and the amount of loose, erodible material on the crust. If the surface consists of non-erodible particles (rocks), then the fraction of the surface that contains rocks discounts the surface's susceptibility to erosion (see Fig. 2). The aerodynamic roughness is computed based upon both the random roughness and any oriented roughness and its row direction relative to the wind direction. If vegetation exists, then the computed friction velocity is carried down through the plant canopy to the surface (a unique attribute of the WEPS erosion submodel).

2.1.1. Hydrology

WEPS maintains the current "state" of the surface on a daily basis, with the modifications to surface wetness maintained on an hourly basis. The user has the option of selecting one of the two hydrology submodels: either (a) the original WEPS hydrology submodel, which performs a complete one-dimensional Darcy's law simulation of the water movement within the soil profile, including infiltration and evaporation; or (b) the WEPP hydrology submodel, which uses Green–Ampt infiltration, a "tipping bucket" approach to water distribution within the soil profile, and an empirical evaporation withdrawal function (Savabi et al., 1995). Both hydrology submodels also use independently developed routines to simulate the soil freeze/thaw and the snow accumulation/melt. The WEPP hydrology submodel uses a less computationally intensive approach. This submodel is the default hydrology component used by NRCS, although the WEPS hydrology component better simulates the diurnal cycling of the surface moisture and more accurately influences the freeze/thaw and freeze/dry winter processes, all of which impact the surface soil erodibility by wind. The WEPP hydrology submodel was added to meet the NRCS runtime requirements, which WEPS had difficulty attaining at the time (circa 2006) with the computer hardware available then. The hydrology submodel accounts for 80–90% of the total runtime for a typical WEPS simulation.. At this time there is no published complete reference of the original hydrology submodel in WEPS outside of the WEPS User's Guide (available as part of the WEPS system) and a chapter in the draft WEPS technical documentation (Durar and Skidmore, 1995).

2.1.2. Plant growth

The plant growth submodel simulates the growth of a plant (crops) under applied daily water and temperature stresses. It was originally based upon the Erosion Productivity Impact Calculator (EPIC) plant growth model (Sharpley and Williams, 1990) but has been heavily modified to meet the WEPS requirements for vegetation influences on wind erosion. The leaf mass and the stem mass interact differently with the wind; therefore, the plant biomass accumulation is divided into the stem, leaf and reproductive components. For better frost damage simulation, the live leaf and dead leaf masses are tracked. To model perennial, winter annual and bi-annual crops, a storage pool accumulates the mass and releases it for regrowth, assuming that all leaf mass is removed. A maximum plant radius prevents one plant from completely covering a large area and is used to divide the stem mass between standing and flat. For crops whose maturity is not purely heat unit-driven, the vernalization parameters can also be set. Unlike EPIC, which grows the biomass based on a heat unit-driven Leaf Area Index (LAI) curve, WEPS grows biomass, divides it into the mass pools and calculates the resulting LAI from the leaf mass. Similarly, the stem biomass is used to calculate a stem area index. Additionally, due to NRCS requests, an individual crop can also be configured such that the after-harvest residue is dependent upon the yield, and if need be, this functionality can be disabled for all crops via a command line option to the WEPS science model. At this time there is no published complete reference of the plant growth submodel in WEPS outside of the WEPS User's Guide (available as part of the WEPS system) and the draft WEPS technical documentation (Retta and Armbrust, 1995).

2.1.3. Decomposition

The residue decomposition is driven by temperature, the soil moisture (on the surface for surface residue and within the soil for buried residue), and the decay rate, which is dependent upon the parent plant material and the component (Steiner et al., 1994; Schomberg et al., 1996). The stem, leaf, chaff and root components are tracked separately. Multiple pools of the residue, based on the age, component, and location, are maintained separately within WEPS. The critical residue parameters that impact wind erosion are the leaf area index, the stem area index, the spatial density of the standing stalks (population) and their average diameter and height, as well as the flat residue mass and the cover fraction.

2.1.4. Soil

The soil submodel simulates the daily changes to the soil and surface that occur due to climatic factors. The ridge and dike height as well as the random roughness are decayed due to cumulative rainfall. The surface crust is formed due to "puddling" on the surface when the precipitation events exceed the infiltration rate, with the resulting crust stability and thickness as well as the amount of loose erodible material on the crust all determined by the parent soil type. Aggregates consolidate, increasing in size, and aggregate stability increases also occur due to cumulative rainfall. Over time, the bulk density trends to a "settled" bulk density value that depends upon the soil type (Rawls, 1983). The aggregate stability and the size are decreased due to freeze/thaw, freeze/dry, and wet/dry cycles. The de-aggregation and re-aggregation processes are reflected in the changes to the size distribution of the aggregates within each soil layer, represented as a modified log-normal distribution (Wagner and Ding, 1994).

2.1.5. Management

The management submodel addresses the variety of land management actions by identifying the primary physical processes involved and by representing each individual management operation as a sequential set of the relevant primary physical processes (Wagner, 2011). Those processes include the following: (1) surface modification (creation or destruction of ridges and/or dikes that form oriented surface roughness, changes in surface random roughness, and destruction of soil crust); (2) soil layer mass manipulation (changes in aggregate size distribution and soil porosity, mixing of soil and residue among soil layers, and soil layer inversion); (3) biomass manipulation (burying and resurfacing residue, clipping standing residue, flattening standing residue, killing live crop biomass, and biomass removal); and (4) soil amendments (manure and residue additions, planting, and irrigation). A complete list of management operation processes is provided in Table 4.

In accordance with the WEPS design philosophy, the management submodel simulates these processes via a physical basis if possible, incorporates the conservation of mass concepts, and employs the functional relationships developed from the field and laboratory data, if available, using a minimum of parameters with the readily available and/or attainable values. These processes are assumed to be dependent with respect to each other and are simulated sequentially. Thus, each management operation is represented by an appropriate ordered list of processes. The individual processes and their order of simulation uniquely describe each specific operation effect on the soil, surface and vegetation present. The typical multi-tool and ganged multi-implement operations also can be easily described in full by repeating the necessary processes for each tool (tillage element), which exist as a component of such operations.

The list of management operations performed for a given management plan (crop rotation/tillage sequence or cyclical list of cultural practices) is specified in a management file. On the dates when operations are to be performed, the management submodel will execute the specified routines required to simulate the effects of those operations listed in the management file. When the final operation is performed for that particular management/crop rotation cycle, the sequence will then be repeated for the subsequent year(s) until the end of the simulation.

2.1.6. Erosion

WEPS is unique in the detail and completeness that the erosion processes are modeled. Thus, an overview of how erosion is modeled within WEPS is provided here.

In WEPS, the friction velocity was selected to drive erosion, but the meteorological input parameter is the wind speed. However, for any given wind speed, under neutral atmospheric conditions in the surface boundary layer, the friction velocity is proportional to the natural logarithm of the surface aerodynamic roughness. Therefore, to obtain the friction velocity, the aerodynamic roughness term of the log-law wind speed profile must be determined.

Table 4
Management Operation Processes.

Action	Process	Description
Soil surface manipulation	Crust	Process of modifying the soil surface crust characteristics
	Roughen	Process of modifying the random surface roughness
	Ridge/dike	Process of creating or destroying ridges and/or dikes (oriented surface roughness)
Soil mass manipulation	Crush	Process of applying forces to the soil that modifies the aggregate structure by breaking down soil aggregates
	Loosen	Process of decreasing the soil bulk density and increasing the porosity (incorporation of air), or the inverse process of increasing the soil bulk density by removing air from the soil, e.g., compaction
	Mix	Process of uniting or blending of soil layer properties, including biomass
	Invert	Process of reversing the vertical order of occurrence of the soil layers within the current specified tillage zone
Biomass manipulation	Flatten	Process of converting standing biomass to flat biomass
	Bury	Process of moving surface biomass into the soil
	Re-surface	Process of bringing buried biomass to the surface.
	Cut/Remove	Process of cutting standing biomass to a prescribed height and placing the cut material on the surface or, optionally, removing (harvesting) the cut material.
	Thin Population	Process of reducing the number of standing biomass stems or stalks by a fraction of the total or to a specified number per unit area and placing the thinned material on the surface or, optionally, removing (harvesting) it
	Kill/defoliate	Process of killing or defoliating live (or dead) biomass
	Remove	Process of removing biomass from the system (harvest, grazing and burning)
	End biomass manipulation	Process that completes the transfer of the killed crop biomass to the residue decomposition pools. This is a WEPS-specific function to address a deficiency in the current model design that does not allow the decomposition process to occur automatically within the model
Soil amendments	Plant	Process of adding seeds/plants to the soil
	Irrigate	Process of adding water on or into the soil
	Add biomass	Process of adding biomass (residue, manure, wood chips) to the surface and/or into the soil

For surfaces without standing biomass, the surface aerodynamic roughness is simply controlled by the roughness of both the soil and the flat biomass cover. The controlling (maximum) roughness, e.g., the random, oriented or flat cover, is calculated, and the appropriate relationship is selected for use in determining the aerodynamic roughness length.

If standing plant biomass is present, additional calculations are performed to determine the friction velocity at the surface. The effectiveness of leaves is significantly reduced due to their tendency to orient parallel to the wind streamlines (Armbrust and Bilbro, 1997). Therefore, an “effective biomass drag coefficient” is computed, and it discounts the effect of the leaves relative to that of the stems on the wind in determining the aerodynamic roughness length above the canopy surface. The under-canopy aerodynamic roughness length is then calculated (Hagen and Armbrust, 1994). Once the aerodynamic roughness length is known, the friction velocity of the surface generated by a given wind speed can then be determined.

To determine the static threshold friction velocity, the potential surface cover must be accounted for and may consist of the following: (a) rocks; (b) crust; and (c) aggregates, with flat and standing biomass above or on those surfaces. The static threshold friction velocities for bare soil surfaces are estimated by equations fitted to wind tunnel data (Hagen, 1991b; Chepil and Woodruff, 1963). If a flat biomass cover is present, the increase in surface area protected from emission is accounted for (Hagen, 1996). Likewise, an increase in the static threshold friction velocity due to surface wetness is also taken into account (Saleh and Fryrear, 1995).

If the computed “friction velocity” generated by a given wind speed exceeds the computed surface “static threshold friction velocity,” then erosion will occur and the erosion submodel will initiate the emission of soil and will use a reduced static threshold friction velocity (dynamic threshold friction velocity), which accounts for the fact that saltating particles return additional energy to the stationary aggregates lying on the surface in the saltation/creep transport capacity equations (Bagnold, 1943).

The transport of soil during wind erosion occurs in three modes. Creep-size aggregates (0.84–2.0 mm diameter) roll along the surface, saltation-size aggregates (0.10–0.84 mm diameter) hop over the surface, and suspension-size aggregates (<0.10 mm diameter) move above the surface in the turbulent flow. Obviously, as wind speed increases, turbulence, or sediment loads change, the diameter of aggregates moving in the various modes also may change slightly; however, in WEPS, these values are assumed constant.

In WEPS, it was assumed that the combined saltation/creep mode of transport has a distinct transport capacity for each surface, based on the surface aerodynamic roughness and wind speed. This assumption generally has been supported by both the field and wind tunnel measurements of the saltation/creep discharge (Greeley and Iversen, 1985). Other properties, such as the soil texture, the quantity of loose erodible material on a crusted surface, etc., may limit the supply of saltation/creep-size particles available for emission (transport), especially on short fields; however, these properties do not impact the carrying capacity of the wind (transport capacity) for these particles on a given surface. It was also assumed that the suspension component does not reach a transport capacity on most eroding fields. Thus, separate equations have been developed for saltation/creep, suspension, and PM_{10} discharge because each responds differently to both the wind forces and the sediment load (Gillette et al., 1998). Separating these erosion components is also useful because they have different potential off-site impacts.

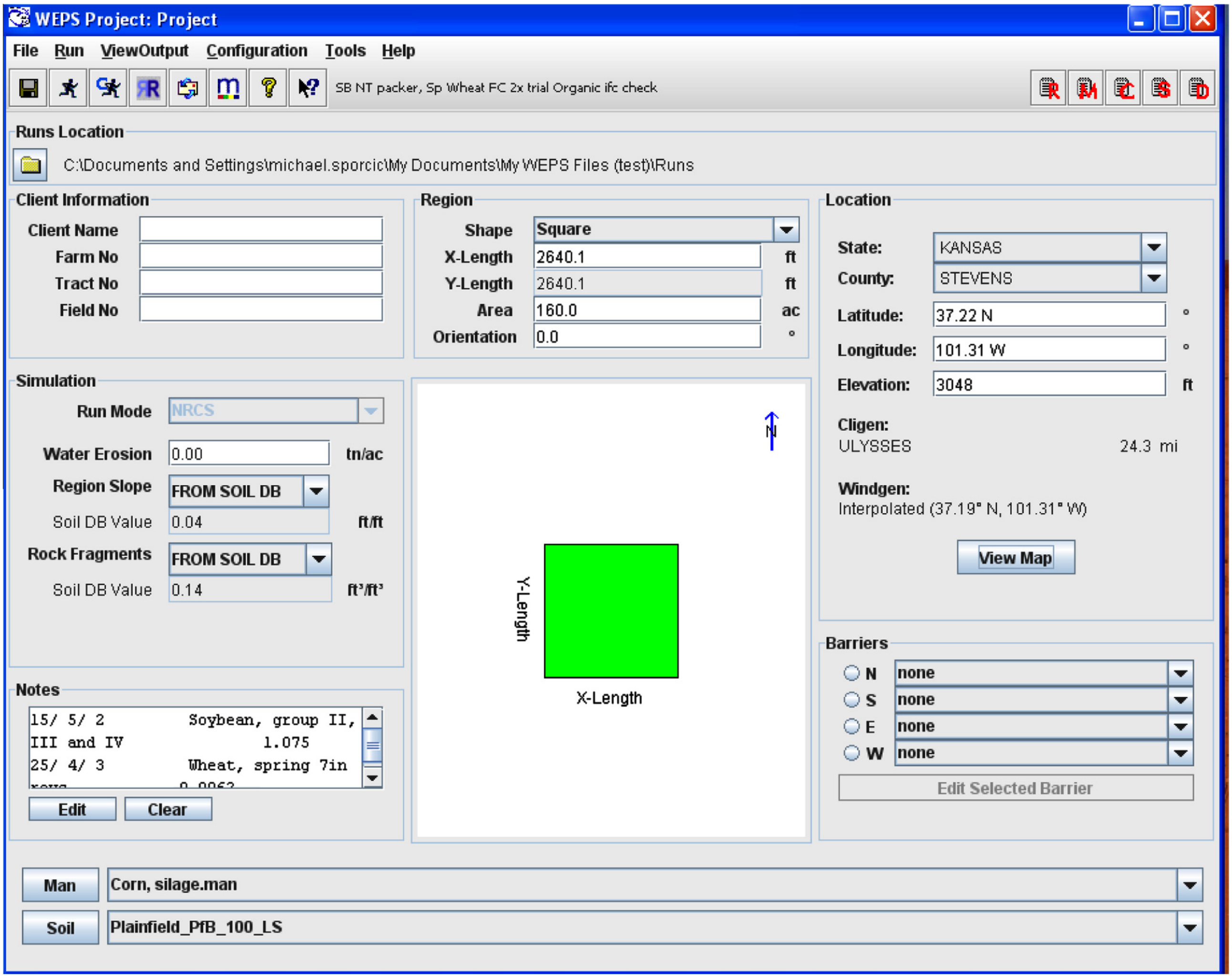
Wind erosion occurs over a wide range of surface conditions. To aid in delineating the erosion rates among the various surfaces, several individual erosion processes were identified in WEPS (Hagen et al., 1999). These processes include: (a) the direct entrainment (emission) of loose soil by wind and/or saltation impacts; (b) the abrasion of soil from clods/crust by saltation impacts; and (c) the breakage of saltation/creep-size aggregates into suspension-size particles. These processes were selected for individual simulation because they differ from one another by approximately an order of magnitude in their ability to supply new suspension or saltation/creep-size mass to the airstream in response to a saltation impact (Mirzamostafa et al., 1998). When the saltation/creep discharge exceeds the transport capacity over a region in a local area of the surface, the deposition of saltation/creep size material occurs. It also was assumed that the coarse fraction of the suspension component begins depositing when moving over areas in the simulation region that are not actively eroding.

For both the saltation/creep and the suspension components, based on the conservation of mass in a control volume, the one-dimensional, quasi-steady state equations for the physical processes were developed (Hagen et al., 1999). They include the following parameters: (a) emission, based upon the surface roughness, biomass cover and aggregate size distribution; (b) abrasion of immobile soil clods and crust by saltation impacts creating additional erodible aggregates (Hagen et al., 1992; Zobeck and Popham, 1991; Mirzamostafa et al., 1998); (c) breakage during the transport of saltation-size aggregates into suspension-size aggregates (Mirzamostafa, 1996); (d) trapping due to changes in surface conditions that cause a decrease in the threshold friction velocity and capacity; and (e) interception of mobile particles due to the standing biomass.

In WEPS, the simulation region is gridded, with the erosion computed within each uniform-sized rectangular cell. The cell size and shape are both variable, depending upon the size and shape of the simulation region. The minimum grid cell X and Y length dimensions are 7 m. Currently, the maximum of 29 × 29 (841) cells are used in a typical field size simulation (greater than 200 m by 200 m). The cell size and number were determined based upon tradeoffs between the erosion computation accuracy and the run-time considerations for typical U.S. cropland field sizes. The number of cells is more than quadrupled to 59 × 59 (3481) cells, if barriers are specified on the simulation region. This was done to properly account for the barrier effects on larger field simulations (that is, to maintain a small enough cell size to properly represent the regions upwind and downwind influenced by the barrier). For each day that erosion occurs, all cells begin with the same initial surface conditions. Likewise, the initial friction velocity for each cell is also the same, except within the influence zone of a wind barrier. The friction velocity is then depressed, based upon: (a) the barrier porosity; (b) the barrier height; and (c) the distance from the barrier for each cell within 15 and 5 times the barrier height downwind and upwind, respectively. As the erosion process proceeds, the surface state is updated dynamically within the erosion submodel for each cell. The effects of the erosion processes are all simulated within the erosion submodel of WEPS; these include: (a) abrading through the surface crust; (b) deflating the erodible-size surface aggregates and therefore increasing the non-erodible aggregates and rocks on the surface; and (c) smoothing of both the oriented and random roughness due to the trapping and sheltering of eroding particles. The updating of the surface occurs at different time intervals and is dependent upon the relative erosive wind energy (level of erosion) occurring at the most erosive grid cell during the previous time step.

2.2. Interface

NRCS would not have been able to implement WEPS without an interface or the national databases that made it easy for the field office staff to select necessary inputs and to view the simulation results easily. Significant effort was expended on developing the interface, iteratively revising it to better meet their needs and assisting them in populating the necessary databases. As many resources were spent, at least time-wise, on the development and expansion of the interface and databases as were spent on the



SB NT packer, Sp Wheat FC 2x trial Organic ifc check

Runs Location: C:\Documents and Settings\michael.sporcic\My Documents\My WEPS Files (test)\Runs

Client Name:
Farm No:
Tract No:
Field No:

Shape: Square
X-Length: 2640.1 ft
Y-Length: 2640.1 ft
Area: 160.0 ac
Orientation: 0.0 °

State: KANSAS
County: STEVENS
Latitude: 37.22 N °
Longitude: 101.31 W °
Elevation: 3048 ft
Cligen: ULYSSES 24.3 mi
Windgen: Interpolated (37.19° N, 101.31° W)

Run Mode: NRCS
Water Erosion: 0.00 tn/ac
Region Slope: FROM SOIL DB
Soil DB Value: 0.04 ft/ft
Rock Fragments: FROM SOIL DB
Soil DB Value: 0.14 ft³/ft³

```
15/ 5/ 2         Soybean, group II,
III and IV                1.075
25/ 4/ 3         Wheat, spring 7in
```

○ N none
○ S none
○ E none
○ W none

Man: Corn, silage.man
Soil: Plainfield_PfB_100_LS

Fig. 3. Main screen of the WEPS user interface.

development of the WEPS science model. However, it is the author's belief that WEPS would never have been implemented within NRCS without these "non-science" components having been addressed and completed as a part of WEPS 1.0.

The WEPS interface, written in Java to be as cross-platform as possible, obtains the required inputs from the user. When a WEPS run is initiated, the interface creates the necessary science model input files from those previously selected inputs, runs the CLIGEN and WINDGEN generators to generate the climate and wind data files, respectively, if configured to do so, and then executes the science model. Upon completion, the interface presents the output in a more user-friendly format than provided by the science model itself. Fig. 3 shows the main WEPS interface screen.

2.2.1. Inputs

Through the interface, there are only four main inputs required by WEPS: (a) location; (b) field geometry; (c) soil component; and (d) management as shown in Fig. 1.

The location can be specified in a variety of ways by the user: (a) latitude/longitude coordinates directly; (b) through a series of political boundary selections (e.g., state/county selections for the U.S.); or (c) by selecting a location from a map. Once the location has been selected, the user will usually have the representative CLIGEN and WINDGEN stations selected based upon the criteria set within the configuration of the user interface. Some of the options are as follows: (a) the nearest station to the specified latitude/longitude; (b) the specified station within a defined polygon region; (c) the interpolated station (currently only available for WINDGEN stations); (d) the user selected; and (e) the specified previously generated or historical data in the CLIGEN and/or WINDGEN file formats. NRCS employs several of these methods, depending upon the region in which the model is being applied. For non-NRCS WEPS release configurations, the default station selection is still the "NRCS" option, but the user is free to select any of the other specific options available, e.g., (a) nearest station with sorted by distance choice list override; (b) nearest station only; (c) file (usually historical data) option; or (d) GIS maps for using the polygons. The WINDGEN station selection also contains the additional "interpolation" option. The user also has the ability to select one of these options as the default as a configuration setting through the configuration menu setup available from the menu bar on the main WEPS screen. The actual WEPS inputs from these two climate files are described in the next section on databases.

Table 5
List of intrinsic soil, layer and surface properties used by WEPS.

Property	Units	Can estimate through interface (Yes/No)
Slope	$m\ m^{-1}$	No
Number of soil layers		No
Organic Matter	$kg\ kg^{-1}$	No
Sand	$kg\ kg^{-1}$	No
Silt	$kg\ kg^{-1}$	Yes
Clay	$kg\ kg^{-1}$	No
Rock Fragments	$m^3\ m^{-3}$	Yes
Very coarse sand (fraction of total soil)	$kg\ kg^{-1}$	Yes
Coarse sand (fraction of total soil)	$kg\ kg^{-1}$	Yes
Medium sand (fraction of total soil)	$kg\ kg^{-1}$	Yes
Fine sand (fraction of total soil)	$kg\ kg^{-1}$	Yes
Very fine sand (fraction of total soil)	$kg\ kg^{-1}$	No
CB (power of Cambell's model)		Yes
Air entry potential	$J\ kg^{-1}$	Yes
Saturated hydraulic conductivity	$m\ s^{-1}$	Yes
pH		Yes
$CaCO_3$	$kg\ kg^{-1}$	No
Cation exchange capacity	$meq\ (100\ g)^{-1}$	Yes
Linear extensibility percent	$(mm\ mm^{-1})\ 100$	Yes

The field geometry is currently restricted to rectangular regions oriented relative to north within the WEPS science model. The user can specify the X and Y lengths and the orientation angle of the region directly selecting from a common set of field shapes in which the size (area) of the simulation region is then specified. Non-rectangular shapes, such as circles, half-circles and quarter circles, are handled by internally converting the region to a representative rectangle of the same area within the interface. This approach was added to the interface in response to the WEPS testing conducted by NRCS; this testing revealed problems with users incorrectly specifying the representative field size to be used for non-rectangular fields.

The soil component consists of the intrinsic soil layer and the surface properties. The temporal soil layer and surface properties are either initialized by the user manually or, more commonly, are assigned default values based upon a few select intrinsic soil property values within the interface. There are 16 surface properties and 30 soil layer properties required for a fully populated WEPS soil input file (Tables 5 and 6). The user has the option to select a soil component in the following ways: (a) by going through a State/County/Series/mapid/component selection process from either a Microsoft Access format NRCS SSURGO database file or directly over the internet through a Simple Object Access Protocol (SOAP) interface, now called a Web Map Service (WMS), connection with the NRCS NASIS SoilDataMart (NRCS, n.d.) website through the following web address (http://SDMDataAccess.nrcs.usda.gov); (b) by selecting a WEPS specific text formatted file; or (c) by manually filling in at least seven (7) soil properties for each soil layer, which is the minimum required to estimate the values for all the remaining properties, if the user does not know or does not want to manually populate all the properties. The NRCS users connect to the NRCS NASIS SoilDataMart website by default.

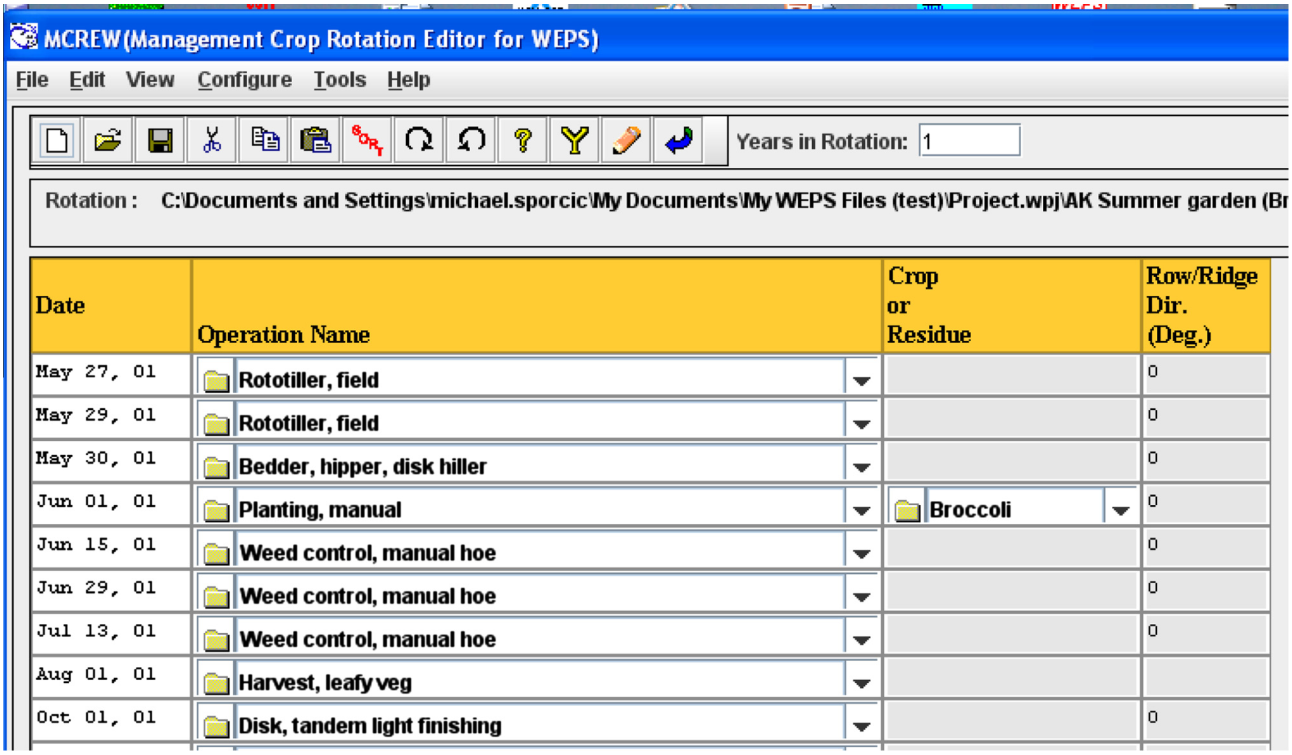
The management/crop rotation files consist of the list of operations that a land manager has prescribed for a particular simulation. These typically include the planting and harvesting operations as well as the tillage and any optional irrigation applied to the field with their respective dates. The user can select from the following: (a) Crop Management Zone (CMZ) template files originally created by NRCS for use by their field office staff when using the 2nd Revised Universal Soil Loss Equation (RUSLE2); (b) previously constructed management files created and saved locally by the user; or (c) the creation of a management/crop rotation file from scratch by opening up the Management/Crop Rotation Editor (MCREW) within the interface. Of course, any previously selected file can also be modified within MCREW. Fig. 4 shows a picture of MCREW with a list of selected operations.

2.2.2. Databases

Several national-scale databases were developed by NRCS with assistance from ARS for use with WEPS. The soil database (NASIS) and the CMZ management/crop rotation files mentioned previously were developed by NRCS outside of WEPS. However, due to under-populated records, required WEPS parameters were originally not available in all soil components to be used with WEPS in the soil database. To address this problem, several directives from the NRCS National Soil Survey Center in Lincoln, NE were sent out to the state NRCS organizations informing them of the need to complete the necessary data population process prior to WEPS implementation. ARS also developed a conversion process to allow

Table 6
List of temporal surface and soil layer properties initialized and used by WEPS.

Property	Units	Can estimate initial value through interface (Yes/No)
Crust thickness	mm	Yes
Crust density	Mg m^{-3}	Yes
Crust stability	ln(J kg^{-1})	Yes
Crust fraction	m^2 m^{-2}	Yes
Loose material on crust (mass)	kg m^{-2}	Yes
Loose material on crust (cover)	m^2 m^{-2}	Yes
Random roughness	mm	Yes
Oriented (ridge) roughness direction	Degrees	Yes
Ridge height	mm	Yes
Ridge spacing	mm	Yes
Ridge width	mm	Yes
Soil dry albedo		Yes
Surface rock fragments	m^2 m^{-2}	Yes
Bedrock depth	mm	Yes
Restriction depth	mm	Yes
Layer thickness	mm	No
Bulk density (wet)	Mg m^{-3}	No
Geometric mean diameter of aggregates	mm	Yes
Geometric standard deviation of aggregates	mm	Yes
Maximum aggregate size	mm	Yes
Minimum aggregate size	mm	Yes
Aggregate density	Mg m^{-3}	Yes
Aggregate stability (dry)	ln(J kg^{-1})	Yes
Water content (initial)	mm^3 mm^{-3}	Yes
Water content (saturated)	mm^3 mm^{-3}	Yes
Water content (field capacity – 1/3 bar)	mm^3 mm^{-3}	Yes
Water content (wilting point – 15 bar)	mm^3 mm^{-3}	Yes



Years in Rotation: 1

Rotation : C:\Documents and Settings\michael.sporcic\My Documents\My WEPS Files (test)\Project.wpj\AK Summer garden (Br

Date	Operation Name	Crop or Residue	Row/Ridge Dir. (Deg.)
May 27, 01	Rototiller, field		0
May 29, 01	Rototiller, field		0
May 30, 01	Bedder, hipper, disk hiller		0
Jun 01, 01	Planting, manual	Broccoli	0
Jun 15, 01	Weed control, manual hoe		0
Jun 29, 01	Weed control, manual hoe		0
Jul 13, 01	Weed control, manual hoe		0
Aug 01, 01	Harvest, leafy veg		
Oct 01, 01	Disk, tandem light finishing		0

Fig. 4. Management/Crop Rotation Editor screen.

NRCS to transform the original RUSLE2 originated CMZ files into WEPS compatible CMZ files. This allowed NRCS to have over 25,000 template management files immediately available for use with WEPS during its implementation within their agency. A "translation file" is provided with WEPS. It describes the specific conversions required between RUSLE2 and WEPS management operation process parameters, automatically handling the majority of differences between the management rotations for the two models.

Additionally, over 300 operations presently exist for simulating tillage, harvesting, grazing, burning, irrigation, and spraying as well as manure and residue applications, and 235 different crop records were developed to simulate the growing of all major agricultural crops in the U.S., including Hawaii and Alaska. NRCS required significant technical assistance in obtaining the necessary parameters for developing operation, crop growth and decomposition records for WEPS. "How to" guides were eventually developed and added to the WEPS User Manual to assist a technical user in the process of populating new crop and operation records. Likewise, NRCS (Gary Tibke, Mike Sporcic, Dave Lightle, and Bruce Wight) populated the wind barrier database provided with WEPS 1.0 to include all typical species of plants used for wind barriers listed in the NRCS practice standards.

NRCS runs WEPS exclusively using stochastic weather files generated by the CLIGEN (Nicks et al., 1989) and WINDGEN (van Donk et al., 2005) generators. However, historical weather data can be used if in the CLIGEN and WINDGEN generator output file formats for non-NRCS releases of WEPS. The station records were expanded for CLIGEN using the Forest Service's Rock:Clime (http://forest.moscowfsl.wsu.edu/cgi-bin/fswepp/rc/rockclim.pl) web-based tool to provide additional coverage for selected agricultural cropping regions in the western U.S. (Elliot et al., 1999). Sixty-eight additional CLIGEN stations were added to the original 2658 stations that previously existed in the CLIGEN database. Climate parameters provided by CLIGEN used in WEPS are: (a) station elevation (acts as default simulation site elevation unless overrode by user); (b) observed monthly average maximum and minimum temperatures (°C), solar radiation (Langleys/day) and precipitation (mm); (c) daily precipitation amount (mm), duration of precipitation event (h), time to peak (h) and precipitation intensity (mm/h); (d) daily maximum, minimum and dewpoint temperatures (°C); and (e) daily radiation (Langleys/day). Likewise, out of an original 1051 WINDGEN wind stations, NRCS rejected over 300 stations for various reasons and had ARS assist in the creation of an additional 23 stations for under-represented regions using the North American Regional Reanalysis (NARR) data (Mesinger et al., 2006) in the western U.S. states. Figs. 5 and 6 show the spatial distribution of CLIGEN and WINDGEN stations in the continental U.S. as currently used by NRCS. WINDGEN generated parameters used in WEPS are: (a) 24 hourly wind speeds (m/s) and (b) the wind direction (degrees from North) for each day.

Originally, the WEPS interface simply selected the nearest station relative to the location selected with an option to manually override that default. However, that approach was deemed unacceptable, especially in the western states, due to the paucity of stations available and the problems associated with selecting a station across a mountain range. Thus, a polygon approach was developed that provided NRCS with the means to specify a selected station for an identified region within a GIS file. This was performed for both CLIGEN and WINDGEN in regions where this was preferred over the other station selection options. Likewise, due to the spatially limited and highly variable wind stations available, NRCS wanted to use interpolated WINDGEN station records to reduce the sometimes very sharp changes in erosive wind energy among adjacent stations. Thus, an interpolation approach was developed by Fred Fox and was applied to the eastern U.S. (east of the Rocky Mountains) for NRCS use. The granularity of the interpolation was set to the county boundary level such that the same interpolated WINDGEN station would be used for all simulations within a county.

A full GIS-compatible package was also added to the WEPS interface for users to be able to see where the CLIGEN and WINDGEN stations were located, where the polygon regions were assigned and where the interpolated WINDGEN regions exist. Additional GIS layers are also available for viewing, e.g., CMZ zones and country, state and county boundaries. Other layers can easily be added for viewing as necessary in the future. The user can also use this "Map" feature to select their simulation site location.

2.2.3. Outputs

WEPS was principally designed to address needs of the NRCS for wind erosion modeling; hence, the most common outputs were tailored to their needs, and the default Summary Erosion Report was designed primarily based upon NRCS input as to what they wanted (see Table 7). Additionally, there are individual Management Rotation, Crop Yield, and Soil Conditioning Index (SCI) reports available. A detail table report is also available; this table displays selected properties, such as the erosion rates, surface conditions, biomass status, etc., on a periodic basis for the entire rotation sequence. However, WEPS provides much more output than

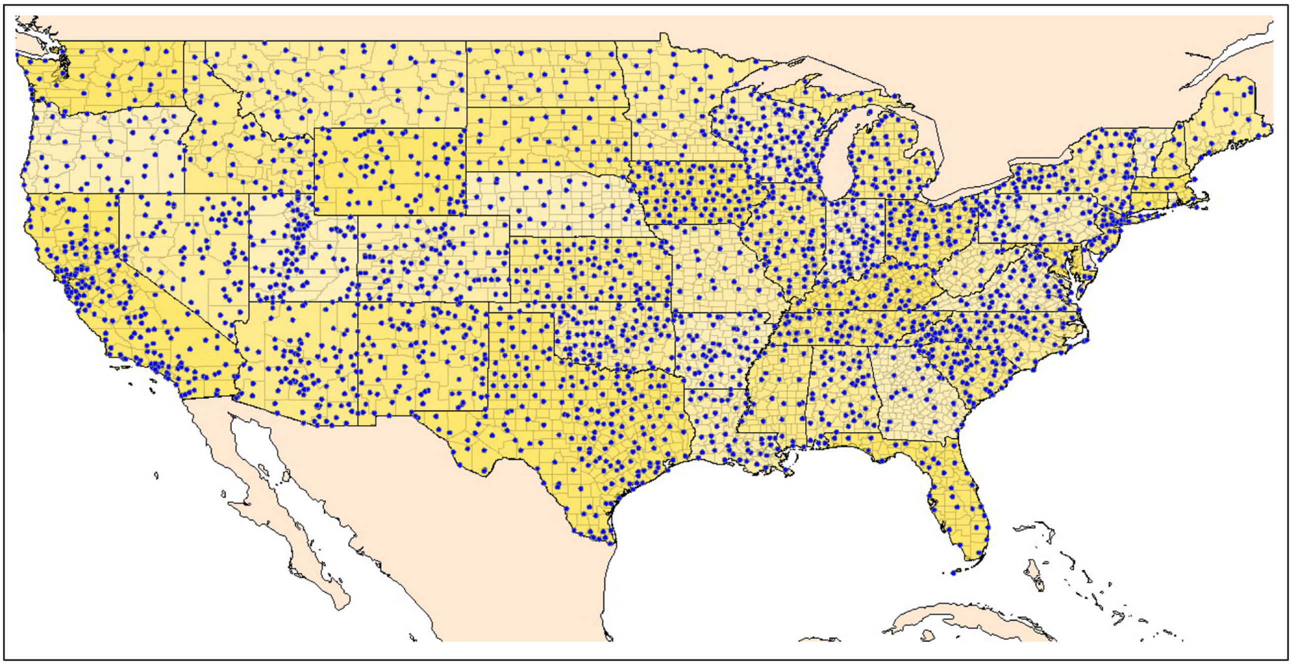


Fig. 5. Continental U.S. distribution of CLIGEN stations used by NRCS.

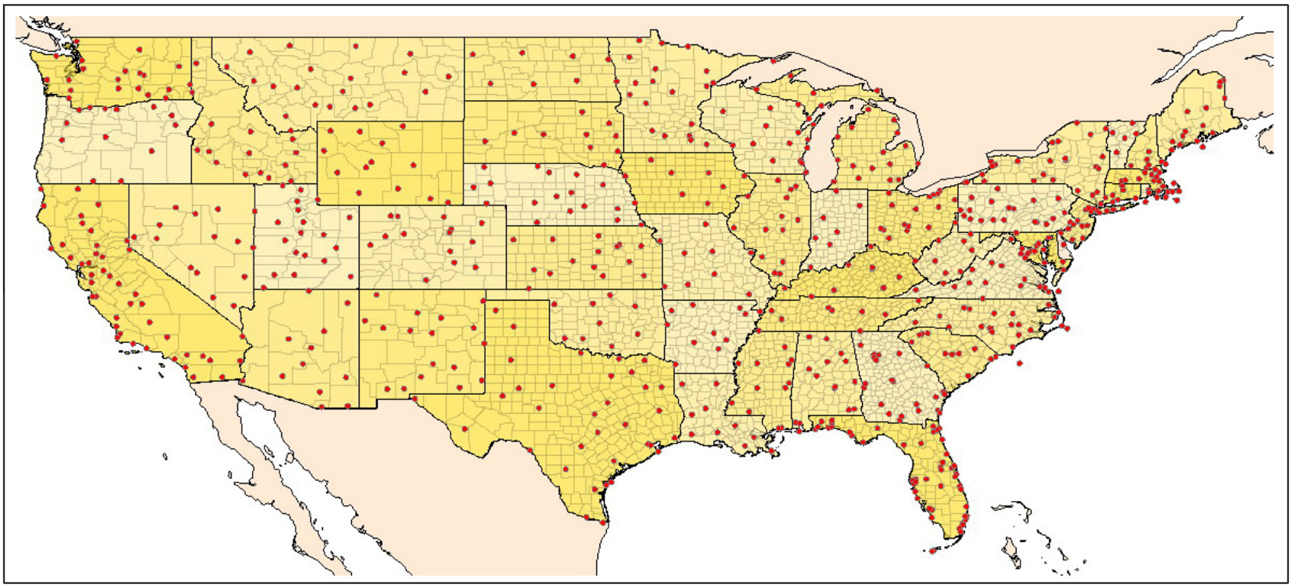


Fig. 6. Continental U.S. distribution of WINDGEN stations used by NRCS.

typical NRCS users currently make use of. For example, a confidence interval is available for the long-term annual average erosion estimate; the ability to describe the fractional areas of a simulation region under active deposition and heavy saltation/creep activity, but with little net erosion occurring (saltation/creep threshold reached); and the ability to plot individual parameters on a periodic basis over time.

3. Development issues

Some development issues have already been mentioned, e.g., database population and vetting, desire for crop yields to be related to harvest residue, etc. Some of these merit additional discussion. The runtime requirements imposed by NRCS were the biggest hurdle WEPS had to overcome. The runtime requirements eventually caused developers to incorporate an alternative hydrology submodel, which was inferior with respect to some important specific wind erosion related processes, e.g., the ability to simulate diurnal re-wetting of the surface and to allow upward migration of moisture in the soil profile, further limiting its ability to simulate surface wet/dry cycles. Additionally, the number of rotation cycles simulated was lowered to 15 cycles at one time to meet the runtime requirements; eventually, the cycle number was extended back to 50 due to improvements in computer hardware and reductions in WEPS runtime due to code modifications (WEPS inherently gives better long-term average annual erosion results when run for longer time periods due to additional cycles providing a more complete statistical sampling of the combination of the weather and wind conditions generated by CLIGEN and WINDGEN).

Due to the familiarity of NRCS users with the strong relationship between the average yield and the after-harvest residue, NRCS insisted crop yields be tied to the after-harvest residue produced. Hence, the WEPS plant growth submodel was extended to provide that feature for the majority of crops. NRCS also submitted the desire to specify an average yield prior to a WEPS run. This was accommodated by allowing a "calibration" run mode that would iteratively run WEPS first without generating any user output except the "adjustment" needed to grow the crops with the desired average yield under the specified location/climate/soil/management conditions and then running WEPS a final time with the adjustments applied to the plant growth processes to achieve the specified average yield.

Because NRCS uses RUSLE2 for predicting water erosion, they desired commonality between the elements in both WEPS and RUSLE2, where possible. Thus, especially in the representation of effects due to management (tillage) processes, effort was expended to align as many of the simulated processes as possible between the two models. Therefore, each specific physical tillage process simulated in WEPS and RUSLE2 was evaluated, and a common definition and common equations were agreed upon between the model developers to promote commonality. Likewise, the coefficients of those common equations, which were assigned to management operations, were made equal between the two models. It was not possible to make all management processes identical due to differences in the two models, but this process did help NRCS during the WEPS implementation phase.

Additionally, NRCS also requested that the Energy Calculator and the Soil Conditioning Index (SCI) be added to the model, even though neither have any direct requirement for simulations of wind erosion. Naturally, further changes to the WEPS interface were requested to "de-clutter" it and to enhance ease of use. Nearly all of these NRCS requests were addressed during the extended testing and implementation phases, held from 2005 to 2010. Fig. 7 shows a map of the U.S., listing the CMZ's WEPS testing/training sessions were conducted during that time period.

4. Future work and uses for WEPS

Several items are on the ARS and NRCS wish list for WEPS: (a) to extend WEPS to work on multiple subregions, e.g., to handle a simulation site with non-homogeneous conditions, such as different soil types and management practices on different regions of the field as well as handling strip cropping practices directly within the model; (b) to reflect the effects of terrain elevation on surface wind speed and thus on wind erosion; (c) to handle the inter-seeding of crops; (d) to natively handle organic soils, e.g., to provide a hydrology submodel to simulate water movement in non-mineral based soils and to modify erosion to account for the difference in particle densities between mineral-based and organic soils; (e) to handle complex field shapes; (f) to include an automated grid sizing and mesh system to allow for better accounting in regions with

Table 7
List of output parametsers available in the WEPS Run Summary report.

General WEPS simulation run information	WEPS Run Date
	Client Name, Farm No., Tract No., and Field No.
	The management rotation file used in the WEPS simulation
	The soil file name used in the WEPS simulation
	Location where the WEPS run is located on the computer
Simulation site information	*X*-length, *Y*-length, area, elevation and orientation
	Mode of WEPS simulation run (NRCS, cycle, dates)
	NRCS soil loss tolerance value (T/ac/yr)
	Site location country, state, county/Parish)
	Site location latitude and longitude coordinates
	CLIGEN and WINDGEN station names
Erosion output	Rotation year, total rotation and crop interval periods, each providing average annual gross loss, and the net soil loss from the field for average annual, creep/saltation, suspension and PM10 emissions (T/ac or kg/m^2)
Management rotation information	Crops grown with the harvest date, above ground residue at harves (lb/ac or kg/m^2), harvest yield (crop dependent units) and the percent moisture content the yield is reported in
Soil Conditioning Index summary	SCI, energy calculator, average annual STIR value, wind and water erosion soil loss values used in SCI calculations and the SCI subfactors
Rotation STIR (Soil Tillage Intensity Rating) Energy	The date of operation, operation name, fuel type used and STIR value computed as well as the, energy used by the operation and the cost per unit area for each operation. In addition, the total rotaton's STIR value, energy used and cost as well as the total per unit area energy used and cost
Crop Interval STIR Energy	The STIR value and per unit area energy and cost for each crop interval (defined by NRCS as the first operation following the harvest of the previous crop to when the crop itself is harvested)
Notes	Relevant information optionally provided here by WEPS and/or the user

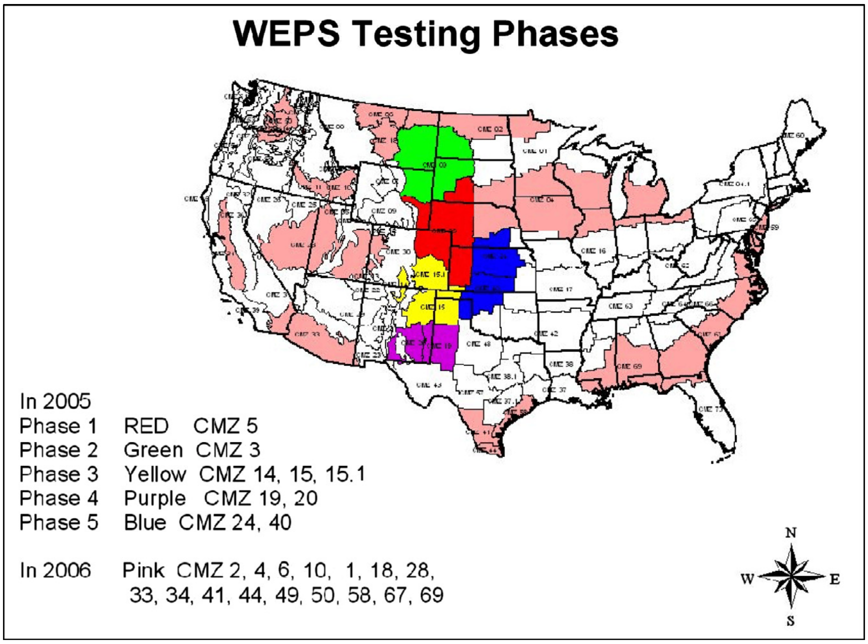


Fig. 7. NRCS WEPS testing locations by Crop Management Zone (CMZ).

wind gradients, e.g., near short barriers; and (g) to integrate wind and water erosion into the same user model (WEPS and WEPP). Work is progressing on many of these fronts with varying levels of effort. In addition to the use of WEPS on agricultural croplands by NRCS, it had originally been envisioned that WEPS would eventually be extended to cover rangelands. Recent discussions have been held regarding the unique to rangeland conditions that would require differences in their handling within WEPS. Specifically, the need to handle spatially sparse and diverse vegetative cover is required.

WEPS has also been modified and incorporated into regional air quality dispersion models. The most recent attempt is with the AIRPACT-3 model in the Pacific Northwest. Likewise, a standalone version of the WEPS wind erosion submodel has been created with a separate user interface, which has been dubbed SWEEP (Single-event Wind Erosion Evaluation Program). Even with a beta quality interface, this tool has been useful to contractors for application to construction zones and disturbed sites and for determining the respective risks of generating dust emissions. Significant potential is envisioned for SWEEP with wide appeal if the interface is revamped and better tailored to these customer-specific needs rather than to the research-oriented interface it currently employs. SWEEP can also serve as an effective teaching tool for those who want to understand the simulated erosion physics during a storm event by using its wide range of graphical outputs.

Additional research is underway at EWERU to determine the after harvest surface conditions that flat residue may leave a field under sufficient wind regimes, thus making the site far more susceptible to wind erosion afterwards. This was an NRCS identified deficiency in WEPS and the results will eventually be incorporated into WEPS. Likewise, the Department of Defense (DOD) is interested in both wind erosion generated and off-road military vehicle trafficking emissions for a variety of reasons. A study is currently being conducted to determine the impact of multiple trafficking passes on off-road trail susceptibility to wind erosion and the speed and degree of recovery following the trafficking. Again, these results are anticipated to be incorporated into WEPS in the future.

5. Summary and conclusions

As a process-based planning tool, WEPS is very good at reflecting the relative effects of various cropland management practices on the susceptibility of a site to wind erosion. WEPS requires only four inputs to make a simulation: (1) the field size, shape and orientation; (2) the soil type; (3) the management/crop rotation practice applied; and (4) the climate experienced at the site. If these inputs are available, WEPS can make a multi-year simulation run, typically in less than a minute, which will reflect the seasonal and year-to-year variability of the climate. WEPS can also provide estimates of the long-term erosion rate and can allow the user to identify when the site is most susceptible to erosion during the crop/rotation cycle. WEPS was a multi-agency, multi-discipline project that took 20 plus years to develop, refine and ultimately be employed by a user agency for use in determining erosion estimates on agricultural cropland fields. However, WEPS advanced the state of the science in wind erosion modeling during that time. Below is a list of publications related to the development, validation and application of WEPS.

Acknowledgements

Due to the total length of time necessary to develop WEPS and to implement WEPS by NRCS, the project could have easily been terminated by the ARS leaders. We thank ARS Administrators (Ed Knipling and Floyd Horn) for supporting WEPS through to completion as well as to the ARS National Program Leaders (Dick Amerman, Steve Rawlins, Mark Weltz and Charlie Walthall) for consistently supporting WEPS during its development and for helping to secure extra funding through ARS management. Thanks is also extended to the EPA for providing significant extramural funds for the necessary research to develop a PM_{10} prediction module for WEPS. Special recognition also goes to Will Blackburn (ARS Northern Plains Area Director) for his unwavering support of WEPS and for his special interest in achieving the implementation of WEPS within NRCS. This was exemplified by Will Blackburn's initial assistance in establishing the quarterly meetings with NRCS, specifically focused on addressing their WEPS concerns prior to implementation, and then in attending each of those meetings.

References

Armbrust, D., Bilbro, J., 1997. Relating plant canopy characteristics to soil transport capacity by wind. Agron. J. 89, 157–162.

Bagnold, R., 1943. The Physics of Blown Sand and Desert Dunes. William Morrow and Co., New York, NY.

Chepil, W., Woodruff, N., 1963. The physics of wind erosion and its control. Adv. Agron. 15, 211–302.

Cole, G., 1984a. A method for determining field wind erosion rates from wind tunnel-derived functions. Trans. ASAE 27 (3), 110–116.

Cole, G., 1984b. A stochastic formulation of soil erosion caused by wind. Trans. ASAE 27 (5), 1405–1410.

Cole, G., 1985. Some wind erosion process measures. Trans. ASAE 28 (4), 1108–1114, 1123.

Cole, G., Higgins, J., 1985. A probability criterion for acceptable soil erosion. Trans. ASAE 28 (6), 1921–1926.

Cole, G., Lyles, L., 1984. "The wind erosion component of EPIC". Prepared for EPIC – Erosion/Productivity Impact Calculator. USDA, ARS TEch. Bul. No. 1768, pp. 139–151.

Cole, G., Lyles, L., Hagen, L., 1983. A simulation model of daily wind erosion soil loss. Trans ASAE 26 (6), 1758–1765.

Durar, A.A., Skidmore, E.L., 1995. Hydrology Submodel. In: L.J. Hagen, L.E. Wagner, J. Tatarko (Eds.) Wind Erosion Prediction System: WEPS Technical Documentation. USDA-ARS Wind Erosion Research Unit, Manhattan, KS, pp. H1–H64. Available from: <http://www.ars.usda.gov/SP2UserFiles/Place/54300520/weps_tech.pdf> [accessed 4.10.2012].

Elliot, W.J., Scheele, D.L., Hall, D.E., 1999. Rock:Clime Rocky Mountain Research Station Stochastic Weather Generator. [Online] Available from: http://forest.moscowfsl.wsu.edu/cgi-bin/fswepp/rc/rockclim.pl [accessed 27.9.2012].

Forest Service, n.d. Rock:Clime. [Online] Available from: http://forest.moscowfsl.wsu.edu/cgi-bin/fswepp/rc/rockclim.pl [accessed 27.9.2012].

Gillette, D. et al., 1998. Relation of vertical flux of particles smaller than 10 microns to total aeolina horizontal mass flux at Owens Lake. J. Geophys. Res. 34 (4), 26009–26015.

Greeley, R., Iversen, J., 1985. Wind as a Geological Process. Cambridge University, New York.

Hagen, L., 1991a. A wind erosion prediction system to meet user needs. J. Soil Water Conserv. 46 (2), 105–111.

Hagen, L., 1991. Wind erosion: emission rates and transport capacities on rough surfaces. ASAE Paper No. 912082, St. Joseph, MI.

Hagen, L., 1996. Crop residue effects on aerondynamic processes and wind erosion. Theor. Appl. Climatol. 54, 39–46.

Hagen, L., Armbrust, D., 1994. Plant canopy effects on wind erosion saltation. Trans. ASAE 37 (2), 461–465.

Hagen, L., Skidmore, E., Saleh, A., 1992. Wind erosion: prediction of aggregate abrasion coefficients. Trans. ASAE 35 (6), 1847–1850.

Hagen, L., Wagner, L., Skidmore, E., 1999. Analytical solutions and sensitivity analysis for sediment transport in WEPS. Trans. ASAE 42 (6), 1715–1721.

Lyles, L., Tatarko, J., 1986. Wind erosion effects on soil texture and organic matter. J. Soil Water Conserv. 41 (3), 191–193.

Mesinger, F. et al., 2006. North American Regional Reanalysis. Bull. Am. Meteorol. Soc. 87 (3), 343–360.

Mirzamostafa, N., 1996. Suspension Component of Wind Erosion. s.l.: Ph.D. dissertation. Kansas State University, Manhattan, KS.

Mirzamostafa, N., Hagen, L., Stone, L., Skidmore, E., 1998. Soil aggregate and texture effects on suspension components from wind erosion. Soil Sci. Soc. Am. J. 62 (5), 1351–1361.

Nicks, A., Lane, L.J., Gander, G.A., 1989. Weather Generator. In: USDA-Water Erosion Prediction Project: Hillslope Profile Model Documentation. West Lafayette (IN 47907): NSERL Report No. 2, USDAJ-ARS, National Soil Erosion Research Laboratory, pp. 2.1–2.22.

NRCS, n.d. Soil Survey Geographic (SSURGO) Database. [Online] Available from: <http://soildatamart.nrcs.usda.gov>[accessed 27.9.2012].

Rawls, W., 1983. Estimating soil bulk density from particle size analysis and organic matter content. Soil Sci. 134 (2), 123–125.

Retta, A., Armbrust, D.V., 1995. Crop Submodel. In: L.J. Hagen, L.E. Wagner, J. Tatarko (Eds.), Wind Erosion Prediction System: WEPS Technical Documentation. USDA-ARS Wind Erosion Research Unit, Manhattan, KS, pp. C1–C16. Available from: <http://www.ars.usda.gov/SP2UserFiles/Place/54300520/weps_tech.pdf> [accessed 4.10.2012].

Saleh, A., Fryrear, D., 1995. Threshold wind velocities of wet soils as affected by wind blown sand. Soil Sci. 160 (4), 304–309.

Savabi, M.R., Skaggs, R.W., Onstad, C.A., 1995. Chapter 6, Subsurface Hydrology. In: D.C. Flanagan, M.A. Nearing (Eds.) USDA Water Erosion Prediction Project (WEPP) Hillslope Profile and Watershed Model Documentation. s.l.: NSERL Report No. 10, National Soil Erosion Research Laboratory, USDA Agricultural Research Service, West Lafayette, Indiana, pp. 6.1–6.14.

Schomberg, H.H., Steiner, J.L., Evett, S.R., Moulin, A.P., 1996. Climatic influence on residue decomposition prediction in the Wind Erosion Prediction System. Theor. Appl. Climatol. 54, 5–16.

Sharpley, A., Williams, J., 1990. EPIC–Erosion/Productivity Impact Calculator: 1. Model Documentation. USDA Technical Bulletin No. 1768, 235pp.

Skidmore, E., 1976. A wind erosion equation: development, application, and limitations. In: ERDA Symp. Series 38, Atmosphere–Surface Exchange of Particulate and Gaseous Pollutants, pp. 452–465.

Steiner, J.L., Schomberg, H.H., Douglas, J.C.L., Black, A.L., 1994. Standing stem persistence in no-tillage small-grain fields. Agron. J. 86, 76–81.

Tatarko, J., Sporcic, M., Skidmore, E. L., (2013). A history of Wind Erosion Prediction Models in the United States Department of Agriculture Prior to the Wind Erosion Prediction System. Aeol. Res. J. 10, 9–24.

U.S. Gov., 2010. Federal Register 75(234), pp. 75961–75962 [Online] Available from: <https://federalregister.gov/a/2010-30673> [accessed 4.10.2012].

van Donk, S.J., Wagner, L.E., Skidmore, E.L., Tatarko, J., 2005. Comparison of the Weibull Model with measured wind speed distributions for stochastic wind generation. Trans. ASABE 48 (2), 503–510.

Wagner, L.E., 2011. Overview of the management submodel in the wind erosion prediction system. In: s.l., International Symposium on Erosion and Landscape Evolution, 18–21 Sep., Anchorage, AK, ISELE Paper No. 11032, ASABE, St. Joseph, MI.

Wagner, L.E., Ding, D.J., 1994. Representing aggregate size distributions as modified lognormal distributions. Trans. ASAE 37 (3), 815–821.

Woodruff, N., Siddoway, F., 1965. A wind erosion equation. Soil Sci. Soc. Am. Proc. 29 (5), 602–608.

Zobeck, T., Popham, T., 1991. Influence of abrader flux and soil properties. Soil Sci. Am. J. 55 (4), 1091–1097.

List of WEPS related publications

Applications and validations of WEPS and the literature used to develop WEPS

Buschiazzo, D.E., Zobeck, T.M., 2008. Validation of WEQ, RWEQ and WEPS wind erosion for different arable land management systems in the Argentinean Pampas. Earth Surface Processes and Landforms 33, 1839–1850.

Coen, G.M., Tatarko, J., Martin, T.C., Cannon, K.R., Goddard, T.W., Sweetland, N.J., 2004. A method for using WEPS to map wind erosion risk of Alberta soils. Environmental Modelling and Software 19 (2), 185–189.

Diaz, E.N., Tatarko, J., Jazcilevich, A.D., Garcia, A.R., Caetano, E., Ruiz-Suarez, L.G., 2010. A modeling study of Aeolian erosion enhanced by surface wind confluences over Mexico City. Aeolian Research 2, 143–157. http://dx.doi.org/10.1016/j.aeolia.2010.04.004.

Feng, G., Sharratt, B.S., 2007. Validation of WEPS for soil and PM10 loss from agricultural fields on the Columbia Plateau of the United States. Earth Surface Processes and Landforms 32, 743–753.

Feng, G., Sharratt, B.S., 2009. Evaluation of the SWEEP model during high winds on the Columbia Plateau. Earth Surface Processes and Landforms 34, 1461–1468.

Fryrear, D.W., Stout, J.E., Hagen, L.J., Vories, E.D., 1991. Wind erosion: field measurement and analysis. Trans. ASAE 34 (1), 155–160.

Funk, R., Skidmore, E.L., Hagen, L.J., 2004. Comparison of wind erosion measurements in Germany with simulated soil losses by WEPS. Environmental Modeling and Software 19 (2), 177–183.

Hagen, L.J., 2004. Evaluation of the Wind Erosion Prediction System (WEPS) erosion submodel on cropland fields. Environmental Modeling and Software 19 (2), 171–176.

Hagen, L.J., Schroeder, P.R., Thai, L., 2009. Estimated particle emissions by wind erosion from the Indiana Harbor Combined Disposal Facility. Pract. Periodical Hazard. Toxic, Radioactive Waste Mgmt. 13 (1), 20–28.

Hagen, L.J., Van Pelt, R.S., Sharratt, B.S., 2010. Estimating the saltation and suspension components from field wind erosion. Aeolian Research 1, 147–153.

Stetler, L.D., Saxton, K.E., 1996. Wind Erosion and PM10 emissions from agricultural fields on the Columbia Plateau. Earth Surface Processes and Landforms 21, 673–685.

van Donk, S.J., Huang, Xuewen, Skidmore, E.L., Anderson, A.B., Gebhart, D.L., Prehoda, V.E., Kellogg, E.M., 2003. Wind erosion from military training lands in the Mojave Desert, California, USA. Journal of Arid Environments 54 (4), 687–703.

van Donk, S.J., Skidmore, E.L., 2003. Measurement and simulation of wind erosion, roughness degradation and residue decomposition on an agricultural field. Earth Surface Processes and Landforms 28 (11), 1243–1258.

Weather Generators/Databases

Hagen, L.J., 2007. Ratios of erosive wind energies on dry days and all days in the western United States. Trans. ASABE 50 (6), 1981–1986.

Skidmore, E.L., Tatarko, J., 1990. Stochastic wind simulation for erosion modeling. Trans. ASAE 33 (6), 1893–1899.

van Donk, S.J., Liao, C., Skidmore, E.L., 2008. Using temporally limited wind data in the Wind Erosion Prediction System. Trans. ASAE. 51 (5), 1585–1590.

van Donk, S.J., Wagner, L.E., Skidmore, E.L., Tatarko, J., 2005. Comparison of the Weibull Model with measured wind speed distributions for stochastic wind generation. Trans. ASAE 48 (2), 503–510.

Hydrology submodel

Durar, A.A. 1991. Simulation of soil-water dynamics for wind erosion modeling, Ph.D. Diss. Kansas State Univ., Manhattan, KS (Diss. Abstr. 91–28491).

Durar, A.A., Steiner, J.L., Evett, S.R., Skidmore, E.L., 1995. Measured and simulated surface soil drying. Agron. J. 87 (2), 235–244.

Saxton, K.E., Rawls, W.J., 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70, 1569–1578.

Soil submodel

Fryrear, D.W., Krammes, C.A., Williamson, D.L., Zobeck, T.M., 1994. Computing the wind erodible fraction of soils. J. Soil Water Conserv. 49 (2), 183–188.

Hagen, L.J., Schroeder, B., Skidmore, E.L., 1995. A vertical soil crushing-energy meter. Trans. ASAE 38 (3), 711–715.

Hagen, L.J., Skidmore, E.L., Fryrear, D.W., 1987. Using two sieves to characterize dry soil aggregate size distribution. Trans. ASAE 30 (1), 162–165.

Kohake, D.J., 2003. Wind erodibility of organic soils. M.S. Thesis. Kansas State University, Manhattan.

Kohake, D.J., Hagen, L.J., Skidmore, E.L., 2010. Wind erodibility of organic soils. Soil Sci. Soc. Am. J. 74 (1), 250–257.

Layton, J.B., Skidmore, E.L., Thompson, C.A., 1994. Winter-associated changes in dry-soil aggregation as influenced by management. Soil Sci. Soc. Am. J. 57, 1568–1572.

Lyles, L., Tatarko, J., 1987. Precipitation effects on ridges created by grain drills. J. Soil Water Conserv. 42 (4), 269–271.

Lyles, L., Tatarko, J., 1988. Soil wind erodibility index in seven north central states. Trans. ASAE 31 (5), 1396–1399.

Potter, K.N., 1990a. Estimating wind-erodible materials on newly crusted soils. Soil Sci. 150 (5), 771–776.

Potter, K.N., 1990b. Soil properties' effect on random roughness decay by rainfall. Trans. ASAE 33 (6), 1889–1892.

Potter, K.N., Zobeck, T.M., 1990. Estimation of soil microrelief. Trans. ASAE 33 (1), 156–161.

Potter, K.N., Zobeck, T.M., Hagen, L.J., 1990. A microrelief index to estimate soil erodibility by wind. Trans. ASAE 33 (1), 151–155.

Saleh, A., 1993a. Soil aggregate and crust density prediction. Soil Sci. Soc. Am. J. 57, 524–526.

Saleh, A., 1993b. Soil roughness measurement: chain method. J. Soil Water Conserv. 48 (6), 527–529.

Saleh, A., 1994. Measuring and predicting ridge orientation effect on soil surface roughness. Soil Sci. Am. J. 58 (4), 1228–1230.

Skidmore, E.L., Layton, J.B., 1992. Dry soil-aggregate stability as influenced by selected soil properties. Soil Sci. Soc. Am. J. 56, 557–561.

Tatarko, J., 2001. Soil aggregation and wind erosion: processes and measurements. Ann. Arid Zone 40 (3), 251–263.

Wagner, L.E., Ding, D.J., 1994. Representing aggregate size distributions as modified lognormal distributions. Trans. ASAE 37 (3), 815–821.

Wagner, L.E., Yu, Y., 1991. Digitization of profile meter photographs. Trans. ASAE 34 (2), 412–416.

Zobeck, T.M., 1989. Fast-Vac – a vacuum system to rapidly sample loose granular material. Trans. ASAE 32 (4), 1316–1318.

Zobeck, T.M., 1991a. Abrasion of crusted soils: Influence of abrader flux and soil properties. Soil Sci. Soc. Am. J. 55 (4), 1091–1097.

Zobeck, T.M., 1991b. Soil properties affecting wind erosion. J. Soil Water Conserv. 46 (2), 112–118.

Zobeck, T.M., Fryrear, D.W., 1986a. Chemical and physical characteristics of windblown sediment, I. Quantities and physical characteristics. Trans. ASAE 29 (4), 1032–1036.

Zobeck, T.M., Fryrear, D.W., 1986b. Chemical and physical characteristics of windblown sediment, II. Chemical characteristics and total soil and nutrient discharge. Trans. ASAE 29 (4), 1037–1041.

Zobeck, T.M., Popham, T.W., 1990. Dry aggregate size distribution of sandy soils as influenced by tillage and precipitation. Soil Sci. Soc. Am. J. 54 (1), 197–204.

Zobeck, T.M., Popham, T.W., 1991. Influence of abrader flux and soil properties. Soil Sci. Soc. Am. J. 55 (4), 1091–1097.

Zobeck, T.M., Popham, T.W., 1992. Influence of microrelief, aggregate size, and precipitation on soil crust properties. Trans. ASAE 35 (2), 487–492.

Zobeck, T.M., Popham, T.W., Skidmore, E.L., Lamb, J.A., Merrill, S.D., Lindstrom, M.J., Mokma, D.L., Yoder, R.E., 2003. Aggregate-mean diameter and wind-erodible soil predictions using dry aggregate-size distributions. Soil Sci. Soc. Am. J. 67, 425–436.

Plant Growth Submodel

Armbrust, D.V., 1990. Rapid measurement of crop canopy cover. Agron. J. 82, 1170–1171.

Armbrust, D.V., Bilbro, J.D., 1993. Predicting grain sorghum canopy structure for soil erosion modeling. Agron. J. 85 (3), 664–668.

Armbrust, D.V., Bilbro Jr., J.D., 1997. Relating plant canopy characteristics to soil transport capacity by wind. Agron. J. 89, 157–162.

Ambrust, D.V., Retta, A., 2000. Wind sandblast damage to growing vegetation. Ann. Arid Zone 39 (3), 273–284.

Bilbro, J.D., 1991. Relationships of cotton dry matter production and plant structural characteristics for wind erosion modeling. J. Soil Water Conserv. 46 (5), 381–384.

Bilbro, J.D., 1992. Sunflower dry matter production and plant structural relationships for wind erosion modeling. J. Soil Water Conserv. 47 (2), 194–197.

Bilbro, J.D., Fryrear, D.W., 1988. Annual herbaceous windbarriers for protecting crops and soils and managing snowfall. Agric. Ecosyst. Environ. 22/23, 149–161.

Bilbro, J.D., Fryrear, D.W., 1991. Pearl millet versus gin trash mulches for increasing soil water and cotton yields in a semiarid region. J. Soil Water Conserv. 46 (1), 66–69.

Bilbro, J.D., Fryrear, D.W., 1994. Wind erosion losses as related to plant silhouette and soil cover. Agron. J. 86 (3), 550–553.

Bilbro, J.D., Undersander, J.D., Fryrear, D.W., Lester, C.M., 1991. A survey of lignin, cellulose, and acid detergent fiber ash contents of several plants and implications for wind erosion control. J. Soil Water Conserv. 46 (4), 314–316.

Hagen, L.J., 1996. Crop residue effects on aerodynamic processes and wind erosion. Theor. Appl. Climatol. 54, 39–46.

Hagen, L.J., Armbrust, D.V., 1994. Plant canopy effects on wind erosion saltation. Trans. ASAE 37 (2), 461–465.

Retta, A., Armbrust, D.V., 1995. Estimation of leaf and stem area in the Wind Erosion Prediction System (WEPS). Agron. J. 87, 93–98.

Retta, A., Armbrust, D.V., Hagen, L.J., 1996. Partitioning biomass in the crop submodel of WEPS (Wind Erosion Prediction System). Trans. ASAE 39 (1), 145–151.

Retta, A., Armbrust, D.V., Hagen, L.J., Skidmore, E.L., 2000. Leaf and stem area relationships to masses and their height distributions in native grasses. Agron. J. 92 (2), 225–230.

Skidmore, E.L., Nelson, R.G., 1992. Small-grain equivalent of mixed vegetation for wind erosion control and prediction. Agron. J. 83 (1), 98–101.

van de Ven, T.A.M., Fryrear, D.W., Span, W.P., 1989. Vegetation characteristics and soil loss by wind. J. Soil Water Conserv. 44, 347–349.

Decomposition Submodel

Schomberg, H.H., Steiner, J.L., Evett, S.R., Moulin, A.P., 1996. Climatic influence on residue decomposition prediction in the Wind Erosion Prediction System. Theor. Appl. Climatol. 54, 5–16.

Schomberg, H.H., Steiner, J.L., Unger, P.W., 1994. Decomposition and nitrogen dynamics of crop residues: residue quality and water effects. Soil Sci. Soc. Am. J. 58, 372–381.

Steiner, J.L., Schomberg, H.H., Douglas Jr., C.L., Black, A.L., 1994. Standing stem persistence in no-tillage small-grain fields. Agron. J. 86, 76–81.

van Donk, S.J., Merrill, S.D., Yanaka, D.L., Krupinsky, J.M., 2008. Crop residue in North Dakota: measured and simulated by the Wind Erosion Prediction System. Trans. ASAE 51 (5), 1623–1632.

Management Submodel

Hagen, L.J., 1999. Development of a tillage system to prevent soil pulverization and wind erosion. In: Scientific Papers of the Agricultural University of Poznan, vol. 1. Poland, pp. 15–57.

Unger, P., Skidmore, E.L., 1994. Conservation tillage in the southern Great Plains. In: R.M. Carter (Ed.), Conservation Tillage in Temperate Agroecosystems, (Chapter 14). Lewis Publishers, Boca Raton, FL, pp. 329–356

Wagner, L.E., Ambe, N.M., Barnes, P., 1992. Tillage-induced soil aggregate status as influenced by water content. Trans. ASAE 35 (2), 499–504.

Wagner, L.E., Ambe, N.M., Ding, D.J., 1994. Estimating a proctor density curve from intrinsic soil properties. Trans. ASAE 37 (3), 1121–1125.

Wagner, L.E., Ding, D.J., 1993. Stochastic modeling of tillage-induced aggregate breakage. Trans. ASAE 36 (4), 1087–1092.

Wagner, L.E., Nelson, R.G., 1995. Mass reduction of standing and flat residues by selected tillage implements. Trans. ASAE 38 (2), 419–427.

Erosion Submodel

Fryrear, D.W., 1986. A field dust sampler. J. Soil Water Conserv. 41 (2), 117–120.

Fryrear, D.W., 1987. Ridging reduces wind damage to cotton. Appl. Agric. Res. 1 (5), 311–314.

Fryrear, D.W., 1992. Measured wind erosion of agricultural lands. A&WMA Trans Series 22 (1), 433–439, ISSN 1040-8177.

Fryrear, D.W., Saleh, A., 1993. Field wind erosion: vertical distribution. Soil Sci. 155 (4), 294–300.

Hagen, L.J., 1991a. A Wind Erosion Prediction System to meet user needs. J. Soil Water Conserv. 46 (2), 106–111.

Hagen, L.J., 1991b. Wind erosion mechanics: abrasion of aggregated soil. Trans. ASAE 34 (4), 831–837.

Hagen, L.J., 2001. Processes of soil erosion by wind. Ann. Arid Zone 40 (3), 233–250.

Hagen, L.J., 2004. Fine particulates (PM10 and PM2.5) generated by breakage of mobile aggregates during simulated wind erosion. Trans. ASABE 47 (1), 108–112.

Hagen, L.J., 2008. Updating soil surface conditions during wind erosion events using the Wind Erosion Prediction System (WEPS). Trans. ASABE 51 (1), 129–137.

Hagen, L.J., Armbrust, D.V., 1992. Aerodymanic roughness and saltation trapping efficiency of tillage ridges. Trans. ASAE 35 (4), 1179–1184.

Hagen, L.J., Skidmore, E.L., Layton, J.B., 1988. Wind erosion abrasion: effects of aggregate moisture. Trans. ASAE 31 (3), 725–728.

Hagen, L.J., Skidmore, E.L., Saleh, A., 1992. Wind erosion: predictions of aggregate abrasion coefficients. Trans. ASAE 35 (6), 1847–1850.

Hagen, L.J., van Pelt, S., Zobeck, T.M., Retta, A., 2007. Dust deposition near an eroding source field. Earth Surf. Process. Landf. 32 (2), 281–289.

Hagen, L.J., Wagner, L.E., Skidmore, E.L., 1999. Analytical solutions and sensitivity analyses for sediment transport in WEPS. Trans. Am. Soc. Agric. Eng. 42 (6), 1715–1721.

Larney, F.J., Bullock, M.S., McGinn, S.M., Fryrear, D.W., 1995. Quantifying wind erosion on summer fallow in southern Alberta. J. Soil Water Conserv. 50 (1), 91–95.

Mirzamostafa, N., 1998. Soil aggregate and texture effects on suspension components from wind erosion. Soil Sci. Soc. Am. J. 62, 1351–1361.

Skidmore, E.L., 1994a. Wind erosion. In: Lal, R. (Ed.), Soil Erosion Research Methods, 2nd ed. Soil and Water Cons. Soc, Ankeny, IA, pp. 265–293.

Skidmore, E.L., Hagen, L.J., Armbrust, D.V., Durar, A.A., Fryrear, D.W., Potter, K.N., Wagner, L.E., Zobeck, T.M., 1994b. Methods for investigating basic processes and conditions affecting wind erosion. In: Lal, R. (Ed.), Soil Erosion Research Methods, 2nd ed. Soil and Water Cons. Soc, Ankeny, IA, pp. 295–330.

Stout, J., 1990. Wind erosion within a simple field. Trans. ASAE 33 (5), 1597–1600.

Stout, J.E., Fryrear, D.W., 1989. Performance of a windblown-particle sampler. Trans. ASAE 32 (6), 2041–2045.

van Donk, S.J., Skidmore, E.L., 2001. Field experiments for evaluating wind erosion models. Ann. Arid Zone 40 (3), 281–302.

Vigiak, O., Sterk, G., Warren, A., Hagen, L.J., 2003. Spatial modeling of wind speed around windbreaks. Catena 52 (3–4), 273–288.

Vories, E.D., Fryrear, D.W., 1991. Vertical distribution of wind-eroded soil over a smooth, bare field. Trans. ASAE 34 (4), 1763–1768.

Zobeck, T.M., Onstad, C.A., 1987. Tillage and rainfall effects on random roughness: A review. Soil Tillage Res. 9, 1–20.