Determining Fugitive Dust Emissions from Wind Erosion

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ABSTRACT

The Western Regional Air Partnership (WRAP) is engaged in an effort to implement Section 309 of the Regional Haze Rule, which is the compilation of the regional emission inventory to be used in air quality models as the basis for tracking progress in achieving the visibility goals under this rule. The WRAP area source emission inventory currently has no wind blown fugitive dust included because of strong concern that previous methodologies used to calculate these emissions yielded misleading results. Thus, the WRAP has assembled a team of contractors to develop this emission inventory by employing an empirical method for determining fugitive dust emissions from wind erosion of vacant lands, including agricultural croplands.

The empirical method for determining windblown dust emissions from vacant lands relies heavily on emission factors developed using wind tunnels. Based upon vacant land categories, wind tunnel study results are reviewed and applied appropriately to each category. Additionally, special consideration is given to agricultural lands due to the influence of non-climatic factors that impact fugitive dust emissions from these lands. The overall goal of this project is to compile a set of PM_{10} and $PM_{2.5}$ emission factors for windblown dust from vacant lands. These emission factors are used to develop a comprehensive emission inventory for the Western Region of the U.S. In addition, to facilitate future inventory revisions and control scenario development, a general methodology and emissions modeling system for estimating fugitive dust emissions from wind erosion is developed.

This paper discusses the characterization of vacant lands subject to wind erosion and the development of PM_{10} and $PM_{2.5}$ emission factors for windblown dust. Data sources and characteristics and the emission inventory estimation methodology are described.

INTRODUCTION

The Western Regional Air Partnership (WRAP) is currently engaged in modeling efforts to implement Section 309 of the Regional Haze Rule. These efforts require the compilation of regional emission inventories for use in air quality models to serve as a basis for tracking progress in achieving the visibility goals set forth in the rule. Due to strong concerns regarding the basic information needed to develop wind blown fugitive dust emissions, the current WRAP area source emission inventory lacks this important source category component. Previous information used to estimate these particulate emissions have yielded false or misleading results. Due to the importance of fugitive emissions from wind blown dust with respect to visibility modeling, the WRAP has proposed the implementation of an estimation methodology developed by the Clark County (NV) Department of Air Quality Management to address this need (MacDougall, 2002)[1].

The overall goal of the proposed project is to compile a set of PM10 and PM2.5 emission factors for windblown dust from vacant lands. These emission factors are to be used to develop a comprehensive emission inventory for the WRAP, 36-km cell size, modeling domain   To facilitate future inventory revisions and control scenario development, a general methodology for estimating fugitive dust emissions from wind erosion is to be developed.

EMISSION ESTIMATION METHODOLOGIES

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)[2]. 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. For this research it was necessary to develop generally applicable categories for use in the dust emission inventory. Maintaining the level of detail available from individual studies would be problematic for modeling the emission of dust from wind erosion susceptible surfaces.

The characterization of surfaces that have been tested for emission potential using portable wind tunnels has been based on several schemes. Dust emission data have been categorized based on soil textural qualities, specifically grouping the sites according to their percent content of silt and clay, or as a function of surface type (e.g., Nickling and Gillies, 1989[3]; James et al., 2001[4]). A constraint for this research was to develop emission factors that could be applied according to information available in the BELD land use database as well as soils databases. In addition, the emission factors would have to be defensible from a scientific perspective.

Nickling and Gillies (1989) reported specific emission rates for 13 different surface types ranging from natural desert to construction sites and mine tailings measured with a portable wind tunnel. Grouping the data based upon similarities in texture and surface morphology, they found variations in the strength of the observed relationship between vertical dust flux and friction speed, which they attributed to differences in the soil texture as well as roughness effects. Nickling and Gillies (1989) did not report emission flux relationships for agricultural lands due to the scatter in their data. The wind tunnel-derived dust emission data set of Nickling and Gillies (1989) covers the widest variety of test surface types undertaken in one study, but even combining the emission flux relationships with flux relationships from other studies (e.g., James et al., 2001; Stetler and Saxton, 1995[5], 1996[6]) does not

provide a means to generalize emissions from a broad range of surface types or utilize the land use and soils databases effectively.

Recently Alfaro *et al*. (2003)[7] carried out a re-analysis of 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 of the Nickling & Gillies (1989) data by Alfaro *et al*. (2003) was based in part on the work of Chatenet *et al*. (1996)[8] in which they found that desert soils can 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 μm, 210 μm, 520 μm, and 690 μm, which are labeled FFS, FS, MS, and CS by Chatenet *et al*. (1996).

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)[9] 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 1. 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 (see Figure 2). For two agricultural soils tested by Nickling and Gillies (1989), for which they did not present emission factors, Alfaro *et al*. (2003) found them to be best modeled by considering them to be an FS type for the Glendale agricultural site and the CS type for the Mesa agricultural site, based on the mean grain sizes reported for these sites by Nickling and Gillies (1989).

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 (Chamley, 1987) and their four dry soil types (silt [FSS], sandy silt [FS] silty sand [MS], and sand [CS]). These relationships are shown in Figure 3. This would allow emission factors to be assigned to different textured soils as described in a soils database. There will be some disparity between the textural classifications used by Chatenet *et al*. (1996) and other soil texture classification as their soil textural triangle has slightly different divisions. These differences can however be reconciled (Figure 3).

For the emission inventory, the four emission curves of Alfaro et al. (2003) were used to generate dust emission from different surfaces. The emission flux equation was assigned to surfaces based on soil texture information in the soils database and its equivalence with one of the four Chatenet et al. (1996) soil geometric mean diameter aggregate classes.

AGRICULTURAL LAND CONSIDERATIONS

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");
- Short-term effects of irrigation (i.e., surface soil wetness);

- Crop canopy cover;
- Post-harvest vegetative cover (i.e., residue);
- Post-harvest replanting (i.e., multi-cropping);
- 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 is outlined below. 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)[10]. 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 were 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.

Long-Term Irrigation Effect Correction Factor

The long-term irrigation effect correction factor accounts for the soil "clodiness" that occurs as a result of long-term irrigation. The correction factor is the ratio of irrigated and non-irrigated soil erodibilities (CARB, 1997). Each soil texture has an associated non-irrigated soil erodibility value (U.S. EPA, 1974[11]; U.S. EPA, 1977[12]); irrigated soil erodibilities were assigned to corresponding non-irrigated soil erodibilities by soil experts (CARB, 1997; Hagen, 2003[13]). The long-term irrigation effect correction factor was developed for each soil texture and was applied to all irrigated croplands, regardless of crop type. This correction factor had a value of 1.0 for all non-irrigated croplands. The correction factor was applied throughout the year and did not have any seasonal variation.

Short-Term Irrigation Effect Correction Factor

The short-term irrigation effect correction factor accounts for the fraction of the month that the surface soil was wet due to irrigation events. The number of "wet days" was determined by the number of irrigation events and adjusted by the texture wetness factor which accounts for surface soil wetness extending beyond the day of the actual irrigation event (dependent upon soil characteristics) (CARB, 1997). The correction factor is spatially variable because it is crop-specific and depends upon geographic irrigation requirements. For each crop type, the number of irrigation events was determined. Irrigation event information was derived from crop budget databases (NRIAI, 2003[14]; SEFMC, 2003[15]), as well as agricultural experts (Lightle, 2003)[16].

Crop Canopy Correction Factor

The crop canopy correction factor accounts for the fraction of ground covered by crop canopy when viewed directly from above. The crop canopy cover correction factor equation contains an exponential function, which results in the correction factor changing significantly with relatively small changes in percent crop cover (CARB, 1997). In the absence of canopy cover, the correction factor is 1.000. With total canopy cover (i.e., 100 percent), the correction factor is 0.0025 (i.e., effectively zero). More realistic canopy cover values of 10 and 20 percent give correction factors of 0.334 and 0.161, respectively. Consequently, windblown emissions can vary significantly for a given crop depending upon the stage of canopy growth. Where possible, crop-specific canopy profiles (i.e., growth curves) were developed. However, in some instances a simplifying assumption of 100 percent canopy cover

from planting to harvest was made. The assumption of 100 percent canopy cover was previously used to estimate agriculture tilling emissions for U.S. EPA's 1996 National Emissions Inventory (Barnard and Stewart, 1992)[17].

Crop calendars were used to develop crop-specific canopy profiles and to establish planting and harvest dates. Initial state-level planting and harvesting data for field crops were obtained from a USDA publication (USDA, 1997a)[18]. More refined crop calendars were prepared as part of the Revised Universal Soil Loss Equation, Version 2 (RUSLE2) which was developed by the USDA ARS (ARS, 2003[19] Lightle, 2003). The RUSLE2 crop calendars were not developed at the state-level. Instead, they were developed for 75 different Crop Management Zones (CMZs). In the Eastern United States, the CMZs were developed based upon temperature and precipitation similarities and were normalized to county boundaries for administrative purposes. In the Western United States, the CMZ boundaries correspond to major land resource and soil area boundaries and relate very closely to topography and climate. In the Western United States, the CMZ boundaries were not normalized to county boundaries (Lightle, 2003).

Post-Harvest Soil Cover Correction Factor

The post-harvest soil cover correction factor accounts for the fraction of ground covered by vegetative debris remaining after harvest when viewed directly from above. The post-harvest soil cover correction factor equation contains an exponential function, which results in the correction factor changing significantly with relatively small changes in percent post-harvest soil cover. Without any post-harvest soil cover, the correction factor is 1.000. With total post-harvest soil cover (i.e., 100 percent), the correction factor is 0.013 (i.e., effectively zero). More realistic post-harvest soil cover values of 10 and 20 percent give correction factors of 0.645 and 0.416, respectively. Unlike canopy cover that varies throughout the growing season, the level of post-harvest soil cover was assumed to stay constant during the period between harvest and planting. As described above for the crop canopy correction factor, the planting and harvesting data from RUSLE2 was used to develop the post-harvest soil cover correction factor (ARS, 2003; Lightle, 2003). The Crop Residue Management Program (CRM) database, maintained by Purdue University's Conservation Technology Information Center (CTIC), provided information regarding the amount of residue left in the field after harvest (e.g., 0-15 percent, 15-30 percent, >30 percent), by crop and by county for the U.S. (CTIC, 2003)[20].

Replanting Correction Factor

Replanting to a different crop refers to the agricultural practice of quickly replanting harvested acreage with a different type of crop. Replanting introduces a new crop canopy to harvested acreage that would otherwise be subject to wind erosion during the period between harvest and the following year's planting. Replanting is a common practice in California's San Joaquin Valley and Imperial County, but it also occurs in agricultural areas in the other WRAP states. The replanting correction factor for a particular crop varies from 0.0 (i.e., no multi-cropping) to 1.0 (i.e., all acreage is multi-cropped). Some multi-cropping information was available within RUSLE2 (ARS, 2003; Lightle, 2003). Additionally, previous studies in California identified the quantity of multi-cropping will be applied to California where past studies provide data on the amount of replanting that occurs (CARB, 1997).

Bare Soil Adjustment Correction Factor

The bare soil adjustment correction factor accounts for the fraction of cultivated area that remains barren during the growing cycle due to uneven ground, uneven irrigation, soil salinity, pest damage, etc. Statistics quantifying bare soil fractions were not identified. However, bare soil fractions of 0.5 percent for crop acreage and 0.05 percent for pasture based on limited visual observations were previously assumed by CARB (CARB, 1997). These bare soil fractions were also used in this study.

These fractions seem reasonable given USDA statistics of overall "crop failure" rates of 2-3 percent of planted cropland (USDA, 1997b)[21], noting that crop failure acreage likely does not correspond exactly with bare soil acreage. Although the bare soil acreage can be relatively small compared to overall agricultural acreage, the contribution from the bare soil area may be significant because many of the other non-climatic correction factors are not applicable (i.e., crop canopy cover, post-harvest vegetative cover, post-harvest planting, etc.) to bare soil areas. The assumed bare soil adjustment correction factors were applied throughout the year and did not vary by month or season.

Border Adjustment Correction Factor

The border adjustment correction factor accounts for the surrounding borders of agricultural fields (excluding pastures) that are not covered in vegetation. Statistics quantifying border fractions were not identified. However, a border fraction of 0.5 percent for crop acreage based on limited visual observations was previously assumed by CARB (CARB, 1997). It was assumed that pastures have no borders. Like the bare soil adjustment correction factor, border acreage can be relatively small compared to overall agricultural acreage. However, the contribution from agricultural field borders may be significant. In fact, it may be more significant than the bare soil areas because the field borders are typically non-irrigated (i.e., long- and short-term irrigation adjustments are not applicable). The assumed border adjustment correction factors were applied throughout the year and did not vary by month or season.

DATA SOURCES

Data required for developing fugitive dust emission factors and emissions include land use/land cover, soil characteristics, and meteorological data. A description of these data and data sources are presented in this section.

Land Use/Land Cover

Land use/land cover (LULC) data were based on the Biogenic Emission Landcover Database (BELD3). The BELD3 datasets were obtained from the EPA's FTP server and processed with the Arc/INFO 7.xx Geographic Information System (GIS). The processing involved importing the data as grid coverages, conversion of polygon coverages and linking the spatial data with land-use attribute tables. The land-use attributes consist of the percentage of agricultural, forest, and other land within each 1-km BELD3 grid cell. The various crops by county further categorize agricultural lands. Forestlands are categorized by tree species. The USGS land types categorize the remaining land in each grid cell. Land use categories include urban lands, grasslands, shrub lands, barren land, wetlands, tundra, ice, water, forestlands and agricultural lands. As the BELD3 database does not include the entire state of Alaska, alternative LULC data were evaluated. The North America Land Cover Characteristics (NALCC) database was used to characterize LULC types for the state of Alaska. The NALCC database is part of an on-going global vegetation database development project. These data are on a 1-km by 1-km grid for the entire North American continent and are presented in four different classification systems and two coordinate system projections. The 24-category classification based on a Modified Level 2 Anderson classification scheme was used. While the USGS LULC classification scheme distinguishes the basic land cover categories, certain relevant details are not represented. For example, although various types of cropland and pasture are represented, the desired detail in terms of crop types relevant to emission factor adjustments due to non-climatic effects are not distinguishable. These data were derived from Advanced Very High Resolution Radiometer (AVHRR) data with a Normalized Difference Vegetation Index (NDVI). The data are available from http://edcdaac.usgs.gov/glcc/tabgoode_globe.html that also provides complete documentation of these data including their development and quality assurance status.

Soil Characteristics

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) was 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/). Figure 4 presents the dominant soil texture class for the conterminous US as represented in the ESSC database. Soil texture data for the state of Alaska were derived from the complete STATSGO database obtained from the USDA since the ESSC datasets include only the conterminous U.S.

Soil characteristics data for Canada and Mexico are also required for this project as the air quality modeling domain for which the PM emissions inventory was developed includes parts of southern Canada and northern Mexico. Soils data for Canada were obtained from the Canadian Soil Information System website of Agricultural and Agri-Food of Canada (http://sis.agr.gc.ca/cansis/nsdbc/slc/v2.1/download_slc.html). The data set presents soil landscapes for all of Canada in terms of soil texture. Soils data for Mexico were obtained from the Comisión Nacional para el Conocimiento y Uso de la Biodiversidad (CONABIO) website (http://conabioweb.conabio.gob.mx/metacarto/metadatos_ing.pl). These datasets describe the dominant soils throughout the country in terms of the full taxonomic descriptions.

Meteorological Data

Meteorological data used for the project consisted of the entire 1996 MCIP datasets for the 36-km WRAP modeling domain. An analysis of the data with respect to threshold friction velocities, precipitation events, and surface characteristics was conducted. With respect to surface characteristics of significance to the project the surface aerodynamic roughness length (z_0) was considered. One of the key parameters in the determination of wind erosion is the friction velocity. Fugitive emissions from wind erosion are not generated until the friction velocity exceeds the threshold friction velocity for the particular land and soil type. The 1996 MCIP datasets for the 36-km WRAP modeling domain wereused to obtain hourly friction velocities at a horizontal spatial resolution of 36-km for the entire WRAP modeling domain. Other relevant meteorological fields are the hourly precipitation rates. Depending on the soil type and amount and duration of precipitation events, fugitive dust emissions may be considerably attenuated. The precipitation fields were obtained from the MCIP datasets.

Unpaved Roads

Unpaved roads represent a potentially significant source of fugitive dust from wind erosion. County-level total unpaved road lengths were obtained from the Federal Highways Administration for all states in the WRAP domain. To apply the emission factor relations needed to develop emissions on unpaved roads, an average width and surface characteristics of the unpaved roads were assumed. Emissions from unpaved roads were calculated at the county-level and spatially allocated to the modeling grid using rural secondary roads as a surrogate. Roadway networks were obtained from the EPA's spatial surrogate database (ftp://ftp.epa.gov/EmisInventory/emiss_shp). These data classify roadways as primary or secondary urban roads and primary or secondary rural roads. The database also

includes roadways for Canada. Fugitive dust emissions for Canada were calculated based on rural secondary roadway area using the same assumptions concerning road width and surface characteristics. Mexican roadway networks were obtained from the GISDataDepot website (http://data.geocomm.com/catalog/index.html). For Mexico all secondary roads were assumed to be unpaved, and emissions were estimated as for Canada.

CALCULATION METHODOLOGY FOR FUGITIVE DUST EMISSIONS

Based on the evaluation of wind tunnel study results, land type and soil characteristics and meteorological data a general methodology for estimating fugitive dust emission factors was developed. The methodology involved several steps including with the categorization of land types and soil characteristics, association of threshold friction velocities with aerodynamic surface roughness lengths, determined by the land type, and application of the dust flux relations for each soil texture. Finally, the emission factors for agricultural lands were adjusted based on non-climatic effects. Emission factors vary spatially based on land and soil characteristics, and temporally based on hourly friction velocities and, in the case of agricultural lands, seasonal and/or monthly crop calendars.

In order to retain information from the high resolution data, while minimizing resource requirements, the modeling grid was defined at 12-km. To apply the relations discussed above, the soil texture attributes were first mapped from the 12 texture classes of the classical soil triangle to the 4 classes for which dust flux relations are identified. Land type attributes were combined with the soil texture to provide a geospatial dataset that includes both attributes. The resulting coverage was overlayed with county boundaries and the WRAP modeling grid. Finally, areal fractions were calculated to obtain the percentage of each soil texture and land type within each of the 12-km grid cells. The Arc/INFO 7.xx GIS software was used to accomplish these data processing steps.

Based on the land types in each grid cell, a threshold friction velocity (u_*^*) was estimated. Using the hourly, gridded friction velocities from the MCIP data for the 36-km modeling domain, emission factors were calculated using the applicable dust flux equations (Figure 1) for each soil texture. Emission factors were calculated only for cases where the friction velocity exceeds the corresponding threshold friction velocity for the particular land type. Non-climatic agricultural adjustments were then applied to the agricultural land types, by county, crop type and month/season using the crop specific calendars and agricultural information assembled for the project.

The final steps required to develop the emission inventory involved the multiplication of the emission factors and activity data (vacant land area), the incorporation of precipitation events and the final aggregation of the gridded, hourly PM emission estimates to the 36-km WRAP modeling domain. These processing steps were coded in a manner consistent with the SMOKE emissions modeling system.

SUMMARY

Emission factors for windblown fugitive dust were determined for vacant land types based on analyses of portable wind tunnel study results. Relationships between soil texture characteristics, threshold friction velocities and dust fluxes were determined for 4 classes of soil texture. Threshold friction velocities were related to land types and aerodynamic surface roughness lengths. Land types were characterized using the BELD database while soil textures were determined from the STATSGO soil databases. The classical soil texture classes were mapped to the four texture classes for which dust flux relationships were determined. Meteorological data defining friction velocities and precipitation events were obtained from the MCIP datasets used for the WRAP air quality modeling efforts. Non-climatic adjustments for agricultural lands were applied based on monthly crop calendars and consideration of agricultural practices within the WRAP states. A general fugitive dust emission

estimation methodology and program code was developed in a manner consistent with the SMOKE emission inventory development processing utilized in the WRAP modeling efforts.

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Figure 1. 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).
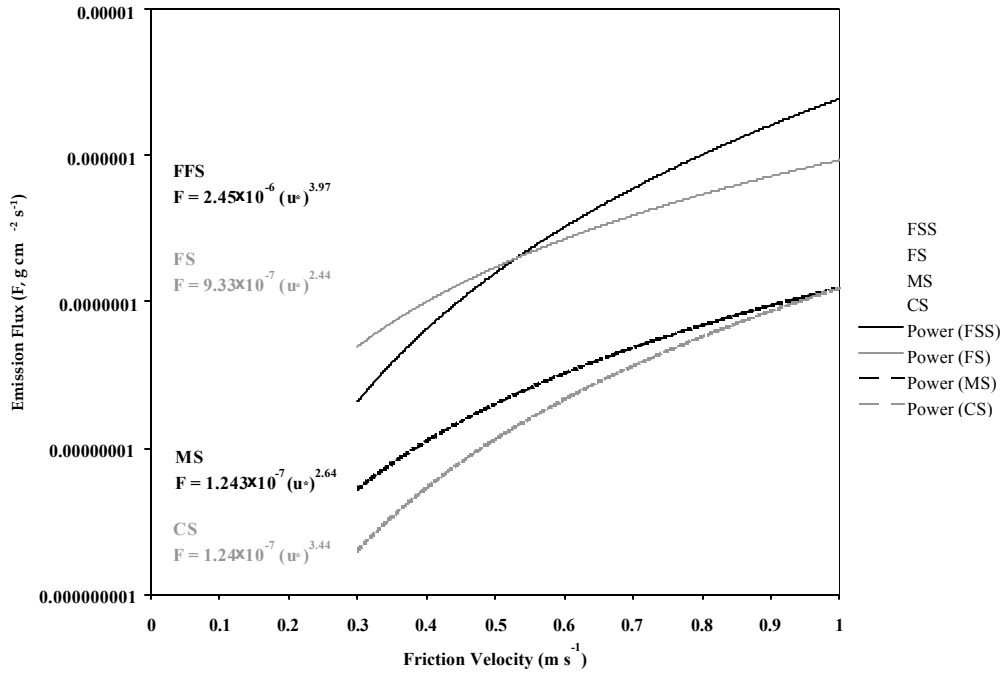

Figure 2. Comparison between the Alfaro *et al*. (2003) model relationship for FS and CS sizes and the wind tunnel flux data of Nickling and Gillies (1989). Ten (out of 13) sites have a dust production potential similar to the FS model and one site (Mesa agricultural) is closely aligned with the CS model (after Alfaro *et al*., 2003).
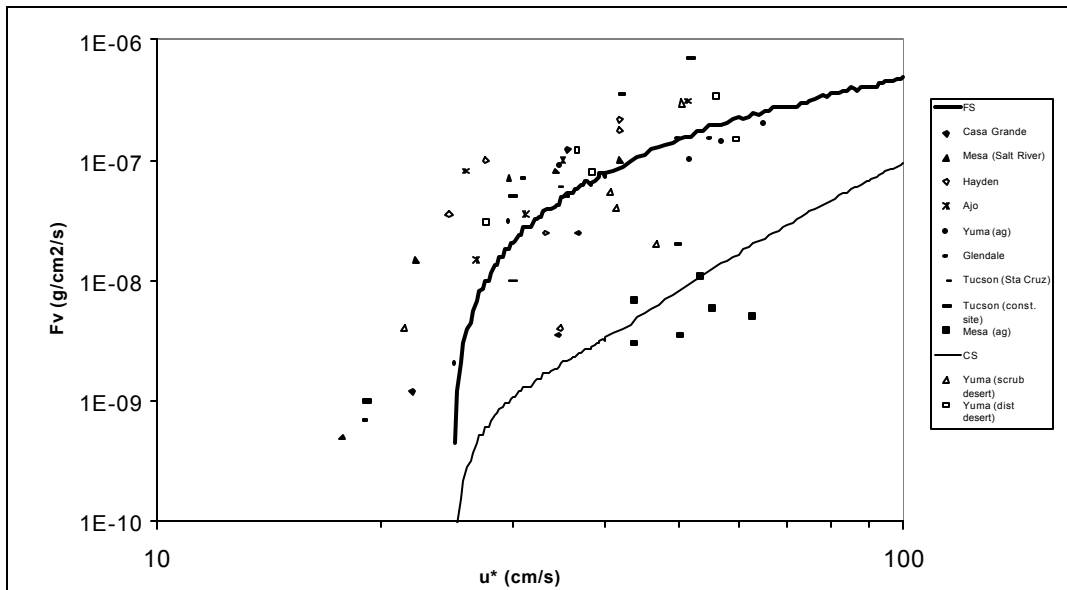
Figure 3. Relations between the soil types deduced by Chatenet *et al.* (1996) from aggregate size distributions of various desert soils and the classical textural soil categories. The "gray" highlighted textural classes indicate the 4 sediment types identified by dry sieving; the arrows indicate the pathways linking these types to the other textures defined in the classical textural diagram. A North American soil texture triangle is shown for comparison purposes.
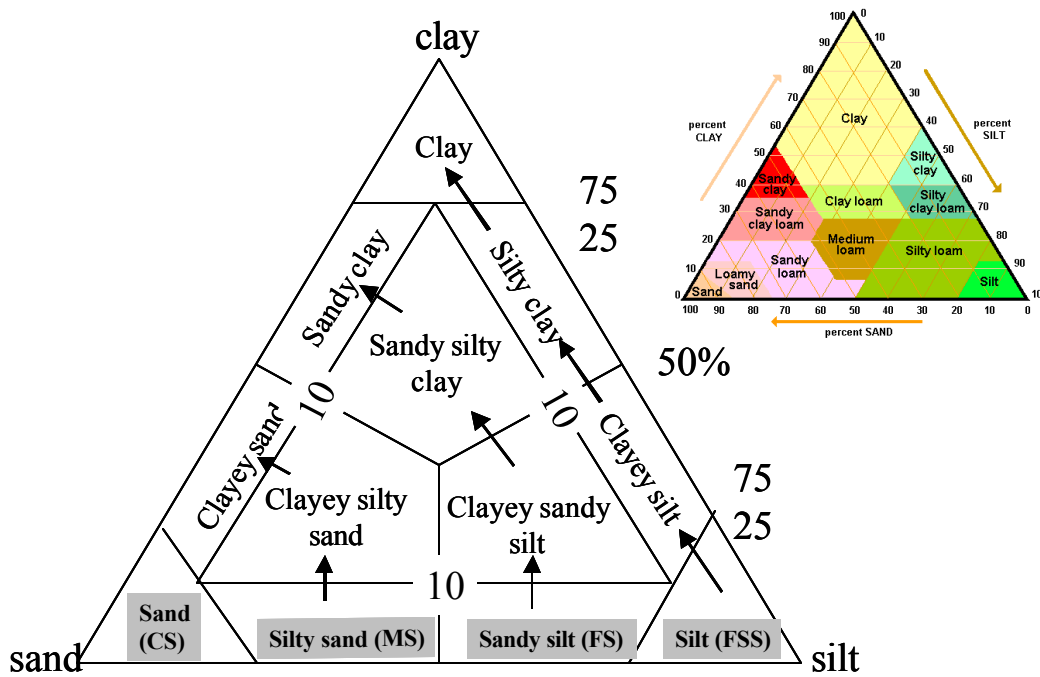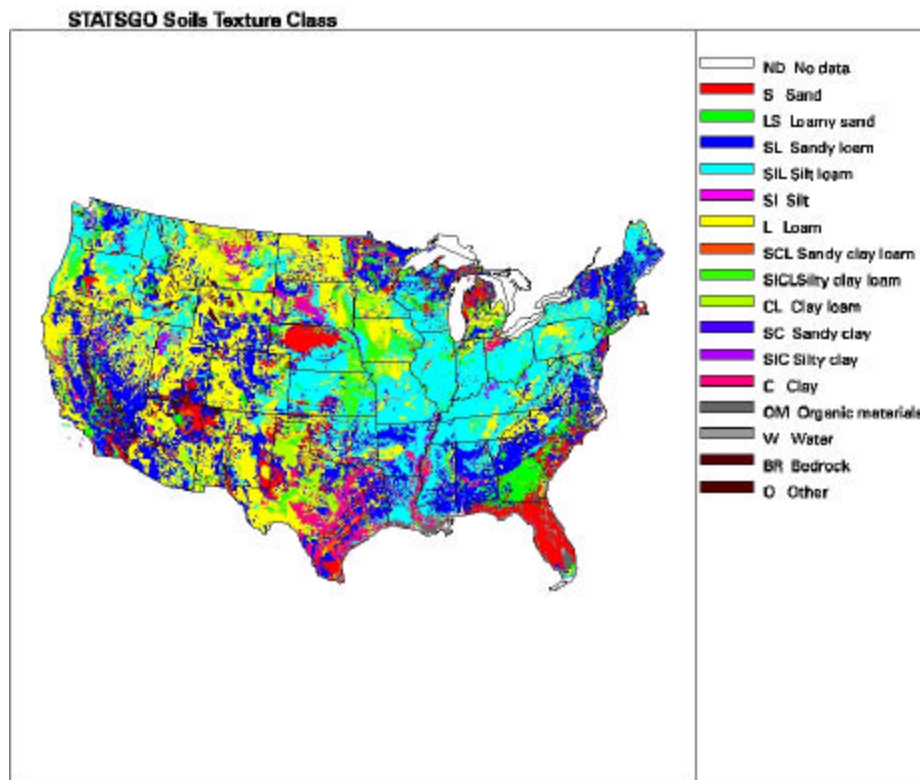

Figure 4. STATSGO Soils Database soils texture class for conterminous U.S.

KEYWORDS

emission inventory
particulate matter
fugitive dust
wind erosion
GIS