ENVIRON

MEMORANDUM

To: WRAP Dust Emission Joint Forum

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Subject: Recommendations for the Phase II Windblown Fugitive Dust Emission Project

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Introduction

The Phase I WRAP windblown fugitive dust project methodology and results have been documented in a project Final Report (ENVIRON, 2004) and Technical Memoranda (Mansell, 2003a; 2003b). The results of the initial model runs and subsequent sensitivity simulations have demonstrated a need to revise and/or update various assumptions associated with the development of the emission inventory. To this end, revised estimation methodologies and algorithms are being evaluated in order to address various shortcomings and limitations of the current version of the model. Many of the assumptions employed in the Phase I methodology are related to a lack of detail in the underlying data used to characterize vacant land types and soil conditions. In addition, the current methodology relies on arbitrarily assigned threshold friction velocities and dust reservoir characteristics.

Various approaches for refining and enhancing the existing version of the windblown dust model were presented and discussed at a recent WRAP Dust Emissions Joint Forum (DEJF) meeting held in Las Vegas, NV. These refinements were mainly focused on improving the determination of surface friction velocities and threshold friction velocities, as well as the calculation of dust emission fluxes. The characterization of the disturbance level of vacant land parcels was also to be considered. Land use datasets to more accurately characterize vacant lands were also to be identified and evaluated for use in Phase II of the Wind Blown Dust project. In addition, a number of studies were identified for review. The algorithms and methodologies used in these studies will be considered for incorporation into the revised wind blown dust model.

This memorandum summarizes the methodologies and various assumptions used in the current dust model, including certain shortcomings of the methods and data sources utilized. Recently published studies are identified and summarized with respect to the algorithms and physical parameters considered. The performance of each of these dust models is also summarized and discussed. Finally, recommendations are presented which seek to incorporate various aspects of these studies into a revised wind blown dust model, as well as to address the numerous assumptions required for implementation of the Phase I dust model.

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Summary of Phase I Methodology

The development of the Phase I Wind Blown Dust model and implementation, including various assumptions incorporated in the estimation methodology, has been documented previously (ENVIRON, 2004; 2003a; 2003b; Mansell, 2003a; 2003b). In summary, the method relies on the characterization of vacant land types and soil conditions, and numerous assumptions regarding dust reservoir characteristics. Wind erosion is initiated in the model based on an arbitrary wind speed assignment, independent of surface conditions. Emission factors, or dust fluxes, were derived from limited wind tunnel study results as a function of wind speed and soil texture. Adjustments were applied to the resulting emission rates based on vegetation density of vacant land parcels. Surface disturbance levels were based on land use types. In addition, adjustments were applied for agricultural lands based on non-climatic factors. Land use characterization was based on the Biogenic Emission Landuse Database (BELD3); soil texture was derived from the State Soil Geographic Database (STATSGO).

Given the lack of detail in the data sets used for characterizing the physical conditions of land parcels and soils a number of assumptions were employed in the methodology. These assumptions were presented and discussed in detail by Mansell (2003b) and can be summarized as follows:

- Threshold wind velocities: The threshold wind velocity is assumed to be 20 mph, independent of land use and soil texture.
- Vacant land stability: The methodology developed relies on the specification of stability of vacant land parcels. The stability characteristics of land parcels are based solely on the land use type.
- Urban land characterization: The stability of vacant urban lands is assumed to be dependent on the percentage of the urban areas considered to be urban core versus urban boundary area. The percentages of the core versus boundary urban areas are assumed constant across the modeling domain.
- Dust Reservoirs: The reservoir properties of vacant land parcels determine the duration of dust events. Limited reservoirs will emit dust for a shorter duration of time than unlimited reservoirs. Reservoir properties are based on the stability characteristics of vacant land parcels.
- Reservoir Depletion and Recharge Times: Assumptions are made concerning the amount of time a reservoir will emit wind blown dust. Also assumed are the reservoir recharge intervals.
- Rain, Snow and Freeze Events: Assumptions are included which determine time intervals after which land parcels will emit dust following precipitation, snow and freeze events. These assumptions greatly impact the number of wind events treated in the methodology as well as the total dust emissions generated.
- Vegetation Density: The percentage of vegetative, or canopy, cover is determined by the

general land use category of vacant land parcels. These percentages are constant for a given land type. Estimated emission factors, or emission rates, are attenuated based on the assumed canopy cover percentage.

These various assumptions have a number of implications with respect to the estimation of fugitive dust from wind erosion. However, in many cases, the data necessary to address these issues on a regional scale domain are lacking. Specifically, the issues and implications identified from the Phase I project work can be summarized as follows:

- Threshold wind velocities:
    - Threshold velocities should be related to the physical properties of the land parcels, particular surface roughness lengths and soil characteristics. Threshold friction velocities can be related to aerodynamic surface roughness lengths.
    - A constant threshold velocity of 20 mph may be too restrictive, suppressing possible dust emissions.

- Vacant land stability:
    - The stability characteristics of land parcels are based solely on the land use type.
    - Dust emission rates can vary considerably for stable versus unstable lands.
    - Stability is related to the soil textures and other physical parameters.
    - Vegetation density, or canopy cover percentages of vacant lands need to be considered in the determination of vacant land stability.
    - More detailed and current land use and soils data need to be obtained to more accurately characterize the stability of vacant lands.

- Urban land characterization:
    - The contribution of wind blown dust from urban lands is considerably less than for other land types and is not a significant fraction of the overall inventory. Improvements for this land category are best postponed until better data can be collected and other more significant issues are addressed.

- Dust Reservoirs:
    - The assumptions regarding reservoir properties are based on the stability characteristics of vacant land parcels.
    - Stable land parcels are assumed to have limited reservoirs
    - Unstable land parcels are assumed to have unlimited reservoirs.
    - The determination of reservoir properties should be related to the actual amount and properties of the soils present.
    - The determination of soil layer depths and other soil properties (e.g. soil moisture), are limited by the available data used to characterize soils.

- Reservoir Depletion and Recharge Times:
    - It is assumed that a limited reservoir will emit for only the first hour of a wind event while unlimited reservoirs are assumed to emit for only 10 hours during a wind event.
    - Wind events must be separated by at least 24 hours.

  - These assumptions limit the amount of dust emission from wind erosion. The time during which any reservoir, limited or unlimited, can emit dust due to wind erosion is more appropriately determined from detailed information concerning the depth of surface soil layers, other soil properties and land use characteristics. In addition, there should be a relationship between the magnitude of the winds and the time required to deplete a dust reservoir.
  - Limited reservoirs may not be depleted within 1 hour while unlimited reservoirs may be depleted in less than 10 hours. Relaxing these assumptions could result in more realistic estimates of windblown dust emissions from the methodology.
  - A reservoir may require less than 24 hours to recharge allowing additional wind events to be initiated.

- Rain, Snow and Freeze Events:
  - The current methodology assumed that a 72-hour interval is required after rain events and ice/snow cover melt, prior to initiating wind erosion.
  - After a freeze period, a land parcel will emit dust again after 12 hours.
  - These assumptions concerning the reservoir recharge times should be more appropriately determined through consideration of soil characteristics such a soil moisture and available water capacity. Incorporation of these parameters in the methodology would involve additional research into developing relationships between soil properties and recharge times, as well as developing more detailed datasets for soils and land use.

- Vegetation Density:
  - Within the current methodology, emission factors, or emission rates, are reduced by a certain amount in order to account for the effects of vegetative cover of vacant lands on dust emission rates. These reduction factors were derived from limited wind tunnel tests for varying wind speeds and percent vegetative cover.
  - Vegetation density information was developed from Federal Geographic Data Committee documentation concerning general characteristics of various land use types. Due to the limitation of the data used for the project, as well as resource constraints, no spatial variation in the vegetation density of a particular land type across the domain was considered.
  - Vegetative density can vary considerable for the same land type across different regions and can have a significant impact on the predicted dust emissions.
  - Vegetation density more appropriately impacts the threshold surface friction velocity required to initiate wind erosion. These issues should be considered for the revised dust model.
  - Improvements to determination of vegetation density as a function of land use and soil characteristics could be made based on more detailed datasets

As part of the Phase II Wind blown Dust project, these assumptions and limitations will be reviewed in an attempt to improve upon the overall estimation methodologies.

Review of Recent Literature

A number of wind blown dust studies have recently been identified in the literature. In this section, these studies are identified and summarized with respect to the algorithms and physical parameters considered. Also discussed are the MacDougall, as implemented for the Phase I Dust Study, as well as Project Team's recommended approach. These studies are compared with each other and summarized with respect to improving the model application for the Phase II Dust Study.

Recent Dust Emission Models

Draxler, et al, 2001 constructed their regional model for estimating PM10 from wind blown dust using the concept of threshold friction velocity which dependent on aerodynamic roughness length of surface Z_o. PM10 vertical mass flux was calculated using Marticorena, et al. 1997 algorithm. The flux is a function of wind velocity, threshold wind velocity, and a coefficient that relates the surface soil texture to PM10 emissions. Emissions start when the friction velocity is greater than the threshold friction velocity at that height. Friction velocity was calculated as a function of the aerodynamics roughness length.

Threshold friction velocity was calculated as the ratio of the threshold velocity for smooth surface (U_{*ts}) to f_{eff} the efficient friction velocity. f_{eff} is defined by Marticorena and Bergamette (1995) as the ratio of friction velocity for a smooth surface to actual friction velocity. To determine this ration, the aerodynamic roughness length for smooth surface (Z_{os}), which defined as the mean soil particle diameter (D_p) divided by 30 (Greeley and Iversen, 1985), and the actual aerodynamic roughness length. Soil samples were collected from the modeled area to determine D_p. Z_{os} was calculated using the measured D_p. Using a mean value of 22 cm/s for U_{*ts} , the actual threshold friction velocity was calculated for different values of aerodynamics roughness lengths.

Using images of the area, a map of surface conditions and geomorphology, the u_{*t} data from the Mojave desert (Gillette, et al., 1980, 1982) they estimated the estimated the threshold friction velocity and surface roughness length for each surface classification. The coefficient that relates the surface soil texture to PM10 emissions was estimated using data for several soils of semi arid areas (Gillette et al., 1997) showing the ratio of vertical flux of PM10 to total horizontal mass flux as function of friction velocity.

In their work, Draxler, et. al, 2001 considered a special case of wind blown dust. Land with vegetative cover has a relatively high threshold velocity and was not considered as emission source. Two types of soil surface conditions were considered, loose undisturbed soil and disturbed soil. All the area was considered as dry and therefore the effect of rain and snow was not considered.

Zender, et al., 2003 developed a Dust Entrainment And Deposition (DEAD) model for studying dust related processes at both local and global scales. They considered three major factors that affect the dust flux: wind friction velocity, vegetation cover and surface soil moisture content. The approach developed by Marticorena and Bergamette (1995) was used to develop the model. For computing the threshold friction velocity they used semi-empirical equation developed by Iversen and White (1982). In this equation, the friction velocity is a function of soil density and particle size, and air density and kinematic viscosity. The surface roughness length was a constant value of 0.01 cm for the entire domain.

The change in threshold friction velocity was calculated using equation developed by Marticorena and Bergamette (1995), as Draxler et. al, 2001 did in their model. Zender used one global value of 0.0033 cm for the roughness length for smooth surface. The effect of moisture content of the surface soil was considered in Zender model. A threshold moisture content was calculated as function of the mass fraction of clay and it was adopted from Fécan et al., 1999. Land covered by vegetation was not considered as dust emitting source.

The vertical mass flux was calculated as a function of the horizontal mass flux, a global tuning factor, source erodibility factor, fraction of bare soil, fraction of clay mass. The horizontal mass flux was calculated as function of friction velocity and threshold friction velocity.

Shao 2001, developed an emission flux model as function of the horizontal mass flux, threshold friction velocity and an empirical function of the diameters of saltating and emitted particles. At his work, Shao emphasized the micro scale and forces working on saltating particles and the impact of these particles on dust emissions. In this model a particle size distribution of the soil is required.

ENVIRON/RMC

The ENVIRON/RMC model refers to the estimation methodology proposed by the Phase I Fugitive Wind Blown Dust project team and documented in ENIVRON, 2003a. Based on a review of wind tunnel studies it was noted that the two important components to characterize the dust emission process from a erodible surface are the threshold friction velocity that defines the inception of the emission process as a function of the wind speed and as influenced by the surface characteristics, and the strength of the emissions that follow the commencement of particle movement. The two critical factors affecting emission strength are wind speed (wind friction velocity) that drives the saltation system, and the soil characteristics.

Threshold Friction Velocities

The methodology relies on the determination of threshold surface friction velocities, u_{*t}, as a function of aerodynamic surface roughness length, z_0. In addition to aerodynamic roughness, the degree of disturbance of the surface also plays a key role in the estimation of threshold friction velocities. Based on the work of Marticorena et al. (1997), relationships between u_{*t} and z_0 where identified and compared with wind tunnel data from Gillette et al. (1980, 1982), Gillette (1988) and Nickling and Gillies (1989). This comparison is presented in Figure 1.

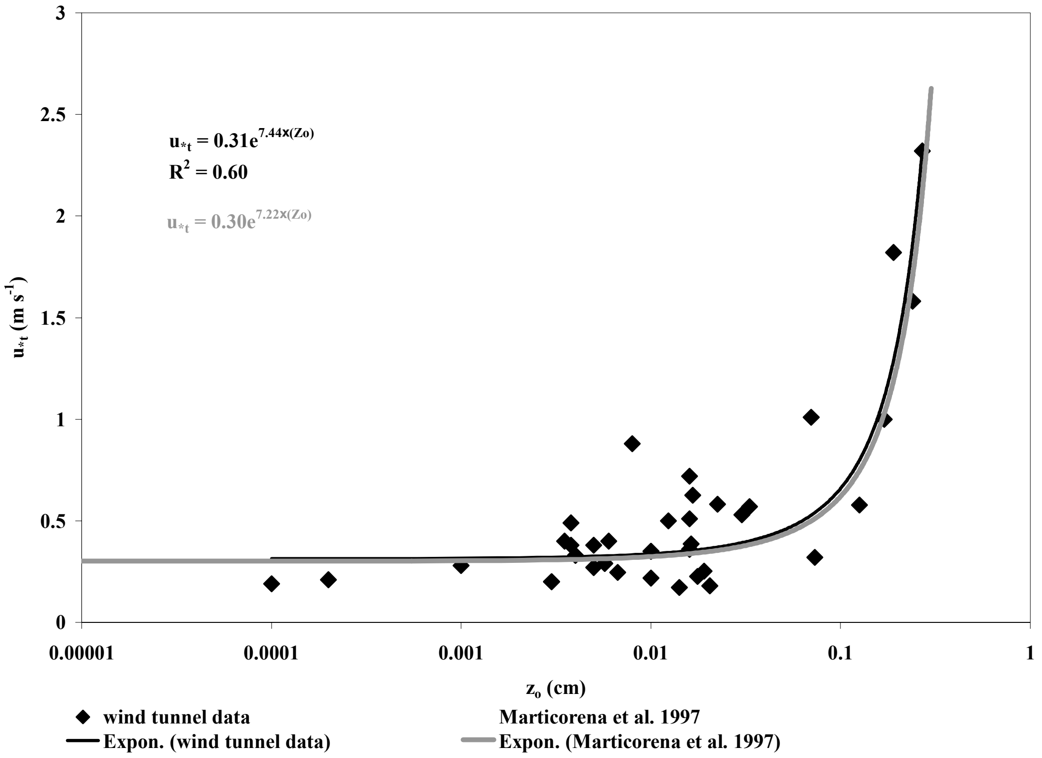

Figure 1. Comparison between the Marticorena *et al*. (1997) modeled relationship of threshold friction velocity and aerodynamic roughness length and wind tunnel data from Gillette *et al*. (1980, 1982), Gillette (1988) and Nickling and Gillies (1989).

Several general relationships can be described for threshold friction velocity data. Two major factors have the greatest influence on the threshold of wind erodible soils: the degree of disturbance and the aerodynamic roughness. For loose or disturbed soils the most important factor that controls the threshold friction velocity is aerodynamic roughness. The effect of surface disturbance on threshold friction velocity can be seen in Table 1 for data from Gillette et al. (1980, 1982), Gillette (1988), and Nickling and Gillies (1989) where surfaces are grouped by land type. For a given surface type, the effect of disturbance is to lower the threshold between ~90 to ~20% of the undisturbed value.

Application of the relationship shown in Figure 1 to assign a threshold friction velocity to a surface requires information on a surface's aerodynamic roughness length. This type of information is not generally available in land use databases, because they were not specifically developed to quantify aerodynamic properties of surfaces. Based on the designation of land use type, the aerodynamic roughness can be assigned based on previously reported values for similar surfaces. A list of surface types and reported aerodynamic roughness lengths (average values with standard deviations are listed if calculated from multiple data sources) is presented in Table 2.

Table 1. Threshold friction velocities for typical surface types calculated from available data and as reported in the literature[1].

Site Type	Average u_{*t}(m s^{-1})	Std. D. u_{*t} (m s^{-1})	Number of	Average u_{*t} (m s^{-1})	Std. D. u_{*t} (m s^{-1})	Number of	% change
	Undisturbed	**Undisturbed**	**Data Points**	**Disturbed**	**Disturbed**	**Data Points**	**[1-(dist./undist.)]**
agricultural fields	1.29	0.74	41	0.55	0.25	37	0.57
alluvial fan	0.72	0.09	2	0.60	0.18	2	0.17
desert flat	0.75	0.06	4	0.51	0.19	4	0.32
desert pavement	2.17	0.67	4	0.59	0.10	5	0.73
fan surface	1.43	0.59	5	0.47	0.25	5	0.67
play, crusted	2.13	0.67	4	0.63	0.50	15	0.70
playa	1.46	0.98	12	0.58	0.56	25	0.60
prairie	2.90	n/a	1	0.24	0.03	3	0.92
sand dune	0.44	0.10	4	0.32	0.05	4	0.27

[1] Sources include: Gillette *et al*. (1980, 1982), Gillette (1988), and Nickling and Gillies (1989).

A degree of uncertainty will exist upon assigning an aerodynamic roughness length to a surface, as it will be complicated by the individual condition of the surface, which can change through time on several scales. For agricultural fields, aerodynamic roughness will change as a function of plant height and cover through a growing season and the tillage practices. For natural surfaces, the aerodynamics can change through the season as well as annually through several years affecting dust production cycles. This is linked to plant growth in response to annual and long term climate variability, which will affect plant cover.

Table 2. Typical surface aerodynamic roughness lengths calculated from available data and as reported in the literature.

Site Type	Average z_o (cm)	Std. D. z_o (cm)	Number of	Estimated	Source	
			Data Points	u_{*t} (m s^{-1})		
agricultural fields (bare)	0.031	0.039	9	0.38	Gillette et al. (1980, 1982), Gillette (1988) Nickling and Gillies (1989)	
desert flat/pavement	0.133	0.180	8	0.79	Gillette et al. (1980, 1982), Gillette (1988) Nickling and Gillies (1989)	
fan surface	0.088	0.148	5	0.57	Gillette et al. (1980, 1982), Gillette (1988) Nickling and Gillies (1989)	
play, crusted	0.059	0.099	15	0.46	Gillette et al. (1980, 1982), Gillette (1988) Nickling and Gillies (1989)	
playa	0.057	0.083	33	0.46	Gillette et al. (1980, 1982), Gillette (1988) Nickling and Gillies (1989)	
prairie	0.049	0.088	4	0.43	Gillette et al. (1980, 1982), Gillette (1988) Nickling and Gillies (1989)	
sand dune	0.007	0.006	4	0.32	Gillette et al. (1980, 1982), Gillette (1988) Nickling and Gillies (1989)	
scrub desert	0.045	0.040	2	0.42	Nickling and Gillies (1989)	
sparse veg. (0.04% cover)	0.370				Wolfe (1993)	
sparse veg. (10.3% cover)	6.800				Wolfe (1993)	
sparse veg. (13.5% cover)	7.200				Wolfe (1993)	
sparse veg. (26% cover)	8.300				Wolfe (1993)	
sparse veg. (8% cover)	5.400				Wolfe (1993)	
thick grass	2.3				Sutton (1953)	
thin grass	5				Sutton (1953)	
sparse grass	0.12				Oke (1978)	
agricultural crops	2-4				Oke (1978)	
orchards	50-100				Oke (1978)	
Decid. Forests	100-600				Oke (1978)	
Conf. Forests	100-601				Oke (1978)	
agricultural crops	15				Deursen et al. (1993)	
urban	100				Deursen et al. (1993)	
Decid. Forests (closed canopy)	121				Deursen et al. (1993)	
Conif. Forests (closed canopy)	134				Deursen et al. (1993)	

Emission Factors

Field and wind tunnel experiments suggest that the emissions are proportional to wind friction speed and approximate theoretical model predictions, but the considerable scatter in the available data make it impossible to clearly define this dependence (Nickling and Gillies, 1993). Different surfaces appear to have different constants of proportionality for the flux versus wind friction velocity relationship, implying that the flux is predictable, but surface and soil properties affect the magnitude of the flux. A detailed discussion of wind tunnel studies, including various limitations and measured data, is provided in ENVIRON, 2003a; 2003b. The findings of the various wind tunnel studies are briefly summarized here.

Recently Alfaro, et al. (2003) re-analyzed the Nickling and Gillies (1989) data and found that the tendency of a surface to emit dust depends not primarily on its textural qualities, but on the size distribution of the loose soil aggregates available for saltation, and the aerodynamic roughness length that conditions the emission threshold. The re-analysis was based in part on the work of Chatenet et al. (1996) in which they found that desert soils could be broadly divided into four populations based upon their soil aggregate populations. The differences between the four groups are based upon the estimated geometric mean diameter of the soil particles. The four size classes are 125 mm, 210 mm, 520 mm, and 690 mm, which are labeled FFS, FS, MS, and CS by Chatenet et al. (1996).

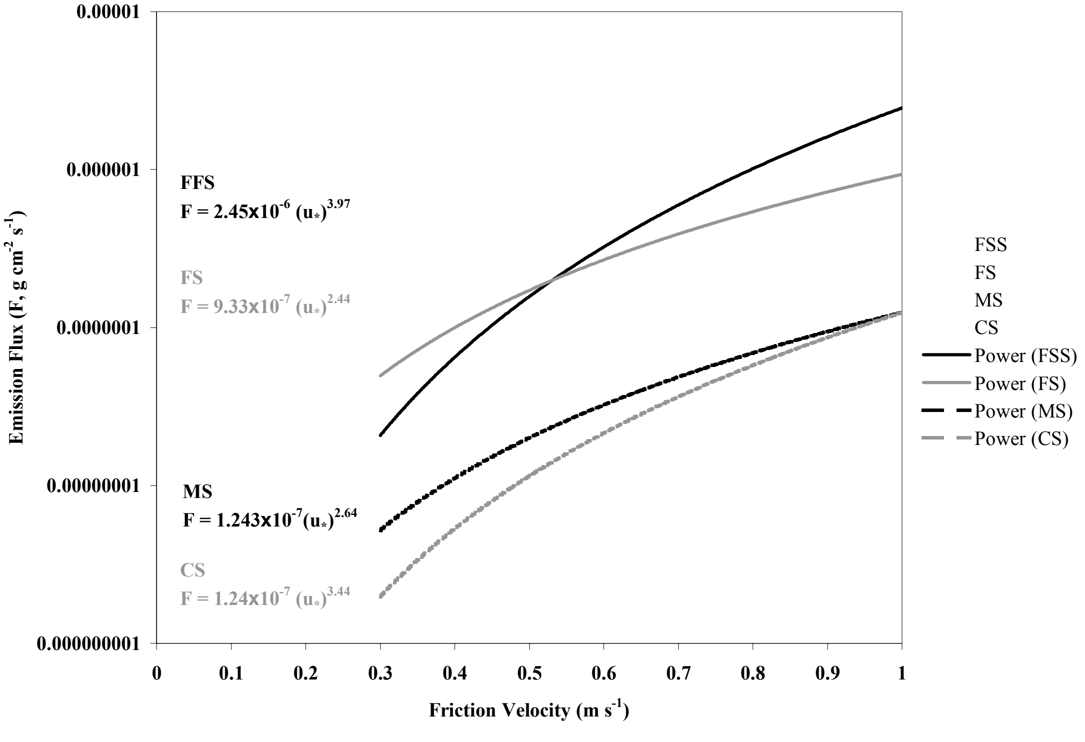

FIgure 2. The emission flux as a function of friction velocity predicted by the Alfaro and Gomes (2001) model constrained by the four soil geometric mean diameter classes of Alfaro et al. (2003).

Alfaro et al. (2003) grouped the Nickling and Gillies (1989) emission data based on these classes then tested how well the grouped data matched predicted output of a dust production model developed by Alfaro and Gomes (2001) that was constrained to use the four different geometric mean diameters. The modeled dust emission relationships for the four size classes are shown in Figure 2. As presented in Alfaro et al. (2003) the emission data from Nickling and Gillies (1989), which fall into the FS class (10 out of 13) are well explained by the model (Figure 3).

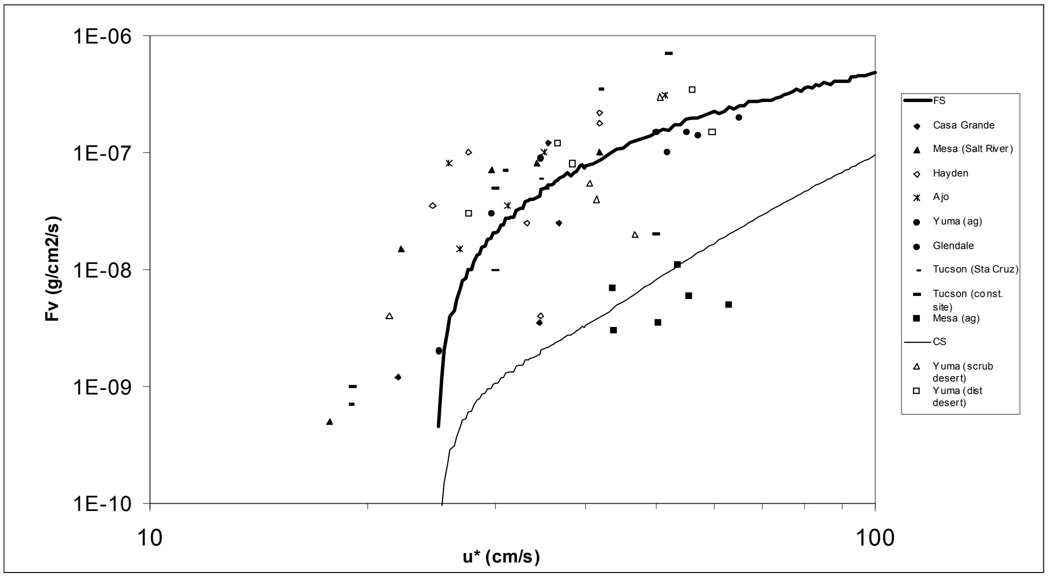

Figure 3. Comparison between the Alfaro et al. (2003) model relationship for FS and CS sizes and the wind tunnel flux data of Nickling and Gillies (1989). Ten (out of 13) sites have a dust production potential similar to the FS model and one site (Mesa agricultural) is closely aligned with the CS model (after Alfaro et al., 2003).

Using the Alfaro et al. (2003) approach, emissions of dust for soils can be confined to four different emission factors, depending on the geometric mean grain size, as determined by the methods of Chatenet et al. (1996). The model predictions were tested against the wind tunnel data set of Nickling and Gillies (1989) and found to fit the measured data satisfactorily. Of key importance is that Chatenet et al. (1996) established relationships between the 12 soil types that are defined in the classical soil texture triangle and their four dry soil types (silt [FSS], sandy silt [FS] silty sand [MS], and sand [CS]). These relationships are shown in Figure 3-5. The soil texture categorization and the relationships among texture assignments and soil groupings are discussed in the next section.

The MacDougall Method

The MacDougall Method refers to the estimation methodology actually implemented as part of the Phase I wind blown Dust Project. A description of the implementation of this method, including the various assumptions required, was discussed above and is documented in detail in ENVIRON, 2004.

A comparison of the salient features of each of the windblown dust emission estimation methodologies is presented in Table 3.

Table 3. Inter-comparison of wind blown dust models.

	Draxler	**Zender**	**ENVIRON/RMC**	**MacDougall**
Emissions	The emissions are function of the friction velocity U_* using Marticorena et al. (1997) equation	The emissions are function of the friction velocity U_* using White (1997) for saltating mass flux and adjusted equation for vertical dust mass flux	The emissions are function of the friction velocity U_* using Alfaro and Gomes (2001) equations for various soil types	The emissions are function of the 10-meter windspeed, U_{10}
Friction Velocity	Friction velocity is a function of wind velocity and surface roughness	Friction velocity is a function of wind velocity and surface roughness	Friction velocity is a function of wind velocity and surface roughness	
Start Emissions	Emission starts when friction velocity is greater than threshold friction velocity U_{*t}	Emission starts when friction velocity is greater than threshold friction velocity U_{*t}	Emission starts when friction velocity is greater than threshold friction velocity U_{*t}	Emission starts when wind velocity U10 is greater than threshold wind velocity U_t
Threshold Friction Velocity	Threshold friction velocity U_{*t} is a function of soil particle diameter, and surface roughness length,	Threshold friction velocity U_{*t} is a function of soil particle diameter and density, and surface roughness length	Threshold friction velocity U_{*t} is a function surface roughness length	Threshold wind velocity is arbitrary assigned to all types of soil and soil surface
Threshold Friction Velocity Values	Values of U_{*t} determined using experimental data data from Mojave desert (Gillette et al 1980, 19982), Geomorphological	Empirical equations as function of particle diameter and density, and surface	Empirical equations as function of surface roughness length (Marticorena et al. 1997 equation)	Not considered

	Draxler	Zender	ENVIRON/RMC	MacDougall
	classification, and Marticorena and Bergametti (1995) method (equation)	roughness length		
Surface Roughness	Used data from Mojave desert (Gillette et al 1980, 19982) and Geomorphological classification. Did not consider vegetative cover (land use)	Used globally uniform value of 0.01 m (D/30) D = mean particle diameter. Developed adjustment factors to account for vegetative fractions of the area.	Developed a table of surface roughness values using published data for various land use types	Adjustment factors for various land use and vegetative cover
Soil moisture or rain factors	Is not considered	Developed a factor to increase threshold friction velocity as a function of moisture content and threshold moisture content. The values of moisture content were taken from the National Center for Environment Prediction (NCEP)	Need to be developed	Assigned number of hours after the rain to start emissions flux.
Soil conditions (disturbed or undisturbed)	Set of equations for loose undisturbed and disturbed soils	Is not considered	Not considerd	Two emission factors, one for disturbed and one for undisturbed soils

Recommended Approach for Phase II

Based on the review of recent dust model applications, it is noted that each utilizes a similar approach to the determination of threshold friction velocities and dust emission flux rates. Based on the particular application, certain simplifying assumptions are incorporated. As with the

ENVIRON/RMC approach, these assumptions are generally required due to a lack of detailed information to fully characterize physical conditions and parameters of erodible surfaces. Nevertheless, each of these applications generally follows the methodology of the ENVIRON/RMC approach, as described above.

It is therefore recommended that Phase II model implementation follow this general approach. The approach for the determination and application of each of the required elements of the model are presented below. In some cases, additional research and/or review of existing datasets will be required. These efforts are to be documented in the form of a Technical Memorandum prepared and delivered to the WRAP DEJF for review prior to development of the fugitive wind blown dust emissions inventory.

Friction velocities

Surface friction velocities will be determined from the aerodynamic surface roughness lengths and the 10-meter wind speeds from the MM5 model simulations. Friction velocity u_*, is related to the slope of the velocity versus the natural logarithm of height through the relationship:

$$\frac{u_z}{u_*} = \frac{1}{\kappa} \ln \frac{z}{z_o}$$

where u_z = wind velocity at height z (m s^{-1})
u_* = friction velocity (m s^{-1})
κ = von Karman's constant (0.4)
z_o = aerodynamic roughness height (m)

Threshold friction velocities

The threshold friction velocities, u_{*t}, will be determined from the relationships developed by Marticorena as a function of the aerodynamic surface roughness length, z_0. This relationship is presented in Figure 1.

Surface roughness lengths

Surface friction velocities, including the threshold friction velocity, are a function of the aerodynamic surface roughness lengths. The surface roughness leng5ths are in turn dependent on surface characteristics, particularly land use/land cover. While these values can vary considerable for a given land type, published data are available which provide a range of surface roughness lengths for various land use types and vegetation cover. These data are presented in Table 2 above. Additional information for roughness lengths as a function of land cover will be identified and reviewed for inclusion in the Phase II model implementation. The final assignments of surface roughness for each land cover type will be documented and approved prior to application of the model.

Emission Fluxes

Emission fluxes, or emission rates, will be determined as a function of surface friction velocity and soil texture. The relationships developed by Alfaro and Gomes (2001) for each of the soil texture groups of Alfaro (2003) will be applied for estimating dust emission fluxes. These relationships are presented in Figure 2 above.

Reservoir characteristics

Dust emissions from vacant lands are limited by the amount of erodible soil available for suspension into the atmosphere. In addition to the amount of soil present, the condition of the soils, including textural and stability, as well as climatological factors influence the total wind blown dust emission potential of a given parcel of vacant land. The amount of soil available for a given land parcel is referred to as the reservoir and can be classified as limited or unlimited. Classification of reservoirs as limited or unlimited has implications with respect to the duration of time over which the dust emissions are generated. In general, the reservoirs should be classified in terms of the type of soils, the depth of the soil layer, soil moisture content and meteorological parameters. Finally, the time required for a reservoir to recharge following a wind event is influenced by a number of factors including precipitation and snow events and freezing conditions of the soils.

Given that the soils database for use in the project does not provide information concerning the moisture content or the depth of the soil layer, certain assumption are made regarding the determination and classification of soil reservoirs. These assumptions are based primarily on the land use type and stability of the vacant land parcel. Reservoirs are classified as limited for stable land parcels and unlimited for unstable land parcels. The assumptions used in the Phase I model application will be reviewed and adjusted appropriately. The final assumptions will be documented and reviewed by the WRAP DEJF prior to implementation in the Phase II model.

The duration and amount of precipitation and snow and freeze events will also affect the dust emissions from wind erosion. In the Phase I application these parameters were somewhat arbitrarily assigned. Barnard (2003) has compiled a set of conditions for treating these events based on seasons, soil characteristics and the amounts of rainfall and snow cover. These conditions were based on limited information found in the literature and additional assumptions. The results of the analysis of Barnard are summarized in Tables 4 and 5.

Table 4. Number of days after precipitation event to re-initiate wind erosion for rainfall amounts (constant) exceeding 2 inches

Soil type	Spring/Fall	Summer	Winter
Sand	3	2.1	4.2
Sandy Loam	3	2.1	4.2
Fine Sand Loam	3	2.1	4.2
Loam	4	2.9	3.8
Silt Loam	4	2.9	3.8
Sandy Clay Loam	4	2.9	3.8

Clay Loam	5	3.6	7.2
Silty Clay Loam	6	4.3	8.6
Clay	7	5	10

Table 5. Number of days after precipitation event to re-initiate wind erosion for rainfall amounts (constant) less than 2 inches

Soil type	Spring/Fall	Summer	Winter
Sand	1	0.7	1.4
Sandy Loam	1	0.7	1.4
Fine Sand Loam	1	0.7	1.4
Loam	2	1.4	2.8
Silt Loam	2	1.4	2.8
Sandy Clay Loam	2	1.4	2.8
Clay Loam	3	2	4
Silty Clay Loam	4	2.8	5.6
Clay	5	3.6	7.2

Soil Disturbance

It has been noted that the level of disturbance of an erodible surface is an important parameter in the estimation of wind blown dust emissions. Disturbed surfaces tend to generate more dust than un-disturbed surfaces. In the application of the Phase I model, different emissions rates were applied for disturbed versus un-disturbed surfaces. The disturbance level of surfaces was assumed to be determined by the land type and invariant in time and across the modeling domain. Thus, assumptions were required to assign surface disturbance based on land cover type. As noted previously, the disturbance level of a surface more appropriately has the effect of altering the threshold surface friction velocity; disturbed surfaces have lower thresholds while undisturbed surfaces exhibit higher threshold friction velocities.

The disturbance level of various surfaces across a regional scale modeling is difficult to determine given the lack of detail in both the LULC soils data available for use in the model. Except for agricultural lands, which are treated separately in the model as described below, vacant land parcels are typically un-disturbed unless some activity is present such as to cause a disturbance, for example, off-road vehicle activity in desert lands, or animal grazing on rangelands.

For the Phase II model application it is recommended that all non-agricultural land types be considered un-disturbed, since there is no a priori information to indicate otherwise for the regional scale modeling domain to be considered. Additional information concerning disturbance levels for certain land types will be investigated to determine whether an assumed percentage of specific land types can be considered disturbed versus un-disturbed. For any disturbed land parcel, threshold surface friction velocities will be adjusted according to a review of the information presented in Table 1.

Data Sources

The various data sets required for implementation of the Phase II recommended approach to wind blown dust estimation are summarized in this section.

Land Use/Land Cover

The Phase I model implementation used the BELD3 land use/land cover (LULC) database to specify vacant land types. Given that these data are based primarily on information from pre-1990 and that the distinction between barren/desert lands and shrub/grasslands was not sufficient to adequately characterize these land types, it s recommended that the LULC data be based on the National Land Cover Database. An evaluation of the NLCD database conducted during Phase I Study revealed that the shrubland and barren land (desert) categories were better represented as distinct land types.

The National Land Cover Data (NLCD) was developed as part of a cooperative project between the U.S. Geological Survey and the U.S. Environmental Protection Agency to produce a consistent land cover data layer for the entire conterminous U.S. based on 30-meter Landsat thematic mapper (TM) data. The NLCD was developed from TM data acquired from the Multi-Resolution Land Characterization (MRLC) Consortium, a partnership of federal agencies that produce or use land cover data. The partners include USGS (National Mapping, Biological Resources, and Water Resources Divisions), the USEPA, the U.S. Forest Service and the National Oceanic and Atmospheric Administration.

The NLCD datasets are available as flat generic raster image files that are easily imported into a GIS (e.g., ARC/Info) and are provided in an Albers Conic Equal Area projection at a spatial resolution of 30-meters. The data can be obtained from the following URL http://edcwww.cr.usgs.gov/pub/edcuser/vogel/states/. The land cover characteristics are defined in terms of the 21 separate categories presented in Table 6.

Table 6. NLCD Land Cover Classification Codes.

Code	Description
11	Open Water
12	Perennial Ice/Snow
21	Low Intensity Residential
22	High Intensity Residential
23	Commercial/Industrial/Transportation
31	Bare Rock/Sand/Clay
32	Quarries/Strip Mines/Gravel Pits
33	Transitional
41	Deciduous Forest
42	Evergreen Forest
43	Mixed Forest
51	Shrubland
61	Orchards/Vineyards/Other
71	Grasslands/Herbaceous

Code	Description
81	Pasture/Hay
82	Row Crops
83	Small Grains
84	Fallow
85	Urban/Recreational Grasses
91	Woody Wetlands
92	Emergent Herbaceous Wetlands

Soil Characteristics

Application of the emission factor relations described above requires the characterization of soil texture in terms of the 4 soil groups considered by the model. The characteristics, or type, of soil is one of the parameters of primary importance for the application of the emission estimation relations derived from wind tunnel study results. The State Soil Geographic Database (STATSGO) will be used to determine the type of soils present in the modeling domain for which the emission inventory will be developed. The STATSGO database was developed by the Natural Resources Conservation Service of the U.S. Department of Agricultural (USDA) and provides detailed information concerning the taxonomy of the soils, including soil texture class, percentage of sand, silt and clay, and the available water capacity of the soil. While the complete STATSGO database available from the USDA includes numerous additional features, those features relevant for this project were considered to be the soils texture class. The soils data are available as geospatial coverages and associated attribute tables for each state in the US. Soils databases were obtained from the Earth System Science Center (ESSC) at Penn State University (http://www.essc.psu.edu/soil_info/).

The classification of soil textures and soil group codes is based on the standard soil triangle that classifies soil texture in terms of percent sand, silt and clay. Combining the soil groups defined by the work of Alfaro, et al. (2003) and Chatenet, et al. (1996) and the standard soil triangle provides the mapping of the 12 soil textures to the 4 soil groups considered in their study. Combining the data from these two soil texture/soil group mappings results in the unique mapping of soil textures to the soil groups for which emission factor data can be applied. Note that an additional soil group was added to distinguish loam soils defined by soil group code 3. The results of combining these soil texture definitions allows the assignment of the loam soil group in terms of standard soil texture. The soil texture mappings are summarized in Table 7.

Table 7. STATSGO soil texture and soil group codes

STATSGO Soil Texture	Soil Texture Code	Soil Group Code
No Data	0	0
Sand	1	4
Loamy Sand	2	4
Sandy Loam	3	2
Silt Loam	4	1
Silt	5	5
Loam	6	3
Sandy Clay Loam	7	2
Silty Clay Loam	8	5

Clay Loam	9	3
Sandy Clay	10	2
Silty Clay	11	5
Clay	12	1

Surface Roughness Lengths

Surface roughness lengths can vary considerably for a given land type, as evidenced by examination of the data in Table 3 above. It is recommended that this information be reviewed and augmented with any additional data identified in the literature. Appropriate assignments of surface roughness lengths by land use type will be developed for application of the Phase II dust model. As noted above, the disturbance level of various surfaces has the effect of altering the surface roughness lengths, which in turn impact the potential for vacant lands to emit dust from wind erosion. The information presented in Table 3 will be reviewed to determine appropriate adjustment to be applied for disturbed surfaces.

Meteorology

As with the Phase I model implementation, gridded hourly meteorological data is required for the dust estimation methodology. For Phase II of the study, the meteorological data will be based on MM5 model simulation results. Data fields required include wind speeds, precipitation rates, soil temperatures and ice/snow cover. The 2002 MM5 model results on the National Unified RPO Grid, at both 12- and 36-km resolution, will be processed as in Phase I and used in the application of the revised wind blown dust model.

Agricultural Land Adjustments

Unlike other types of vacant land, windblown dust emissions from agricultural land are subject to a number of non-climatic influences, including irrigation and seasonal crop growth. As a result, several non-climatic correction or adjustment factors were developed for applicability to the agricultural wind erosion emissions. These factors included:

- Long-term effects of irrigation (i.e., soil “clodiness”);
- Crop canopy cover;
- Post-harvest vegetative cover (i.e., residue);
- Bare soil (i.e., barren areas within an agriculture field that do not develop crop canopy for various reasons, etc.); and
- Field borders (i.e., bare areas surrounding and adjacent to agricultural fields).

The methodology used to develop individual non-climatic correction factors for the Phase I study was described in detail in ENVIRON, 2004. Most of these methods were based upon previous similar work performed by the California Air Resources Board (CARB) in their development of California-specific adjustment factors for USDA’s Wind Erosion Equation (WEQ) (CARB, 1997). These correction factors were developed for specific soil textures, crop types, and geographic locations and then applied to the wind erosion estimates developed from the wind tunnel studies. Correction factors are developed only for the 17 field crops specifically identified in the BELD3.1 data set (i.e., alfalfa, barley, corn, cotton, grass, hay, oats, pasture, peanuts, potatoes, rice, rye, sorghum, soybeans, tobacco, wheat, and miscellaneous crops). Due to the insufficient characterization of the wind erosion emission processes for orchards and vineyards, correction factors for this type of agricultural land were not developed.

For the Phase II dust model implementation, it is recommended that these same non-climatic adjustments be applied. However, because the BELD3 database will not be used, these factors will need to be related to the agricultural land types available in the NLCD LULC data. It is proposed to use the exiting county-level crop percentages from the BELD3 database and link these data to the aggregated agricultural land parcels from the NLCD data to be used. Consideration will also be given to the possibility of updating the county-level crop percentages based on a review of the most recent agricultural survey.

Proposed Project Schedule

Assuming a project start date of July 1, 2004, the following schedule is proposed for completion of the Phase II Wind Blown Dust Emission Project:

- July 1, 2004: Project initiation
- July 16, 2004: Delivery of Technical Memorandum detailing the revised dust emission estimation methodology and datasets.
- July 30, 2005: Delivery of Draft Fugitive Dust Emission Inventory for 2002 and Draft Final Report
- August 20, 2004:Delivery of Final 2002 Dust \Emission Inventory and Project Final Report.

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