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USE OF VEGETATION TO PROMOTE CAPTURE OF FUGITIVE DUST ON U.S. ARMY INSTALLATIONS

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USE OF VEGETATION TO PROMOTE CAPTURE OF FUGITIVE DUST ON U.S. ARMY INSTALLATIONS

1. Purpose.

This Public Works Technical Bulletin (PWTB) discusses the use of vegetation for the control and capture of fugitive dust on U.S. Army installations. The United States Environmental Protection Agency (USEPA) describes fugitive dust as: “Significant atmospheric dust that arises from the mechanical disturbance of granular material exposed to the air. Dust generated from these open sources is termed "fugitive" because it is not discharged to the atmosphere in a confined flow stream.” (USEPA 1972)

a. All PWTBs are available electronically in Adobe® Acrobat® portable document format [PDF]) through the World Wide Web (WWW) at the National Institute of Building Sciences’ Whole Building Design Guide (WBDG) Web page, which is accessible through this Universal Resource Locator (URL):

http://www.wbdg.org/ccb/browse_cat.php?o=31&c=215

2. Applicability. This PWTB applies to all continental U.S. (CONUS) Army training and testing facilities.

3. References.

a. Army Regulation (AR) 200-1, “Environmental Protection and Enhancement,” 21 February 1997.

b. Clean Air Act (CAA), as Amended, 1990.

c. AR 200-2, “Environmental Effects of Army Actions,” 23 December 1988.

d. AR 200-3, “Natural Resources – Land, Forest and Wildlife Management,” 20 March 2000.

e. National Environmental Policy Act (NEPA) of 1969 (Public Law [PL] 91-190, 42 United States Code [USC] 4321), 01 January 1970.

4. Discussion.

a. The Clean Air Act currently regulates the amount of particulate in the air and the USEPA is expected to implement even more stringent rules that regulate the amount of dust allowable on and near Army installations.

b. Army Regulations 200-1 through 200-3 are in place for protection and management of environmental resources at Army facilities. Army land resource management personnel are responsible for the management of natural resources, which can be damaged by excessive airborne dust in the air and dust deposited on Army lands.

c. NEPA requires federal agencies to integrate environmental values into their decision-making processes by considering the environmental impacts of their proposed actions and reasonable alternatives to those actions. Capturing fugitive dust with vegetation would be a mitigation technique to minimize the impact of dust created by Army training lands.

d. Vehicle movement on unpaved roads and trails on U.S. Army installations generates significant particulate matter emissions that consist mainly of fugitive dust. The topography, vegetative groundcover, wind direction, and other localized terrain features can significantly limit the amount of dust emissions which are transported regionally. Considerable evidence shows that vegetative groundcover bordering an emission source captures dust at rates significantly higher than are accounted for by the dispersion models used for regulatory purposes.

e. Foliage, especially tall, dense vegetation is hypothesized to control fugitive dust emissions by: (1) capturing particles on leaves through gravitational settling, (2) electrophoresis (movement of charged particles due to electrical field gradients), (3) thermophoresis (movement of particles due to temperature gradients), and (4) extra particle settling time provided in stilling zones characterized by decreased wind speeds within the foliage. The three key factors associated with vegetative capture of fugitive dust particles are the height of vegetation, density of vegetation, and proximity of vegetation to the source of emissions.

f. For the best protection from fugitive dust, vegetation should be as tall as possible and the leaves should be as fine as possible. Consequently, conifers (e.g., red cedar or shortleaf pine) are most effective due to the structure of the leaves (needles) and because they hold their leaves year-round.

g. This report discusses the use of vegetation on U.S. Army installations to decrease dust plumes caused by vehicle movement along unpaved roads and off-road areas. The report summarizes the key factors associated with vegetation capture of dust particles.

h. Appendix A contains background information on the basic factors affecting fugitive dust.

i. Appendix B discusses the use of vegetative windbreaks for the control of fugitive dust movement across a landscape.

j. Appendix C discusses types of vegetation that improve dust capture and protection on training areas.

k. Appendix D contains conclusions and summary information.

l. Appendix E contains references cited.

m. Appendix F contains a list of acronyms and abbreviations used, along with their spellouts.

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APPENDIX A

INTRODUCTION TO FUGITIVE DUST FACTORS

At U.S. Army installations, vehicle movement on unpaved roads and trails generates significant particulate-matter emissions which consist mainly of fugitive dust (Figure A-1). Localized terrain features such as topography, vegetative groundcover, wind direction, and others can significantly limit the amount of dust emissions which are transported regionally. Considerable evidence shows that when vegetative groundcover borders an emission source, dust is captured at rates significantly higher than those accounted for by dispersion models used for regulatory purposes.

Figure A-1. Military equipment on terrain without vegetative groundcover can create significant fugitive dust.

Foliage — especially tall, dense vegetation – is hypothesized to control fugitive dust emissions by: (1) capturing particles on leaves through gravitational settling, electrophoresis, and thermophoresis; and (2) providing extra particle settling time in stilling zones characterized by decreased wind speeds within the foliage. The key factors associated with vegetative capture of fugitive dust particles are:

- height of vegetation,
- density of vegetation, and
- proximity of vegetation to the source of emissions.

The leaf area index (LAI) defines an important structural property of plant canopy because it is an indicator of the number of leaf layers in the vegetation relative to a unit of ground area. LAI quantifies the plant canopy structure and is highly related to a variety of canopy processes, such as water interception, evapotranspiration, photosynthesis, respiration, and leaf litter. In addition, LAI is a good measure of foliage density and is related to wind interception and the capture of ambient aerosol, the mixture of liquid and solid particles contained in surrounding air.

The capture of an ambient aerosol near its source is important because if fugitive dust emissions are dispersed by winds to heights above the foliage, they will not be captured by vegetation. For example, under unstable atmospheric conditions a sizeable fraction of particulate matter (PM) released from an unpaved road can be lofted above the highest trees if they are located a significant distance downwind of the release point. In contrast, tall and dense trees adjacent to an unpaved road will capture PM emissions at a high level of efficiency.

Vegetative ground covers (e.g., grasses, shrubs, and trees) that border an open dust emission source capture a significant amount of fugitive dust within a short distance. Near the source, where emissions are traditionally measured, most of the dust plume’s mass lies within the first 2 m above ground level (Grantz et al. 1998; Countess et al. 2001). In addition, existing research on thermal effects (Flagan 2001) and electrostatic effects (Gieseke 1972), windbreaks in agricultural areas, and anecdotal observations all support the notion that vegetative surfaces are very effective at capturing dust.

Figure A-2 illustrates an example of the changing particle size distribution of a fugitive dust plume as it is transported downwind from a source and potentially into the “regional transport layer.” A fugitive dust source, such as a vehicle moving on an unpaved road, emits a cloud with a wide range of particle sizes. At a distance of 5 m from the source, virtually the entire particle mass is contained within a layer that extends to about 6 m above the ground surface.

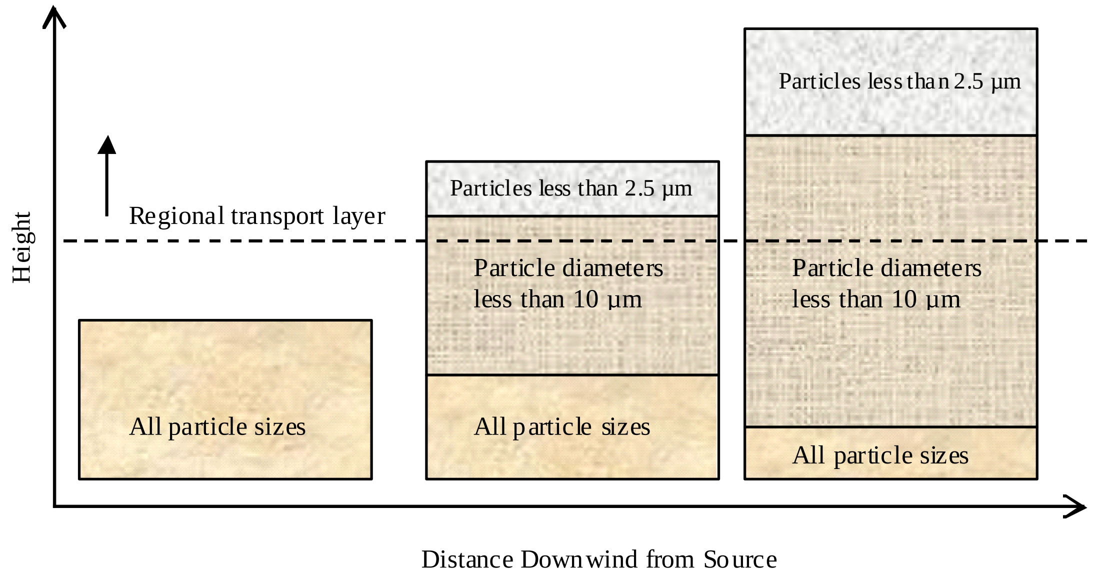

Figure A-2. Particle size distributions of a fugitive dust plume transported downwind of the source and into the regional transport layer. The figure's axes represent the relationships between height and distance variables with particle size behavior in any unit of measure.

As the dust plume drifts downward, the larger particles are preferentially removed from the atmosphere (due to gravity), but the smaller particles tend to disperse upward. If this dust plume is intercepted by tall vegetation downwind of the dust source, fewer particles will be lofted into the regional transport layer, or, above a height of about 10 m from the ground surface.

For any vegetation that creates moderate-to-high airflow blockage, the height of groundcover relative to the vertical profile of horizontal dust flux is important. As the distance between the center of the dust source and the beginning of vegetation increases, the effective height of the dust plume will increase. At the same time, any shielding of the dust source by the vegetation may be lost. Even sources surrounded by a forest would be characterized by a large source-to-groundcover transport distance if the source area itself is very large, such as the training and testing areas found on Army installations.

APPENDIX B

VEGETATIVE WINDBREAKS AS DUST COLLECTORS

Windbreaks are barriers used to reduce and redirect wind, and they have been used in agricultural settings for decades to alter microclimate in sheltered areas. Historically, field windbreaks have been planted to control wind erosion and protect crops in agricultural fields. A typical multi-row windbreak is composed of dense conifer trees to reduce wind velocity, tall broadleaf or conifer trees to extend the area of protection, and low shrubs to stop lower winds and provide wildlife habitats (Wilson and Josiah 2004). Windbreaks should be oriented perpendicular to prevailing winds to provide the most effective protection from wind erosion that causes fugitive dust emissions. In addition, the porosity of the windbreak is most important for determining how and to what extent a windbreak will capture fugitive dust particles.

As wind blows against and partially through a windbreak, air pressure builds up on the upwind side. Dense windbreaks are not desirable for low-level fugitive dust plumes, since air will move up and over the top of the windbreak. The three-dimensional aerodynamic structure of windbreaks is complex. Zhou et al. (2002) approximated the aerodynamics of windbreaks by using two structural descriptors: (1) vegetative surface area density (vegetative surface area per unit canopy volume) and (2) cubic density (vegetative volume per unit canopy volume).

Air will flow around the windbreak locations where tree density is high, and will converge at the spots where the density is low. The key components that determine a windbreak structure’s effectiveness in reducing wind speed include height, density, width, species, and orientation with respect to the wind. The maximum downwind extent of the wind reduction “shadow” depends on the windbreak height as the most important factor. The wind reduction “shadow” is positively correlated to the extent of the “stilling zone” and the efficiency of vegetative capture of fugitive dust.

The ideal vegetation for capture of dust from adjacent sources consists of native species that are tall, long-lived, and have good rates of growth. The vegetative windbreak should be oriented perpendicular to the prevailing wind direction.

The windbreak’s overall density should be 40%–60% during warm seasons for effective wind erosion control. This density also should be maintained during winter conditions, when most deciduous trees have lost their leaves. Typically, this means that a coniferous species with a shrub understory is desirable in order to prevent gaps between trees that can cause wind tunneling through the vegetation (Figure B-1).

Figure B-1. Tall coniferous trees in a windbreak will provide high shrub density in both summer and winter.

Densities of cedar trees are classed as “high” during both summer and winter seasons (University of Toronto 2002). Deciduous trees have medium densities during the summer season and low densities during winter after leaves have fallen.

A maximum 50% density is recommended for dust control from upwind sources because of the need to capture and slow down most of the airborne particles within the windbreak. Otherwise, fine particles will be transported over the windbreak and injected into the atmosphere’s transport layers.

Evergreen windbreaks typically are less porous than deciduous windbreaks. Tightly planted and dense short species such as multiple rows of eastern red cedar (*Juniperus virginiana*) may be less desirable for vegetative capture than multiple rows of taller and less-dense hedge trees such as Osage orange (*Maclura pomifera*).

It is well known that tree leaves and needles provide extensive surfaces for the deposit of airborne contaminants. In a review of the capacity of trees to intercept atmospheric deposition, Augusto et al. (2002) stated that deposition “depends on the height, LAI, foliage longevity, canopy structure, form or shape of leaves, topographic position and the distance to the forest edge." The authors also note that:

> On similar soils, coniferous species usually are taller than hardwood stands of the same age, have a higher LAI, and often have persistent foliage. Thus, it is not surprising that coniferous species intercept more elements from the atmosphere, compared to hardwood species.

Generally, single-row windbreaks are used for soil erosion control (Wilson and Josiah 2004), and are planted perpendicular to the area to be protected. The area protected by the windbreak is a function of the average height of the vegetation. As a general rule, the area protected is 10-15 times the average height (H) of the vegetation composing the windbreak. As an example, if the average height of the vegetation is 30 m, then the area protected is 300-450 m^2.

Two single-row windbreaks, with the space between rows equal to 15 times the height of the mature vegetation, may be better protection than one double-row windbreak. The two single-row windbreaks will protect twice the area while using the same amount of land as one double-row windbreak. If the area to be protected is extremely unobstructed, more rows will be needed to effectively influence wind speeds. One important consideration in windbreak design is maximizing the diversity of species to reduce the risk of insect, disease, or environmental problems, while also providing wildlife habitat.

APPENDIX C

VEGETATION AND FUGITIVE DUST CAPTURE

Pace and Coward (2003) proposed that the near-source/near-surface depletion of particles is composed of two parts: (1) the particles that are removed as they pass within and through nearby vegetation, and (2) the particles that pass over, but are close to the top of vegetation. Vertical profiles of horizontal dust flux from mechanically generated fugitive dust sources show that most of the dust mass leaving the source is contained in the air layer between the surface and 2 m above the surface. Thus, the need for treatment can be significant of enhanced deposition particles that are initially below the height of surrounding vegetation.

The effectiveness of vegetative ground cover in capturing fugitive dust particles is affected by the airflow blockage created by the ground cover and by the transport distance between the center of the dust source and the near edge of dominant vegetation. Depending on the vegetation's characteristics, the transport environment may range from essentially open to one that has a high degree of airflow blockage.

At one extreme is a dust transport environment that is open, such as an open field with grass-covered surface, or a desert area with scattered vegetation on otherwise bare ground. In the case of the grass-covered surface, the dust-laden airflow passes over the vegetation as it would any type of shallow ground cover. In the case of the scattered vegetation, the dust-laden airflow passes between and around the vegetative structures. In both cases, there is little vegetation to block the airflow. As a result, the distance between the source and the near edge of the bordering vegetation is not an important factor.

At the other extreme is a dust transport environment with significant airflow blockage such as a forest with tall, relatively dense vegetation. Because vegetation height is greater than dust plume height, the separation between the edge of the source and the edge of the vegetation is important, as discussed below.

If a narrow dust source is imbedded within the forest, as is the case of an unpaved road that cuts through the trees (Figure C-1), the transport environment may be represented as an open notch in the tree canopy. Within the notch, the airflow is substantially reduced compared to the ambient airflow that passes over the forest, except when the wind direction matches the road direction. If the notch is deep enough relative to its width, the airflow at the bottom of the notch may actually move in a direction opposite to the flow above the forest. In any case, it is likely that most of the dust emissions generated within the notch will not pass from the notch into the open atmosphere.

Figure C-1. Example of dust capture from Shelby truck on narrow, unpaved road that cuts through trees and vegetation.

If the trees are sufficiently distant from the road (e.g., road creates more than 25 m of bare or grass-covered soil), the ambient airflow above the forest will dip down over the road. As the emissions are transported by the air away from the road and approach the forest, part of the airflow will pass into the forest and the rest will be diverted upward. The fraction of the airflow that passes into the forest will depend on the density of the forest and the resultant degree of airflow blockage that it creates.

The portion of air that passes into the forest will enter into a relatively quiet zone, with much lower net transport speed and a very good opportunity for dust deposition. The top of this relatively quiet layer within the forest may be represented in terms of the displacement height, which according to Slinn (1982), is of the order of 0.8 times the height of the trees. Above the displacement height, however, a more pronounced effect of the ambient wind is experienced. In other words, the airflow above the trees is similar to what would be found if only the tops of the trees were superimposed at ground level on an open field.

Since much of the particle mass from dust that passes into the forest will be captured over a relatively short travel distance (estimated to be approximately 200 m), the fraction of dust particles collected will be approximately the same as the fraction of the transport air that passes into a forest as opposed to being diverted upward (Countess et al. 2001). Even the dust particles that are diverted above the trees have some opportunity for enhanced capture on the treetops.

For any vegetation that creates moderate to high airflow blockage, its height relative to the vertical profile of the horizontal dust flux is important. As the distance between the center of the source area and the beginning of such groundcover increases, the effective height of the dust plume will increase, and any shielding of the source by the vegetation may be lost. Even sources surrounded by a forest would be characterized by a large source-to-ground cover transport distance if the source area itself is large. Examples would include a large construction site or an open training/testing area that is surrounded by a forest.

The effectiveness of a shorter, denser ground cover with height near the dust plume should be evaluated in a manner similar to the forest. An example would be a windbreak bordering an unpaved road on an open training area. The closer the windbreak is to the dust source, the higher the particle removal fraction because the dust plume will have less opportunity to expand vertically.

The following are general guidelines for the use of buffer vegetation to provide protection against particle deposition downwind:

- Vegetation should be as aerodynamically rough as possible; that is, the height should be as tall as possible and the leaves should be as fine as possible. (Raupach and Leys 1999).

- Protection against particle deposition by a porous barrier extends downwind from a windbreak or tree belt for a distance equal to 5–10 times the average height of the trees. Local protection is generally most effective when the barrier is close to the receptor.

APPENDIX D

SUMMARY AND CONCLUSIONS

Unpaved roads and off-road vehicle areas with unpaved surfaces represent a large source of fugitive dust emissions at U.S. Army installations. However, dust is often emitted in close proximity to nearby vegetation that can reduce the plume mass of PM-10[*] through:

1) Deposition on vegetation by impaction, interception, and diffusion, as well as, electrophoresis and thermophoresis.

2) Enhanced gravitational settling of particles in “stilling zones,” where the wind velocity is reduced by the vegetation.

Thus, vegetation that borders a source area offers the potential for significant control of dust emissions while offering low associated cost or maintenance requirements.

Determination of the transport of dust plumes from unpaved roads and off-road vehicle movements must account for the depletion of particles near the source of the emissions (while the plume is still close to the ground). It is proposed that near-source and near-surface depletion of particles is composed of two parts: (1) the particles that are removed as they pass within and through nearby vegetation, and (2) the particles that pass over, but close to the top of vegetation. Vertical profiles of horizontal dust flux from mechanically generated fugitive dust sources show that most of the dust mass leaving the source is contained in the air layer between the surface and a height of 2 m above the surface.

The height, spacing, and porosity of vegetative windbreaks are important in reducing wind speeds and deposition (Raupach and Leys 1999). Moderate effectiveness of a windbreak will reduce the average wind speed for a distance of approximately 30 times the average vegetation height (Borrelli et al. 1989). Vegetative buffer areas can decrease wind speeds by 60%–80% from near the barrier to a distance of approximately 10 times the vegetation height. If placed at a distance of about 20 times the vegetation height, the buffer can reduce wind speeds by about 20% (Nordstrom and Hotta 2004).

[*] particulate matter of 10 microns or less.

For the best protection from fugitive dust, vegetation should be as tall as possible, and the leaves should be as fine as possible. Consequently, conifers such as red cedar or shortleaf pine are most effective due to their leaf structure (fine needles) and because they hold their leaves year-round.

Not all wind barriers have the proper placement, exist in sufficient quantities, or can retain effectiveness through time. This is due to difficulties in controlling many aspects of plant growth, leafiness, and flexibility.

Finally, vegetative windbreaks are subject to proper growing conditions, and therefore, are most difficult to establish in arid regions, where they may do the most good for dust suppression. Areas with short and sparse vegetation will exhibit higher levels of fugitive dust and will benefit from the addition of tree windbreaks adjacent to open training areas.

APPENDIX E

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APPENDIX F

ACRONYMS AND ABBREVIATIONS

Term	Spellout
AR	Army Regulation
BMP	best management practice
CAA	Clean Air Act
CONUS	Continental United States
DA	Department of the Army
DC	District of Columbia
ERDC	Engineer Research and Development Center
HQUSACE	Headquarters, U.S. Army Corps of Engineers
LAI	leaf area index
NEPA	National Environmental Policy Act
NW	Northwest
PDF	Portable Document Format
PL	Public Law
PM	particulate matter
POC	point of contact
PWTB	Public Works Technical Bulletin
URL	Universal Resource Locator
US	United States
USC	United States Code
USEPA	United States Environmental Protection Agency
WBDG	Whole Building Design Guide
WWW	World Wide Web