Supplementary Information

Kelp Model

Initation of motion of a grain begins when the driving forces acting on that grain, $F_{driving}$, are equal to the resisting forces acting on the grain, $F_{resisting}$.

$$F_{driving} = F_{resisting} \qquad [1]$$

In this case, kelp contributes to the driving forces of the grain by translating a tension force, F_t, along its stipe, modifying this balance to the following

$$F_{driving} + F_t = F_{resisting} \qquad [2]$$

First, we quantify the force balance acting on the kelp frond, in which the buoyant force, Fb, the drag force, Fd, result in the tension force, Ft, acting along the length of the kelp stipe. We then quantify the force balance acting on only the grain. We then apply the tension force to the force balance acting on the grain to determine the onset of motion of

Forces on Kelp

The Buoyant Force

Since the kelp frond has a different density than that of the water surrounding it, a net buoyant force acts in the upward direction. This density difference is partially attributed to the pneumatocysts, or large gas-filled bladders, which allow kelp fronds to float within the water column. The buoyant force is given by

$$F_b = (\rho_k - \rho_f)gV \qquad [3]$$

where ρ_k is the kelp density (kg/m^3), ρ_f is the fluid density (kg/m^3), g is acceleration due to gravity (m/s^2) and V is the volume of the kelp frond (m^3). Due to the buoyant force's dependence on material properties, it remains constant and acts in the upward direction regardless of current conditions.

For bull kelp specifically:

$$F_b = 2\text{ N};\ 12\text{ N};\ 25\text{ N} \qquad [4]$$

The density of kelp is not well-reported, and thus, instead we rely on empirical measurements of the mean buoyant force for each kelp species we consider (Friedland and Denny, 1995; Utter and Denny, 1996; Denny et al., 1997; Stevens et al., 2001) . However, the relationship of the buoyant force and the size of the kelp frond are not well correlated. Here, we utilize empirical measurements of kelp buoyant force made in past studies (Friedland and Denny, 1995; Utter and Denny, 1996; Denny et al., 1997).

The Drag Force

A drag force acts over the cross sectional area of a kelp frond in the direction of flow as the fluid moves past the frond. The drag calculation for a kelp frond varies from species to species, as plant shape and size is highly variable, and can be modeled by the following generalized relationship (Utter and Denny, 1996).

$$F_{dk} = 0.5\rho_f u^{\beta} A_k S \qquad [5]$$

Where u is the current velocity (m/s), β is an empirically determined exponent that changes based on the shape of the kelp frond. A value of β=2 is assigned for non streamlined objects, while for streamlined objects and plates oriented parallel to the flow β=1.5 is typical [*Vogel*, 1984]. β determines how quickly drag increases as a function of the current velocity. A_k is the area of the kelp frond (m^2), and S_d is an empirically determined shape parameter similar to the drag coefficient (Friedland and Denny, 1995; Utter and Denny, 1996).

For bull kelp specifically:

$$F_{dk} = 0.5\rho_f u^{1.6} A_{xs} 0.016 \qquad [6]$$

The Tension Force

A tension force is generated in the kelp frond as the kelp stretches in the flow. As such, when a stipe is not being stretched, or equal to or less than its original length, the tension force on the frond is zero (Utter and Denny, 1996). However, when the kelp is stretched beyond its initial length, a tension force extends along the stipe in the direction of stretching. The tension force depends on the overall change in length of the kelp stipe, the kelp stiffness, and the cross sectional area of the frond. The general formulation of the tension force is as follows

$$F_t = E[(L+\Delta L)/L]^c A_{xs} \qquad [7]$$

Where E is the stiffness of the kelp stipe (Pa), a measured empirical property, L is the unstretched length of the kelp frond (m), ΔL is the change in length of the kelp frond (m), and c is an empirically determined exponent (Utter and Denny, 1996; Denny et al., 1997).

For bull kelp specifically:

$$F_t = 1.2\text{x}10^7[(L+\Delta L)/L]^1 A_{xs} \qquad [8]$$

In the static solution of the force balance used in this study, the kelp is not accelerating, and has reached a stable position within the water column. In this configuration, the tension force will balance the drag and buoyant forces acting on the frond.

Forces on the Grain

The forces acting on a sediment particle are gravity, F_g, buoyancy, F_b, and lift and drag due to flow over the bed, F_l and F_d, respectively, and a resisting force, F_r.

The Gravitational Force

The gravitational force is given by the submerged weight of the grain, where

$$F_g' = F_g - F_b = (\rho_s\text{-}\rho)gV \quad [9]$$

where ρ_s is sediment density (kg/m^3), typically 2650 kg/m^3 for coarse sand, ρ is fluid density, 1000 kg/m^3 for water, g is acceleration due to gravity (m/s^2), and V is grain volume (m^3).

The Drag Force

The formulation of the drag force is similar to that presented for kelp, though the shape parameter replaced with a drag coefficient, C_d, typically 0.4 for sediment grains. Further, the drag acting on the grain depends on the square of the velocity averaged over the grain cross-section.

$$F_d = 0.5\rho_f C_d u^2 A_{xs} \quad [10]$$

The Lift Force

The formulation of the lift force is similar to that the drag force, with slight modification

$$F_l = 0.5\rho_f C_l(u_{top}^2 - u_{bottom}^2)A_{xs} \quad [11]$$

where C_l is the lift coefficient, typically 0.2 for sediment grains, u_{top} specifies the velocity on the top of the grain (m/s), and u_{bottom} specifies the velocity at the bottom of the grain (m/s).

The Resisting Force

The force resisting downstream motion of the grain is specified as follows

$$F_r = F_n \tan\phi = (F_g'\cos\beta - F_l)\tan\phi \quad [12]$$

where F_n is the effective weight of the sediment grain (gravity minus buoyancy and lift), β is the bed slope, and tanϕ is the angle of repose, which is analogous to a coefficient of friction, typically about 30°.

The Onset of Motion of only a Grain

A sediment grain at the surface of a riverbed will begin to move when the force resisting downstream motion is equal to the force driving downstream motion, such that

$$(F_g'\cos\beta - F_l) \tan\phi = F_d + F_g'\sin\beta \quad [13]$$

Solution Method for Kelp Force Balance

It should be noted that we model the kelp frond as a point mass on an elastic string in a 2-dimensional, x,z coordinate space. We first determine the force balance for the point mass at every x,z pair in the coordinate space. We impose a law of the wall velocity profile through the water column, which has the form

$$u(z) = (u_*/\kappa) \ln(z/z_0) \quad [14]$$

where u_* is the shear velocity (m/s), κ is von Karman's constant, typically 0.4, z is the specified depth within the water column (m), and z_0 is the median grain size over 30, for hydraulically rough flows (Wiberg and Smith, 1987). Given this velocity profile, and the assumption of steady and uniform flow, we solve equations [6] and [8] for each point within the coordinate space. Since the buoyant force is imposed and constant, we do not need to explicitly solve for it in our model.

We then determine the point in the coordinate space in which the drag, buoyant, and tension forces balance, resulting in a net force of zero acting on the point mass. To do this, we split the tension force into the x and z components, and balance them separately, as follows

$$F_{net\,x} = F_{d\,k} - F_{t\,x} \qquad [15]$$

$$F_{net\,z} = F_b - F_{t\,z} \qquad [16]$$

We then locate the coordinate pair where the net force in both x and z are zero. This location represents the static solution to the kelp force balance. The tension force acting along the length of the stipe is then applied to the grain force balance as and additional driving force. The new force balance on the grain is calculated as follows

$$[F_g' \cos\beta - (F_l + F_{t\,z})] \tan\phi = F_d + F_g' \sin\beta + F_{t\,x} \qquad [17]$$

The tension force acting in the z direction reduces the resisting force, similar to the lift force, ultimately making the grain more mobile. The tension force acting in the x direction adds to the driving forces of drag and gravity, further increasing the mobility of sediment grains.

Supplementary References

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