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Primary Research Paper

Measuring the surface roughness of stream stones

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Abstract

Measuring the fine-scale heterogeneity of stones and other substrates is a challenge for benthic ecologists. I describe a method for measuring the roughness of stones that is based on the ratio of two surface area measurements: one that follows substrate contours and one based on a similar-sized modified spheroid. This roughness index is easily measured, assesses the entire surface of stones, and enables the measurement of replicate stones. Roughness measurements of 14 rock types demonstrated that values obtained were consistent with perceived roughness and porosity. Application of the roughness index to a published data set produced a curvilinear relationship between stone roughness and the biomass of algae in roughness-associated crevices.

Introduction

The distribution of benthic organisms is correlated with environmental heterogeneity at a variety of scales. For example, many fishes show longitudinal patterns of distribution in river systems (Wright & Li, 2002), whereas macroinvertebrates and algae are often influenced to a greater extent by local or small-scale heterogeneity (Archambault & Bourget, 1996; Wright & Li, 2002), resulting in more patchy distributions. Small-scale heterogeneity includes the size distribution and surface texture of substrates, which can influence productivity (Cardinale et al., 2002) and the availability of refuges (Bergey, 2005). Such small scales are especially relevant to small organisms, including protozoans and unicellular algae, and small dispersal stages of larger organisms, such as barnacles.

Small-scale heterogeneity remains a difficult factor to measure, especially at the scale of individual stones. The shape of stones can generally be described by three parameters: form, roundness and surface texture (reviewed by Barrett, 1980). Form describes the geometric shape of a stone, roundness describes the curvature of the corners and surface texture describes the small-scale roughness of the stone surface. Equations and sets of comparative images have long been available for both form and roundness, and these stone characteristics influence the effectiveness of benthic flow refugia for stream dwelling macroinvertebrates (Holomuzki & Biggs, 2003). In contrast, methods for measuring surface roughness are more recent (i.e. no numerical parameters were available at the time of Barrett's (1980) review) and there is no consensus on any method of measuring roughness (Taniguchi & Tokeshi, 2004), despite numerous studies demonstrating biological effects of 'rough' vs. 'smooth' substrates (e.g. Dudley & D'Antonio, 1991; Bergey, 1999; Downes et al., 2000).

Overview of methods for measuring roughness

As a step in measuring roughness, many methods entail reproducing a surface profile. Clifford et al.

(1989) developed a roughness meter that used a motorized stylus to trace the surface of stones and produced a vertically exaggerated chart showing roughness peaks, the chart was then digitized for analysis. A variety of other methods have also been used. Carpenter profile tools, which consist of an array of vertical pins in a frame, can mirror the coarse-scale roughness of substrates by the displacement of pins, and measures of this displacement indicate coarse to medium-scale roughness (e.g. Underwood & Chapman, 1989; Sanson et al., 1995). More recently, laser profilometers have been used to chart the fine-scale roughness of substrates (e.g. Hills et al., 1999). Another approach has been to cast substrates with latex (Sanson et al., 1995) or plaster of Paris (Commito & Rusignuolo, 2000), coat the cast surface with ink or graphite to increase contrast, section the casts and scan the sections into a computer. Alternatively, surfaces can be photographed and the contrasts in brightness used to indicate elevational or textural changes (Schmid, 2000; see discussion in Sanson et al., 1995).

Converting profiles into a measure of roughness can involve calculation of a summary statistic (Clifford et al., 1989) or involve determining the area available to organisms of varying size. Bourget (1988) developed an electronic curvimeter to measure the proportion of surface accessible to and actually used by sessile species, such as barnacles. In this curvimeter method, wheels of 1–96 cm diameter were rolled over a 4 m length of substrate, and measurements included the total distance traveled by the wheels and the areas that the wheels contacted the substrate; both of which decreased with increasing wheel size. Sanson et al. (1995) describe a similar method in which image analysis is used to visually roll a circle over the surface. Gaps where the circle does not contact the image are delineated. An additional step can be used to determine the area available to smaller circles (organisms) within these delineated gaps.

Fractal geometry is starting to be used to describe the surface texture of substrates in freshwater benthic studies. Fractal methods have been used to describe textural differences in constructed substrates with a checkerboard arrangement of heights (Taniguchi & Tokeshi, 2004), estimate the fractal dimension of riverbed topography (Robson et al., 2002), and describe the substrate-water interface of streambeds (Schmid et al., 2002). Fractal geometry has also been used in marine benthic studies (e.g. Hills et al., 1999; Commito & Rusignuolo, 2000) and is widely used for measuring the surface texture in biomedical and related applications (e.g. Pimienta & Tawashi, 1999; Anselme et al., 2000; Arnold & Bailey, 2000).

All of these methods for determining roughness require specialized equipment or software and many require special expertise. Additionally, these methods measure roughness over only part of a stone, most often along a single transect. My objective was to develop a simpler method of measuring surface roughness of entire stones.

Description of method

This new method uses a ratio of two measures of surface area, one that follows the substrate's contours and a second that is based on a modified spheroid of similar dimensions.

Index of roughness = wetted layer surface area/stone shape equation area, using the methods described below and reviewed by Bergey & Getty (2006).

In the wetted layer technique (Harrod & Hall, 1962), the dry substrate is weighed, dipped into a detergent solution and reweighed to obtain the weight of the adhering detergent solution. This weight is converted to area using the regression relationship between the detergent solution weight and the surface area of spheres or other simple geometric objects. The detergent solution thinly coats all surfaces; hence the measurement reflects surface area at a micro-scale; a scale that also includes porosity.

The Graham et al. (1988) shape equation uses orthogonal stone measurements to approximate area: Surface area $= 1.15(LW + LH + WH)$, where L = length, W = width and H = height. The shape equation is based on the formula for the surface area of a spheroid, but is modified to be more realistic for stone shapes by incorporating three different diameters. The result is the surface area of a smooth, rounded stone.

Dividing the contour-following measurement of Harrod & Hall (1962) by the generalized shape measurement of Graham et al. (1988) produces a dimensionless number. Values range from slightly less than 1 for stones with flattened surfaces, for which Graham's equation overestimates surface area, to values of 15 or more for very porous stones. Values for most water-worn rocks are less than 5. This roughness index is analogous to many of the indices of form and roundness, which also compare two measures of area, volume or angularity.

Comparative roughness of different rocks

Measurements were made on 10 replicate stones of each of 14 rock types (Table 1). Data for the smooth granite are from Bergey & Getty (2006). Stones within each set varied in size and usually included gravel, pebbles and smaller cobbles. Stones were cleaned of any adhering soil and debris and air dried. Perpendicular length, width and height were measured to the nearest 0.01 mm using digital calipers. A Mettler Toledo PG503-S analytical balance, which measured to the nearest 0.001 g, was used for measuring stone weights. Stones were weighed dry, placed in a detergent-water solution for approximately 10 s, drained for 30 s, touched on the lower edge to a paper towel to remove any forming drops and re-weighed. In the second weighing the stone was placed on a piece of pre-tared weighing paper to protect the balance. The conversion equation for calculating surface area from the weight gain by wetting was determined by regression between the weight gain of wetted balls and marbles and the area of these spheres.

Roughness values ranged from 0.71 for very smooth, surf-rounded greywacke to 20.03 for very rough and highly porous travertine (Table 1). Travertine is produced by the deposition of calcium carbonate from waters flowing from limestone springs (Hynes, 1972) and travertine from Desperado Spring was notably rough and appeared sponge-like because of abundant air spaces. Other porous rocks also had high roughness and included pumice, which had enough air spaces that dried stones floated in water; scoria, which like pumice had air pockets that formed as lava cooled, but is much denser; and limestone, whose porosity was very fine and seen only indirectly as small bubbles emerging into the detergent solution. Despite the small-scale porosity of limestone, this rock commonly has endolithic blue–green algae in streams (including Brier Creek, the collection site: Bergey & Weaver, 2004) and in marine (Golubić, 1969) and terrestrial habitats (Gerrath et al., 2000). The small particle size in siltstone renders it smooth to the touch, but the porosity of the sampled rocks produced an elevated roughness.

Gypsum and granite both had paired rough and smooth rock types. The two gypsum samples

Table 1. Rocks measured for roughness, including the type of rock (Sed = sedimentary, Met = metamorphic, Ign = igneous), the location collected, mean roughness ($n = 10$) and the associated standard error

Rock description	Type	Collection site	Roughness	SE
Limestone	Sed	Brier Crk, Marshall Co., OK	4.37	0.78
Travertine	Sed	Desperado Spring, Johnston Co., OK	20.03	1.47
Gypsum (smooth)	Sed	Outcrop, Woodward Co., OK	0.87	0.05
Gypsum (rough)	Sed	Outcrop, Woodward Co., OK	2.78	0.36
Siltstone	Sed	Dry ravine, Texas Co., OK	2.21	0.23
Sandstone #1	Sed	Kiamichi River, LeFlore Co., OK	1.51	0.22
Sandstone #2	Sed	Medicine Crk, Comanche Co., OK	2.84	0.20
Greywacke	Sed	Pacific Ocean shoreline, Clallam Co., WA	0.71	0.02
Chert	Sed	Kiamichi R., LeFlore Co., OK	1.07	0.09
Schist	Met	Cook River, South Island, New Zealand	1.30	0.08
Granite (smooth)	Ign	Cimmaron R., Cimarron Co., OK	0.87	0.04
Granite (rough)	Ign	Outcrop, Comanche Co., OK	2.99	0.31
Scoria	Ign	Tubs Springs, Baca Co., CO	4.79	0.58
Pumice	Ign	Lake Taupo, North Island, New Zealand	10.94	2.29

were collected at different locations in the same weathered outcrop, and differences were likely the result of differential weathering, content of impurities, and/or conditions during stone formation. The rough granite was terrestrially weathered and, although rounded in overall shape, had a dull, very grainy surface. In contrast, the smooth granite was water-worn. For both pairs of rock types, the smooth version had roughness values of a little less than 1 and the rough versions had values approaching 3.

The sandstone samples were both water-worn, but were collected at different sites and differed from each other in the smoothness of the surface and, possibly, in porosity. Like limestone, sandstone may have endolithic algae (Bell, 1993). Greywacke, which is lithic sandstone, lacks porosity and, as mentioned above, the sample was remarkably smooth and rounded, and consequently had a very low roughness. Schist, a metamorphic rock, had a smooth surface, but has pressure-induced planes, which produce crevices on the sides of this stone, resulting in a slightly elevated roughness measurement.

In testing this roughness index, I tried a variation in the roughness formula of using surface area estimated from foil weight (reviewed in Bergey & Getty, in press) as a substitute for Graham et al.'s (1988) shape equation. Although the foil wrap technique more closely follows the contours of stones, neither technique takes account of fine-scale roughness. Roughness values produced using foil wrap area were slightly higher than values produced using the Graham et al. (1988) shape equation; the mean roughness of the 14 rock types was 4.63 and 4.01, respectively. This difference was not significant (paired *t*-test: $t_{13} = -1.502$, $p = 0.157$). Additionally, the relationships among the types of stones were unchanged. Of the two methods, surface area is more easily measured using Graham et al.'s (1988) shape equation; hence, this method was adopted for the roughness index.

Example application of the roughness index

The usefulness of quantifying surface roughness is illustrated by re-assessing algal biomass data from a common garden experiment, in which algae colonized four substrate types that represented a gradient in roughness (Bergey, 2005). In order of perceived roughness, glass bottles were the smoothest substrate, followed by greywacke, schist and pumice rocks. After an incubation period of three weeks in a springbrook, substrates ($n = 16$ per substrate type) were scrubbed and chlorophyll *a* biomass was measured for both the algae removed by scrubbing and the algae remaining on the scrubbed substrates (see Bergey, 2005 for further methodological details). Chlorophyll *a* remaining on substrates after scrubbing was considered a measure of the biomass of algae within protective crevices.

Protected algal biomass increased with the perceived roughness of the four substrates (Bergey, 2005). These data follow the common pattern of rougher substrates having more algal biomass than smoother substrates.

Consideration of substrate roughness enables testing the actual relationship between roughness and algal protection in crevices (Fig. 1; logarithmic regression, adjusted $R^2 = 0.84$). The non-linear relationship indicates that small changes in the roughness of smoother substrates will have greater impact on algal biomass than small changes in the roughness of rough substrates.

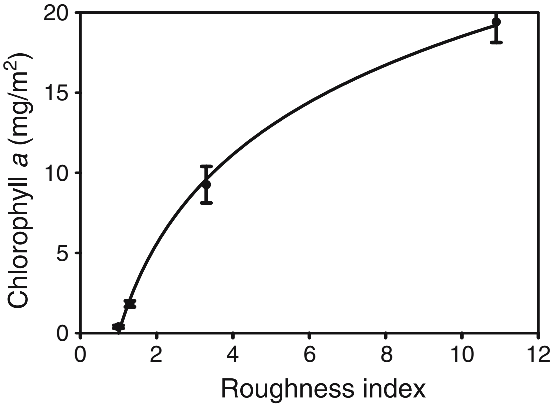

Figure 1. Relationship between the roughness index and chlorophyll *a* biomass of algae within protective crevices of substrates in a common garden experiment. Substrates in order of roughness are glass bottle < greywacke < schist < pumice. Chlorophyll and most roughness data are from Bergey (2005). Circles are substrates means and error bars are ±1 SE ($n = 16$/substrate).

Conclusion

Advantages of this index of roughness are (1) measurement of the entire surface rather than a single transect; (2) the ease of measurement, in terms of both being rapid and in not requiring specialized skills or equipment; and, as a consequence (3) the practicality of measuring multiple substrates. Additionally, measurements correspond to perceived roughness and are easily interpreted. The roughness index can be used to place individual stones or samples of stones along a smooth to rough gradient in studies of organismal settlement and survival, or to investigate changes in surface roughness of substrates caused by the colonization of sessile or sedentary organisms, including black flies, barnacles, and seaweeds.

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