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# A note on the use of drag partition in aeolian transport models

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ABSTRACT

Sediment transport equations used in wind erosion and dust emission models generally incorporate a threshold for particle motion ($u_{*t}$) with a correction function to account for roughness-induced momentum reduction and aerodynamic sheltering. The prevailing approach is to adjust $u_{*t}$ by the drag partition $R$, estimated as the ratio of the bare soil threshold ($u_{*ts}$) to that of the surface in the presence of roughness elements ($u_{*tr}$). Here, we show that application of $R$ to adjust only the entrainment threshold ($u_{*t} = u_{*ts}/R$) is physically inconsistent with the effect of roughness on the momentum partition as represented in models and produces overestimates of the sediment flux density ($Q$). Equations for $Q$ typically include a friction velocity scaling term ($u_*^n$). As $Q$ scales with friction velocity at the soil surface ($u_{s*}$), rather than total friction velocity ($u_*$) acting over the roughness layer, $u_*^n$ must be also adjusted for roughness effects. Modelling aeolian transport as a function of $u_{s*}$ represents a different way of thinking about the application of some drag partition schemes but is consistent with understanding of aeolian transport physics. We further note that the practice of reducing $Q$ by the vegetation cover fraction to account for the physically-protected surface area constitutes double accounting of the surface protection when $R$ is represented through the basal-to-frontal area ratio of roughness elements ($\sigma$) and roughness density ($\lambda$). If the drag partition is implemented fully, additional adjustment for surface protection is unnecessary to produce more accurate aeolian transport estimates. These findings apply equally to models of the vertical dust flux.

## 1. Introduction

Many of the world's active aeolian environments are covered with rocks and vegetation that attenuate wind flow over the land surface and influence the magnitude and spatial distribution of sediment transport. Representing these dynamics presents a challenge for accurate aeolian transport modelling. Drag partition schemes are used in aeolian transport and dust emission models to account for the momentum reduction and aerodynamic sheltering of the soil surface induced by non-erodible roughness. After Gillette and Stockton (1989) and Raupach et al. (1993), application of drag partition schemes has followed the practical hypothesis that the main dynamical effect of adding roughness to an erodible surface is to increase the threshold wind friction velocity ($u_{*t}$) such that:

$$u_{*t}(D, R) = \frac{u_{*ts}(D)}{R} \tag{1}$$

where $u_{*ts}(D)$ is the threshold wind friction velocity of the bare soil as a function of grain size $D$, and $R$ is the drag partition that is calculated as a function of the roughness frontal area index $\lambda$ (Raupach et al., 1993, Shao and Yang, 2008) or the ratio of the aerodynamic roughness lengths of the soil substrate ($z_{0s}$) and rough land ($z_0$) surface (Marticorena and Bergametti, 1995). In application,

$$R = \left(\frac{\tau_s'}{\tau}\right)^{1/2} = \frac{u_{*ts}}{u_{*tr}} \tag{2}$$

where $\tau'_S$ is the average shear stress (N m$^{-2}$) at the exposed and unsheltered soil surface, $\tau$ is the total shear stress on the surface in the presence of roughness, and $u_{*ts}/u_{*tr}$ is the ratio of threshold wind friction velocity of the soil substrate to the rough land surface (Raupach et al., 1993). The prevailing approach has been to implement the drag partition through Eq.(1) to estimate the streamwise sediment flux density $Q$ (g m$^{-1}$ s$^{-1}$) following (e.g., after Kawamura, 1951):

$$Q = C\frac{\rho_a}{g}u_*^3\left(1 - \frac{u_{*t}^2(R)}{u_*^2}\right)\left(1 + \frac{u_{*t}(R)}{u_*}\right) \tag{3}$$

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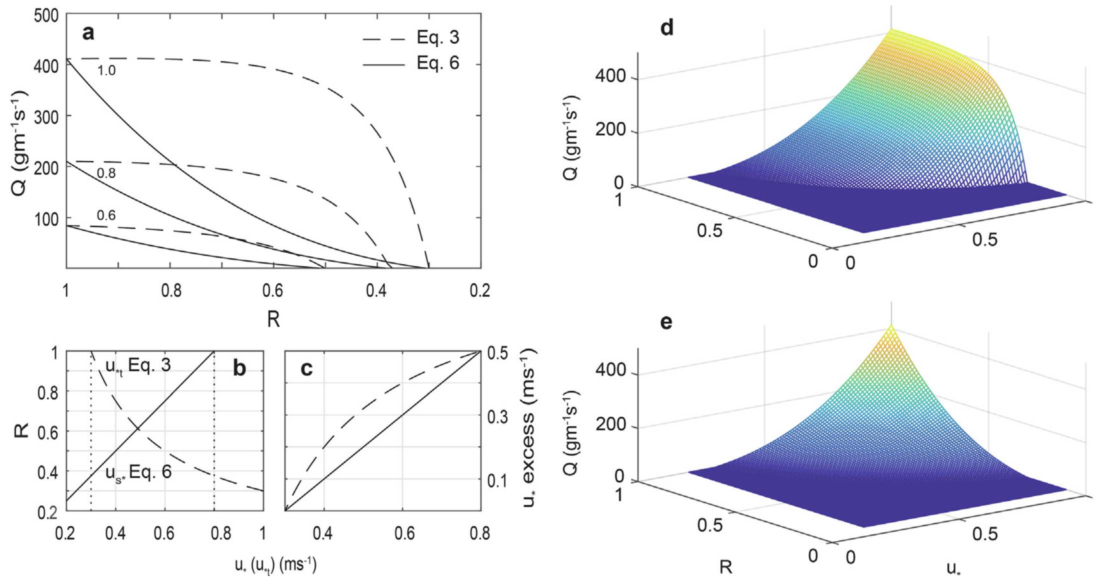


**Fig. 1.** Graph (a) illustrating the effect of incomplete (Eq. (3)) and complete (Eq. (6)) implementation of the drag partition $R$ on streamwise sediment flux density $Q$ (g m$^{-1}$ s$^{-1}$) for soil threshold wind friction velocity $u_{*ts} = 0.3$ m s$^{-1}$ and total wind friction velocities ($u_* = u_*$) of 0.6, 0.8 and 1 m s$^{-1}$. Differences in $Q$ responses to increasing roughness (decreasing $R$) are determined by the nonlinear increase in $u_{*t}$ with decreasing $R$ if only adjusting $u_{*ts}$ by $R$ (Eq. (3)), while for Eq. (6) $u_{s*}$ responds linearly to the adjustment of $u_*$ by $R$, shown in panel (b) for $u_{*ts} = 0.3$ m s$^{-1}$ and $u_* = 0.8$ m s$^{-1}$. Using the same values of $R$ from (b), panel (c) shows that for a given reduction of $u_*$ from 0.8 m s$^{-1}$ to $u_{s*}$, Eq. (3) produces a nonlinear increase in excess wind friction velocity (calculated as $u_* - u_{*t}$) compared to that produced by Eq. (6). Over a range of wind friction velocities and roughness densities, $Q$ (Eq. (3)) remains large and then rapidly declines at large roughness densities (d) when it should decline with increasing roughness (e). Values of $Q$ for (a), (d) and (e) were calculated using Kawamura (1951), with $C = 2.78$, $\rho_a = 1230$ kg m$^3$, and $g = 9.8$ m s$^{-2}$.

where $u_*$ is the total wind friction velocity over the rough surface (m s$^{-1}$), $\rho_a$ is the air density (g m$^{-3}$), $g$ is the acceleration of gravity (m s$^{-2}$), and $C$ is a dimensionless fitting parameter. The vertical dust mass flux $F$ (g m$^{-2}$ s$^{-1}$) is then typically calculated as a function of $u_*$, $u_{*t}$ and/or $Q$ following empirical (e.g., Marticorena and Bergametti, 1995) or physically-based (e.g., Shao, 2004; Kok et al., 2014) dust emission schemes. Explicit in Eq. (3) is that $u_*$ represents the total shear stress ($\tau$) acting on the roughness elements ($\tau_r$) and soil surface ($\tau_s$), which can be partitioned such that:

$$\tau = \rho_a u_*^2 = \tau_r + \tau_s \tag{4}$$

In the absence of surface roughness, $\tau_r = 0$ and the total shear stress $\tau = \tau_s$. Expressing the shear stresses as friction velocities gives the total wind friction velocity $u_*$, that is the sum of fiction velocities on the roughness elements ($u_{r*}$) and soil surface ($u_{s*}$) (Chappell and Webb, 2016).

An alternative approach for implementing the drag partition is to directly reduce the wind momentum flux at the soil surface ($u_{s*}$), rather than adjusting the interial force through $u_{*t}$ (e.g., Okin, 2008; Webb et al., 2014). In this case, the drag partition is expressed as the shear stress ratio $R = u_{s*}/u_*$ (following Eq. (2)) such that:

$$u_{s*} = u_* R \tag{5}$$

Implementing the drag partition using Eq. (5) to estimate $Q$ follows:

$$Q = C\frac{\rho_a}{g}u_{s*}^3\left(1 - \frac{u_{*ts}^2(D)}{u_{s*}^2}\right)\left(1 + \frac{u_{*ts}(D)}{u_{s*}}\right) \tag{6}$$

noting that the threshold wind friction velocity $u_{*ts}$ is expressed only as function of soil properties such as grain diameter ($D$) as it represents the shear stress at the surface required to entrain soil grains (Gillette and Stockton, 1989). This implementation of the sediment transport equation is consistent with its derivation over ideal (bare, smooth) surfaces for which $\tau = \tau_s$ (Durán et al., 2011). In the absence of roughness, Eq. (3) and Eq. (6) therefore produce the same values of $Q$. However, when the drag partition $R$ is applied to estimate $Q$ over rough surfaces following Eq. (3), the approach does not produce the same value as Eq. (6). Here, we show following theory based on experimental evidence that application of the drag partition to model aeolian transport following Eq. (3) is incomplete, leading to considerable overestimation of $Q$ and $F$. Furthermore, we show that misinterpretation of the Raupach et al. (1993) drag partition scheme may have led to inappropriate adjustment of some models to account for surface protection by vegetation.

## 2. Application of drag partition corrections

Applying the drag partition following Eq. (3) assumes that the entire effect of the momentum partition can be expressed through $u_{*t}$ (i.e., Eq. (1)). That is, as non-erodible roughness increases on a surface, the value of $R$ decreases and $u_{*t}$ increases. The wind friction velocities in Eq. (3) remain unadjusted as $u_*$. If the effect of $R$ is represented as a reduction in wind momentum following Eq. (5), the ratios expressed in brackets in Eq. (6) will produce the same value as the terms in brackets in Eq. (3) so that:

$$\left(1 - \frac{u_{*t}^2(R)}{u_*^2}\right)\left(1 + \frac{u_{*t}(R)}{u_*}\right) = \left(1 - \frac{u_{*ts}^2(D)}{u_{s*}^2}\right)\left(1 + \frac{u_{*ts}(D)}{u_{s*}}\right) \tag{7}$$

Consequently, $Q$ calculated following Eq. (3) will scale with the total wind friction velocity ($u_*$) while $Q$ calculated following Eq. (6) will scale with the surface wind friction velocity ($u_{s*}$) that is smaller due to the momentum partition, so for $R < 1$:

$$u_*^3\left(1 - \frac{u_{*t}^2(R)}{u_*^2}\right)\left(1 + \frac{u_{*t}(R)}{u_*}\right) > u_{s*}^3\left(1 - \frac{u_{*ts}^2(D)}{u_{s*}^2}\right)\left(1 + \frac{u_{*ts}(D)}{u_{s*}}\right) \tag{8}$$

For the same momentum partition over non-erodible roughness, $Q$ calculated following Eq. (3) will be larger than $Q$ calculated following Eq. (6), and therefore physically inconsistent. In this comparison, Eq. (6) provides a robust reference as it is consistent with both drag partition measurements and theory (e.g., Marshall, 1971; Gillette and Stockton, 1989; Gillies et al., 2007; Brown et al., 2008), and with formulation of aeolian transport equations (Durán et al., 2011). The effect on $Q$ is illustrated in Fig. 1 for a range of $R$ and wind friction velocities. Following Eq. (3), when $u_*$ exceeds $u_{*t}$, transport rates rapidly approach those predicted for bare surfaces even at small $R$ (large density of roughness). In contrast, $Q$ predicted using Eq. (6) follows a response more consistent with our understanding of aeolian transport processes, where transport rates decrease with increasing roughness on the bed (e.g., Lyles and Allison, 1981; Leys, 1991; Armbrust and Bilbro, 1997; Gillies et al., 2006). If a drag partition is used to account for the effects of non-erodible roughness on $Q$ following Eq. (3), then the correction $R$ must be applied to both the threshold wind friction velocity inside the brackets and the wind friction velocity outside the brackets. Correct implementation of Eq. (3) is therefore:

$$Q = C\frac{\rho_a}{g}(R.\ u_*)^3\left(1 - \frac{u_{*t}^2(R)}{u_*^2}\right)\left(1 + \frac{u_{*t}(R)}{u_*}\right) \tag{9}$$

While accurate estimation of $R$ has proven difficult following Raupach et al. (1993) and Marticorena and Bergametti (1995) due to challenges of parameterising the schemes (Pierre et al., 2014), not adjusting the $u_*^n$ term by $R$ likely explains a large part of observed differences between $Q$ estimated from measured $u_{s*}$ and the drag partition schemes (e.g., Webb et al. 2014). Not adjusting $u_*^n$ by $R$ would suggest that aeolian transport scales with the total wind friction velocity (i.e., over the non-erodible roughness) and not with the reduced fiction velocity acting on the exposed soil surface. Our comparison of Eq. (3) with Eq. (6) is agnostic of how $R$ is obtained. Observed underestimation of $Q$ following Raupach et al. (1993) has been due to parameterization of the drag partition scheme (e.g., Li et al., 2013), rather than the issue we address here of how drag partition is applied in aeolian transport equations. In the majority of dust model applications, it is impractical to validate the drag partition and so the apparent error in $Q$ given by Eq. (3) has likely been hidden by parameterization uncertainties (Shao et al., 2015). Other sources of uncertainty affecting aeolian transport models in aerodynamically rough environments include: (1) uncertainty in how the streamwise sediment flux density scales with $u_{s*}$ within plant interspaces; (2) uncertainty in the effect of interception of sediment flux by vegetation; and (3) uncertainty in the effect of sediment supply limitation on the scaling and magnitude of sediment flux (e.g., Macpherson et al., 2008).

## 3. Accounting for the vegetation cover fraction

In typical applications of the drag partition (Eq. (3)), the vegetation cover fraction is often used to scale (reduce) the streamwise sediment flux density (e.g., Marticorena and Bergametti, 1995; Zender et al., 2003; Shao, 2008), for example:

$$Q = (1 - f_c)C\frac{\rho_a}{g}u_*^3\left(1 - \frac{u_{*t}^2}{u_*^2}\right)\left(1 + \frac{u_{*t}}{u_*}\right) \tag{10}$$

where $f_c$ is the fractional vegetation cover. The physical basis for the inclusion of $(1 - f_c)$ is that it reduces aeolian transport to the erodible portion of the land surface by removing the surface fraction that cannot contribute sediment. Depending on vegetation type, it is often the basal cover of vegetation that reduces the surface area over which aeolian transport can occur, although $f_c$ is estimated in global models as the vegetation canopy cover from Normalised Difference Vegetation Index (NDVI) or Leaf Area Index (LAI) data (Shao, 2008). The adjustment to $Q$ is justified when used with drag partition schemes that do not explicitly represent physical surface protection by roughness in addition to aerodynamic sheltering effects (e.g., Marticorena and Bergametti, 1995; Okin, 2008). It may also be justified for roughness with small frontal area but large fractional ground cover. However, in the Raupach et al. (1993) drag partition given by:

$$R(\lambda) = \frac{u_{*ts}}{u_{*tr}} = \left(\frac{\tau_s'^{\prime}}{\tau}\right)^{1/2} = \left[\frac{1}{(1 - m\sigma\lambda)(1 + m\beta\lambda)}\right]^{1/2} \tag{11}$$

where $\tau''_s$ is the maximum shear stress at the soil surface, $\sigma$ is the basal-to-frontal area ratio of roughness elements, $\beta$ is the ratio of the drag coefficient for isolated roughness elements to the drag coefficient for the surface, and $m$ accounts for nonuniformity of the surface stress, the factor $(1 - \sigma\lambda)^{-1/2}$ explicitly accounts for the amplification of $\tau'_s$ over the erodible surface area due to "occupation of a fraction $\sigma\lambda$ of the total surface area by the bases of roughness elements" (Raupach et al., 1993; 3025). This implies that adjusting $Q$ by $(1 - f_c)$ constitutes double accounting for the physically-protected surface area. Models that also adjust $F$ by $(1 - f_c)$ compound the scaling if $F$ is dependent on $Q$ that itself has already been adjusted (e.g., LeGrand et al., 2019). Should the drag partition be implemented fully (i.e., following Eq. (6) or Eq. (9)), additional adjustment of $Q$ and $F$ for surface protection would be unnecessary to produce more accuracte estimates of aeolian transport.

## CRediT authorship contribution statement

**Nicholas P. Webb:** Conceptualization, Formal analysis, Writing - original draft. **Adrian Chappell:** Conceptualization, Formal analysis, Writing - review & editing. **Sandra L. LeGrand:** Conceptualization, Writing - review & editing. **Nancy P. Ziegler:** Conceptualization, Writing - review & editing. **Brandon L. Edwards:** Formal analysis, Writing - review & editing.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Supplementary data

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## References

Armbrust, D.V., Bilbro, J.D., 1997. Relating plant canopy characteristics to soil transport capacity by wind. Agron. J. 89, 157–162.
Brown, S., Nickling, W.G., Gillies, J.A., 2008. A wind tunnel examination of shear stress partitioning for an assortment of surface roughness distributions. J. Geophys. Res. 113, F02S06. https://doi.org/10.1029/2007JF000790.
Chappell, A., Webb, N.P., 2016. Using albedo to reform wind erosion modelling, mapping and monitoring. Aeolian Res. 23, 63–78.
Durán, O., Claudin, P., Andreotti, B., 2011. On aeolian transport: grain-scale interactions, dynamical mechanisms and scaling laws. Aeolian Res. 3, 243–270.
Gillette, D.A., Stockton, P.H., 1989. The effect of nonerodible particles on wind erosion of erodible surfaces. J. Geophys. Res. 94, 12,885–812,893.
Gillies, J.A., Nickling, W.G., King, J., 2006. Aeolian sediment transport through large patches of roughness in the atmospheric inertial sublayer. J. Geophys. Res. 111 (F02006). https://doi.org/10.1029/2005JF000434.
Gillies, J.A., Nickling, W.G., King, J., 2007. Shear stress partitioning in large patches of

roughness in the atmospheic inertial sublayer. Bound.-Layer Meteorol. 122, 367–396.
Kok, J.F., Mahowald, N.M., Fratini, G., Gillies, J.A., Ishizuka, M., Leys, J.F., Mikami, M., Park, M.-S., Park, S.-U., Van Pelt, R.S., Zobeck, T.M., 2014. An improved dust emission model - Part 1: Model description and comparison against measurements. Atmos. Chem. Phys. 14, 13023–13041.
Kawamura, R., 1951. Study of sand movement by wind, Translated (1965) as Hydraulic Engineering Laboratory Report HEL-2-8, pp. 57. Univ. of California, Berkeley, Calif.
LeGrand, S.L., Polashenski, C., Letcher, T.W., Creighton, G.A., Peckham, S.E., Cetola, J.D., 2019. The AFWA dust emission scheme for the GOCART aerosol model in WRF-Chem v3.8.1 geoscientific model. Development 12, 131–166.
Leys, J.F., 1991. Towards a better model of the effect of prostrate vegetation cover on wind erosion. Vegetatio 91, 49–58.
Li, J., Okin, G.S., Herrick, J.E., Belnap, J., Munson, S.M., Miller, M.E., Vest, K., Draut, A.E., 2013. Evaluation of a new model of aeolian transport in the presence of vegetation. J. Geophys. Res. 118 (1–19), 2013. https://doi.org/10.1002/jgrf.20040.
Lyles, L., Allison, B.E., 1981. Equivalent wind erosion protection from selected crop residues. Trans. ASAE 24, 405–408.
Macpherson, T., Nickling, W.G., Gillies, J.A., Etymezian, V., 2008. Dust emissions from undisturbed and disturbed supply-limited desert surfaces. F02S04002008. J. Geophys. Res. 113. https://doi.org/10.1029/2007JF000800.
Marshall, J.K., 1971. Drag measurements in roughness arrays of varying density and distribution. Agr. Meteorol. 8, 269–292.
Marticorena, B., Bergametti, G., 1995. Modeling the atmospheric dust cycle: 1. Design of a soil-derived dust emission scheme. J. Geophys. Res. 100, 16,415–416,430.
Okin, G.S., 2008. A new model of wind erosion in the presence of vegetation. F02S10002008. J. Geophys. Res. 113. https://doi.org/10.1029/2007JF000758.
Pierre, C., Bergametti, G., Marticorena, B., Kergoat, L., Mougin, E., Hiernaux, P., 2014. Comparing drag partition schemes over a herbaceous Sahelian rangeland. J. Geophys. Res. Earth Surf. 119, 2291–2313.
Raupach, M.R., Gillette, D.A., Leys, J.F., 1993. The effect of roughness elements on wind erosion threshold. J. Geophys. Res. 98, 3023–3029.
Shao, Y., 2004. Simplification of a dust emission scheme and comparison with data. J. Geophys. Res. 109 (D10202), 2004. https://doi.org/10.1029/2003JD004372.
Shao, Y., 2008. Physics and Modelling of Wind Erosion. Kluwer Academic Publishers, London.
Shao, Y., Yang, Y., 2008. A theory for drag partition over rough surfaces. J. Geophys. Res. 113, F02S05. https://doi.org/10.1029/2007JF000791.
Shao, Y., Nickling, W., Bergametti, G., Butler, H., Chappell, A., Findlater, P., Gillies, J., Ishizuka, M., Klose, M., Kok, J.F., Leys, J., Lu, H., Marticorena, B., McTainsh, G., McKenna-Neuman, C., Okin, G.S., Strong, C., Webb, N.P., 2015. A tribute to Michael R. Raupach for contributions to aeolian fluid dynamics. Aeolian Res. 19, 37–54.
Webb, N.P., Okin, G.S., Brown, S., 2014. The effect of roughness elements on wind erosion: the importance of surface shear stress distribution. J. Geophys. Res.: Atmos. 119, 6066–6084.
Zender, C.S., Bian, H., Newman, D., 2003. The mineral dust entrainment and deposition (DEAD) model: description and 1990s dust climatology. J. Geophys. Res. 108, 4416–4439.