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Prediction of sediment-bound nutrient delivery from semi-arid California watersheds

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[1] Soil carbon (C), nitrogen (N), and phosphorus (P) are lost from hillslopes in particulate forms through soil erosion. The fate of the eroded C (e.g., sequestration or oxidation) may affect the global C budget, and delivery of N and P to waterbodies can lead to eutrophication. Whereas the magnitude of particulate nutrient losses may be similar to or greater than dissolved losses, it is rarely estimated. We couple a sediment delivery model with measurements of C, N, and P in soil to account explicitly for hillslope sediment transport processes that yield sediment-bound nutrients to fluvial networks. The model is applied to a site in California dominated by coastal sage scrub and gopher-rich grasslands. Although the magnitude of sediment delivery predicted by the model has been tested with reservoir sedimentation records, no data exist to test the predicted rates of nutrient delivery. Nevertheless, the model results are provocative; it predicts that losses of particulate C from sage covered hillslopes (23 kg/ha/yr) are nearly double that from grassland hillslopes (13 kg/ha/yr), despite a lower annual sediment yield from the sage hillslopes. The model predicts similar average annual N and P losses for sage and grasslands but dramatic differences in the frequency and magnitude of delivery events. Nutrient delivery from grasslands is chronic whereas delivery from the coastal sage is highly episodic, with large pulses driven by fire frequency. These results suggest that changes in the vegetation community can alter the delivery regime of sediment-bound C, N, and P.

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1. Introduction

[2] Soil erosion strips nutrients from hillslopes, depleting soil C, N, and P and augmenting these nutrients in surface waters. Loss of soil organic carbon (SOC) from hillslopes degrades soil quality [Lal, 2001] and, once eroded, it may be oxidized to CO₂, converted to dissolved organic carbon [Schlesinger and Melack, 1981], or sequestered in terrestrial or offshore deposits [Ritchie, 1989; Stallard, 1998]. The specific fate of eroded SOC has implications for the global C budget. For example, eroded SOC that is oxidized quickly augments present atmospheric CO₂ [Schlesinger and Melack, 1981], whereas SOC sequestered in offshore sedimentary deposits represents a net CO₂ sink [Berner, 1982]. As with SOC, the erosion of N and P from hillslopes locally diminishes soil fertility, particularly because N and P are often limiting nutrients for plant growth. In addition,

the loss of N and P from hillslopes contributes to the eutrophication and degradation of downstream waterbodies [Dunne and Leopold, 1978].

[3] Loss of C, N, and P in particulate forms often represents a significant portion of total losses from hillslopes. Meybeck [1982] estimated that, on a global basis, 95% of the phosphorus, 55% of the nitrogen, and up to 40% of the carbon transported in rivers is in particulate form. A review by Barisas *et al.* [1978] concludes that the majority of the N and P transported in overland flow from agricultural fields is in particulate forms. In Britain, sediment-bound P accounts for 25–93% of the total phosphorus transported by rivers [Walling *et al.*, 1997; Withers *et al.*, 1999]. Moreover, nutrients transported in particulate or dissolved forms follow different paths once they enter the fluvial system. Particulate-bound nutrients usually have longer residence times in watersheds than dissolved forms and their path from source to sink is more circuitous. Whereas dissolved forms of nutrients follow the trajectory of the water, particulate forms may become

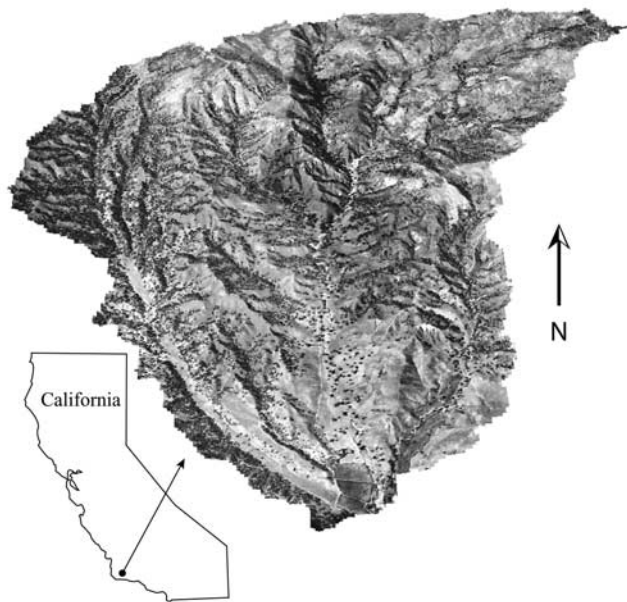


Figure 1. Three-dimensional perspective of Sedgwick Reserve, the topographic template for the numerical model and the site of the field measurements. Watershed dimensions are approximately 6 km (north-south) by 4 km (east-west). Lighter-shaded hillslopes are grasslands while darker hillslopes in the center of the image are dominated by coastal sage scrub. Dark dots are trees.

stored in point-bars, the channel bed, and floodplains [Walling *et al.*, 1997].

[4] Estimating the annual loading of dissolved C, N, and P to fluvial networks is relatively straightforward [Likens *et al.*, 1977] but it is more challenging to measure the flux of particulate-bound nutrients from landscapes [Horowitz, 2000]. Typically, the delivery of particulate-bound nutrients to rivers is estimated by sampling the suspended sediment in rivers, measuring nutrient concentrations in the sediment, and estimating an annual yield. Unfortunately, most soil erosion and sediment movement in rivers is highly episodic [Benda and Dunne, 1997; Bormann *et al.*, 1969; Likens *et al.*, 1977], requiring continuous sampling of suspended sediment in rivers and streams. Measurements of suspended sediment introduces the additional complication of separating allochthonous sources of C, N, and P from autochthonous sources [Meybeck, 1982], a problem made more difficult with distance downstream.

[5] Numerical models provide an alternative approach for estimating the delivery of particulate C, N, and P from hillslopes. Models of the erosion and transport of sediment-bound nutrients have generally been applied in the context of agricultural fields where overland flow is the dominant form of erosion [e.g., Arnold and Allen, 1996; Liu *et al.*, 2003; Viney *et al.*, 2000; Williams *et al.*, 1980]. Few studies, however, have focused on the loss of soil C, N, and P from non-agricultural landscapes where overland flow is not necessarily the dominant mode of transport. Notably, Rosenbloom *et al.* [2001] modeled the transport of C along hillslope profiles using a slope-dependent sediment flux equation. Here we demonstrate the utility of coupling spatially explicit measurements of C, N, and P with a

geomorphic model that simulates the contributions to sediment transport by the individual processes known to be important on semi-arid hillslopes in California (e.g., bioturbation, landslides).

2. Sediment Delivery Model

[6] Gabet and Dunne [2003b] created a numerical model to study the effects of climate, topography, and vegetation on the delivery of sediment from hillslopes to streams in a Mediterranean landscape (Figure 1). The model was used to assess the impact of anthropogenically forced or climatically induced vegetation conversion on the magnitude and frequency of sediment production. In the model, rainstorms and fires are stochastically generated from probability distribution functions constructed from historical records and are used to drive equations, calibrated from fieldwork, that determine the sediment flux from the various transport processes observed in the grasslands and coastal sage scrub of central California. The details of the model are given by Gabet and Dunne [2003b]; only the general functioning of the model is presented here.

[7] The landscape is divided into a network of hillslope strips, extending from the valley bottoms to the ridge tops. The vegetation type, grassland or coastal sage scrub, assigned to each strip determines the suite of relevant sediment transport processes that move sediment from the hillslope to the valley bottom (Figure 2). On the coastal sage scrub hillslopes, the model accounts for the three main processes that transport sediment in this vegetation community. First, a hillslope hydrology subroutine, coupled with an infinite slope stability analysis, determines whether landslides are triggered during the model-generated storms and the volume of each landslide is calculated as a function of hillslope angle [Gabet and Dunne, 2002]. The second process, dry ravel, is the rolling and sliding of soil and rock particles down a slope. Field measurements were used to calibrate a physically based equation that predicts the annual sediment flux from dry ravel as a function of slope angle [Gabet, 2003b]. This form of dry ravel, instigated by animal movement, the wind, or loss of cohesion, is a soil-creep process. Post-fire dry ravel, the release of particles trapped behind burning vegetation and litter, can be an

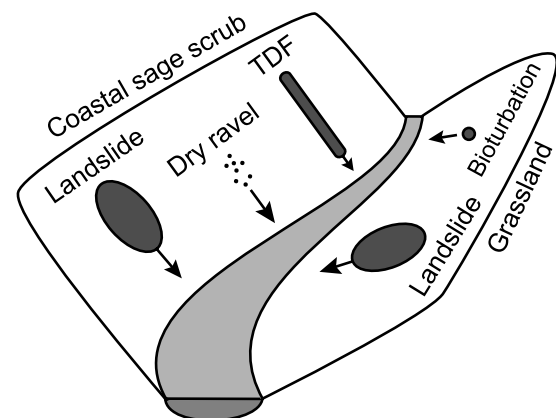


Figure 2. Vegetation community determines the suite of dominant sediment transport processes. TDF is thin debris flow.

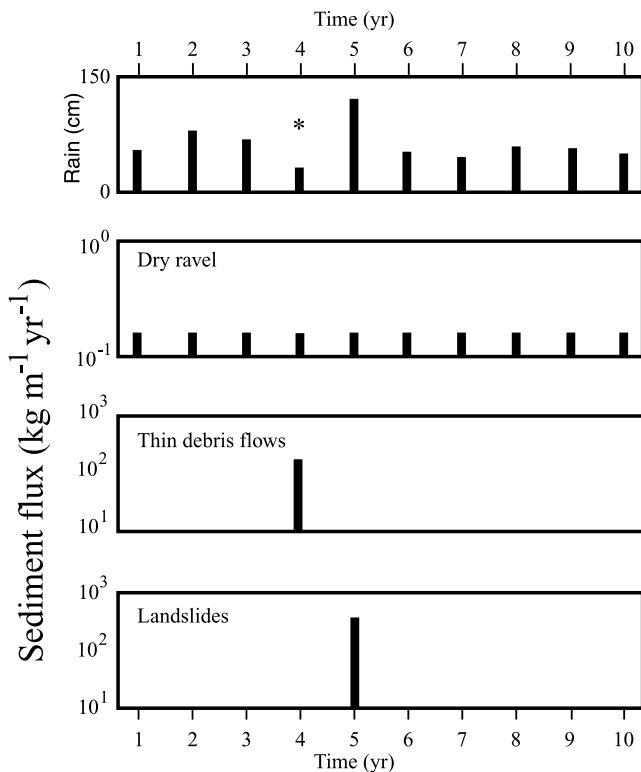


Figure 3. Predicted 10-year time series of annual sediment delivery from one hillslope vegetated with coastal sage scrub. A fire is indicated by the asterisk in Year 4. After the fire, soil hydrophobicity leads to thin debris flows during the winter. A year later, a shallow landslide is triggered when high rainfall soaks soils weakened by a decrease in the root strength of the burnt vegetation.

important source of sediment in other semi-arid environments [Florsheim *et al.*, 1991] but was found to be negligible at our field site. Third, thin debris flows occur when a hydrophobic layer [DeBano, 1981] is created below the soil surface after a fire [Gabet, 2003a; Wells, 1987]. During a rainstorm, the top layer of soil above the hydrophobic layer becomes quickly saturated and may fail as a small debris flow. Thin debris flows strip the top 1–2 cm of soil and their occurrence can also be predicted with an infinite slope stability analysis [Gabet, 2003a]. The presence of a biotic mat of fine sage roots (presumably to capture fog drip) and moss at the soil surface appears to be critical in the development of thin debris flows. Hydrophobic layers may preferentially form at the interface between the biotic mat and the underlying soil because of differences in thermal conductivity. Numerous rainfall simulation experiments revealed that the biotic mat, a spatially continuous porous layer, also inhibits the generation of overland flow during even the most intense rainfall (e.g., 140 mm/hr) or after fires [Fierer and Gabet, 2002].

[8] When a simulated fire burns a hillslope strip with sage scrub, there are two effects. First, root strengths, important in anchoring the soil, are decreased thus increasing the potential for shallow landslides. Root strengths reach a minimum 3 years after the fire, at which point the root strength contribution of new vegetation begins to dominate.

Second, the infiltration capacity immediately after the fire is reduced to zero at 1–2 cm below the soil surface, simulating the creation of a hydrophobic layer and increasing the susceptibility to thin debris flows. The infiltration capacity recovers to pre-fire rates over the following 5 years.

[9] In the grasslands, only two processes appear to be dominant: landslides and soil creep by bioturbation. Landslides in the grasslands are modeled in the same fashion as in the sage scrub, albeit with different root strength parameters. Bioturbation by pocket gophers (*Thomomys bottae*), a soil creep process, has been shown to transport significant quantities of soil down hillslopes and field measurements were used to develop a slope-dependent sediment flux equation [Gabet, 2000]. Although the infiltration capacity of the soil in the grasslands is sufficiently low to generate overland flow, the amount of sediment eroded is controlled by the vegetation cover [Gabet and Dunne, 2003a]. Under the ungrazed scenarios modeled by Gabet and Dunne [2003b], the grass cover is sufficiently thick to protect the cohesive soils from raindrop impact and the sediment loss is negligible relative to the other processes. In addition, grazing may influence the potential for landsliding and gopher bioturbation in ways that we are unable to predict. Because of the rapid regrowth of grass after a fire and the lack of significant hydrophobicity, fires do not alter the modeled sediment transport processes in the grasslands.

[10] The annual sediment yields calculated for each process can be summed to predict the total yield of sediment from each hillslope strip (Figure 3). To ensure that the model sampled the entire probability distribution of fires and rainstorms, the model was run for 10,000 years to calculate annual averages. The results were tested against reservoir sedimentation data and found to match reasonably well [Gabet and Dunne, 2003b]. The strength of this model for estimating particulate losses of C, N, and P is that it recognizes that different sediment transport processes transport soil from different depths. For example, thin debris flows remove the surface layers of soil, gophers remove soil from 0–30 cm depth, and landslides remove the entire soil column (Figure 4). Owing to the heterogeneous distribution of C, N, and P through a soil profile, these various transport

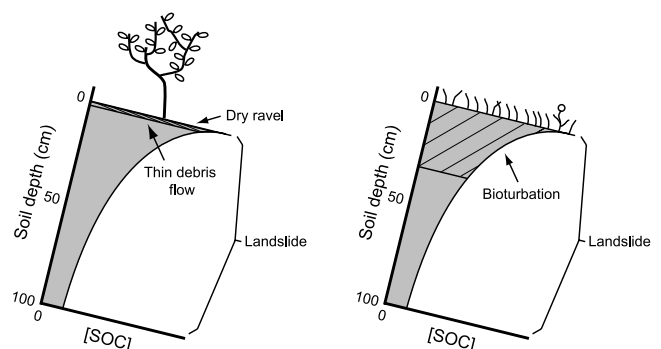


Figure 4. Different transport processes erode soil with different concentrations of C, N, and P. A typical profile of [SOC] is shown. The hatched and shaded areas indicate the regions of the soil profile affected by individual transport processes in the sage (left profile) and grasslands (right profile).

processes will differ in terms of their relative contributions to nutrient movement down a hillslope.

3. Materials and Methods

3.1. Field Site

[11] Sedgwick Reserve, a University of California Natural Reserve, was the site for the fieldwork and served as the topographic template for the numerical model. Sedgwick Reserve (35°36'N, 121°04'W) is located in the Santa Ynez Valley, near Santa Barbara, CA, in the western foothills of the Transverse Ranges (Figure 1). The bedrock is composed of the Paso Robles Formation, a Pleistocene fanglomerate that has been incised into moderately steep (20°–45°) rolling hillslopes. Mean annual rainfall is approximately 50 cm, with most of it falling in the winter and early spring. The soils at the site range from Xerorthents to Haploxerolls and are generally silty clay loams with smectitic-type clays [Gessler *et al.*, 2000; Shipman, 1972].

[12] There are three main vegetation types at Sedgwick Reserve, exotic annual grasses (*Bromus* and *Avena*), coastal sage scrub (*Artemisia* and *Salvia*), and pine forest; this study is restricted to the grasslands and the sage scrub. There is little overlap between these two vegetation communities and the boundary separating them is sharp. Although the grasslands are broadly distributed throughout Sedgwick Reserve, they do not occupy slopes steeper than 35°. The present distribution of vegetation is indicative of the conversion of native plant communities to exotic grasses for pasturage, a common practice in the region. Aerial photographs of Sedgwick Reserve from the 1930s reveal a distribution of vegetation identical to today's, indicating that the conversion occurred at least 70 years prior to this study.

3.2. Soil Sampling

[13] The soil samples for nutrient analysis were collected at Sedgwick Reserve in late May 2002. Each hillslope process transports soil from different depths in the soil profile, therefore care was taken to sample soils from the appropriate locations. Topography has an important influence on soil nutrient concentrations [Gessler *et al.*, 2000], so we were careful to distinguish between convergent and planar portions of the hillslopes when selecting sampling sites.

[14] Because colluvial hollows, convergent areas on hillslopes, are typically the source of shallow landslides [Campbell, 1975; Dietrich *et al.*, 1995], we sampled soils from three hollows in both vegetation types. The soil-bedrock contact defines the failure plane of shallow landslides at Sedgwick [Gabet and Dunne, 2002]; therefore we sampled entire soil profiles in the hollows (down to the C horizon) at 10-cm depth intervals. Although grassland soils generally have laterally homogeneous distributions of soil nutrients, the spatial distribution of nutrients in shrubland communities (e.g., coastal sage scrub) may be markedly heterogeneous, with islands of fertility centered around individual plants [Schlesinger *et al.*, 1996]. As a result of this patchy distribution of nutrients, our limited samples in the sage scrub ($n = 3$) may not be representative of the entire site.

[15] To measure the nutrient concentrations of the material that would be lost through post-fire thin debris

flows, we sampled the top 1–2 cm of soil from each of the three aforementioned soil pits in the coastal sage scrub. Although the thin debris flows are not limited to the colluvial hollows and have been observed on planar slopes, careful examination of this top layer of soil indicated that it was dominated by a laterally extensive biotic crust [Gabet, 2003a], suggesting that the top 1–2 cm samples from the hollows are likely to be representative.

[16] The soil creep processes (bioturbation in the grasslands and dry ravel in the sage) occur throughout the landscape and are not topographically constrained. As a result, fresh gopher mounds on the soil surface were sampled from convergent ($n = 9$) and non-convergent ($n = 9$) sections of hillslope and an average was calculated from all of the samples. Material caught in dry ravel traps in the sage scrub [Gabet, 2003b] were sampled ($n = 3$) to estimate the nutrient concentrations.

3.3. Nutrient Measurements

[17] We measured total C, N, and P in all the soil and sediment samples. We measured total pools of C, N, and P instead of the specific pools of these nutrients because we were less concerned with the form of the nutrient and more concerned with the total amounts of nutrients moving through the landscape. There is an insignificant amount of inorganic C (as calcium carbonate) in the Sedgwick soils [Fierer *et al.*, 2003], therefore total C should be equivalent to total organic C. The N and P may be in predominately organic or inorganic forms depending on soil depth. Total C and N content was measured with a Fisons (Danvers, Massachusetts) NA1500 C/N analyzer. Total P content was measured by ALS Chemex (Sparks, Nevada) using a four acid digestion followed by ICP-AES analysis (method ME-ICP06).

4. Results

4.1. C, N, and P in the Soil Profiles

[18] Except for the upper 15 cm, the sage and grassland sites have similar soil C concentrations, [C], through the soil profile (Figure 5). Near the soil surface, the grassland sites have higher [C] than the sage sites, presumably a result of the dense network of shallow grass roots. The soils under sage scrub vegetation have uniformly lower soil N concentrations, [N], than the grassland sites (Figure 5). The lower [N] in the fire-prone sage may be due to the volatilization of nitrogen in plants, litter, and soil during fires [DeBano and Conrad, 1978] or due to the presence of N₂-fixing plants in the grassland sites. Down to a depth of about 60 cm, the soil P concentration, [P], in the sage scrub is higher than in the grassland sites. Below 60 cm, the two soil types have nearly identical [P], probably because a similar parent material underlies both vegetation types (Figure 5).

4.2. C, N, and P in Surface Samples

[19] In the gopher mound samples collected on the soil surface, the [C] and [N] are similar to their concentrations in the soil ~15 cm below the soil surface, reflecting the source of the mound material (Figure 5). The concentrations of C, N, and P in the thin debris flow samples reflect the organic-rich biotic mat found in the uppermost layers of the

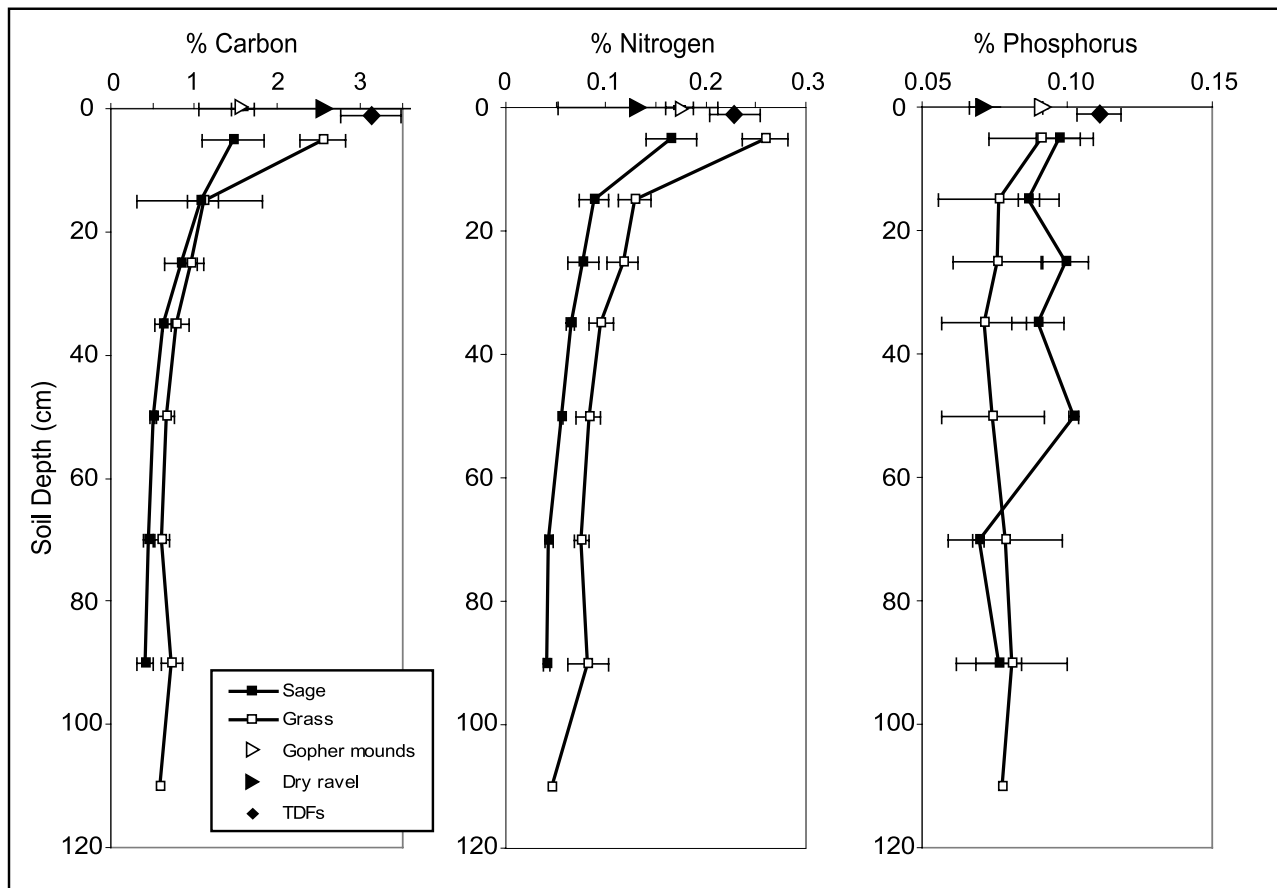


Figure 5. Percent C, N, and P in the soil profiles and surface samples. The grassland sites have higher [C] near the soil surface. The gopher mound samples have [C] representative of their source, 0–30 cm below the soil surface. The dry ravel samples in the sage are slightly lower in [C] than the TDF samples. Open symbols represent grassland samples and solid symbols represent sage scrub samples. Error bars denote 1 s.e.

sage scrub soil profiles. In contrast, the dry ravel material has lower concentrations of C, N, and P than we would expect for material originating from the top layers of the soil profile. The lower nutrient concentrations may result from the preferential transport of material with a high particle density, namely sand and gravel, by the dry ravel process.

4.3. Modeled Yields of C, N, and P

[20] As reported by *Gabet and Dunne* [2003b], the predicted average annual sediment yield is $710 \text{ kg ha}^{-1} \text{ yr}^{-1}$ from the coastal sage scrub and $980 \text{ kg ha}^{-1} \text{ yr}^{-1}$ from the grasslands; the sediment yield from each individual process is shown in Figure 6A. These individual yields were multiplied by the appropriate nutrient concentrations (Figure 5) to determine the average annual yields of C, N, and P (Table 1, first two rows). Whereas the sage scrub produces nearly 30% less sediment than the grasslands, the average annual C yield from the sage is nearly twice that of the grasslands. This difference is primarily due to the post-fire thin debris flows that occur in the sage scrub (Figure 6b). Although the fire recurrence interval is 81 years [Keeley *et al.*, 1999], thin debris flows remove the top layer of organic matter-rich soil. In contrast, the main transport

process in the grasslands, bioturbation by gophers, removes soil from deeper layers of the soil profile where [C] is not particularly high.

[21] Despite the differences in the transport processes between the sage and the grasslands (Figures 6c and 6d), the average annual yields of N and P are similar (Table 1). However, the temporal nature of the nutrient movement in the two vegetation types is substantially different. The magnitude and frequency of delivery events can be categorized as “chronic” (i.e., occurring regularly on timescales of days to months) and “catastrophic” (i.e., occurring on timescales of decades to millennia). For example, soil creep is a chronic process whereas landslides and fire-related processes are catastrophic. In the sage scrub, the loading of particulate-bound nutrients is more catastrophic than in the grasslands where nutrient movement is dominated by bioturbation, a chronic process (Figure 7).

[22] It is important to note two key assumptions in the use of this model. First, we assume that the pools of nutrients measured in the soil samples were at or near steady state. The elapsed time since the conversion of native vegetation to grasslands may not have been sufficient to reset the distribution of nutrients to reflect the grassland influence. Second, we assume that the recurrence intervals of the

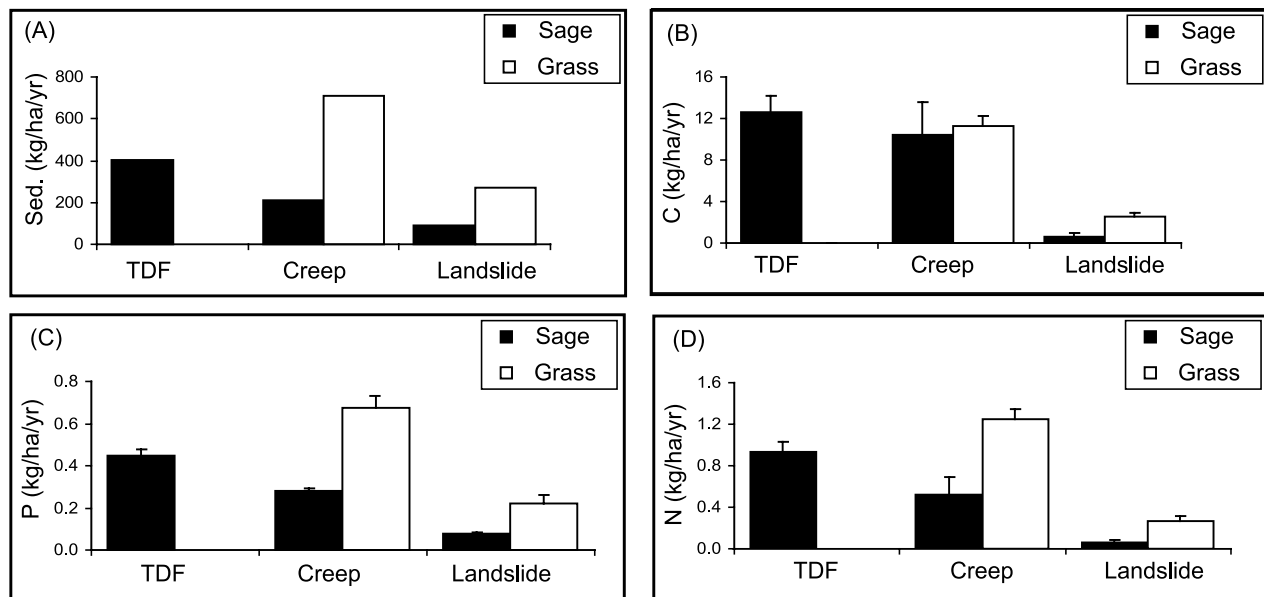


Figure 6. (a) Sediment yields from each transport process predicted by the sediment delivery model. C, N, and P yields were determined as the product of the sediment yield and the appropriate concentration of C, N, and P. (b) Although soil creep in the grasslands delivers much more sediment than in the sage, the yields of C from both vegetation communities are similar owing to the relatively higher [C] of the creeping sage soil. (c) Soil creep in the grasslands erodes more than twice the amount of N than the coastal sage but this is nearly balanced by the N loss by thin debris flows in the sage. (d) The P yields show similar patterns according to vegetation type as the N yields. Error bars in all graphs represent the standard error of the nutrient analyses propagated through the sediment yield calculations.

catastrophic events are sufficiently high such that the soil nutrient pools reach a steady state condition between events.

5. Discussion

5.1. Comparison With Field Measurements

[23] We do not have watershed-scale data from our field site to test the accuracy of our spatially and temporally integrated estimates of particulate C, N, and P loading. Additionally, there are few published data sets on particulate C, N, and P yields and fewer still from semi-arid environments. Results from our model are in broad agreement with the limited field measurements from published studies (Table 1). We recognize that many of these studies were conducted in regions with different climates, vegetation communities, and disturbance regimes and, therefore, direct comparisons are not entirely appropriate. Nevertheless, our

predictions of C yield are within the range of yields for mountainous semi-arid landscapes reported by *Stallard* [1998] and *Smith et al.* [2001]. The predicted values of N and P yields, however, are higher than those measured by *DeBano and Conrad* [1976] for a field site similar to ours. This discrepancy may be due to the absence of thin debris flows at their field site, an important source of eroded particulate N and P at Sedgwick Reserve. Thin debris flows are more likely to occur in soils with a biotic mat at the soil surface, as found in the coastal sage scrub ecotype [*Gabet*, 2003a].

5.2. Implications of C, N, and P Losses

[24] Although we are unable to verify whether the precise values of nutrient yields predicted by the model are accurate, relative differences in the predicted magnitude and frequency of nutrient delivery between the grasslands and

Table 1. Modeled and Measured Annual Sediment and Particulate C, N, and P Yields ($\text{kg ha}^{-1} \text{yr}^{-1}$)^a

Study	Location Description	Method	C	N	P
Present	sage scrub; steep rolling hills, semi-arid	numerical model	23.4 ± 3.6	1.5 ± 1.5	0.8 ± 0.03
Present	grasslands; steep rolling hills, semi-arid	numerical model	13.8 ± 1.1	1.5 ± 1.5	0.9 ± 0.07
<i>Likens et al.</i> [1977]	forest; New Hampshire, USA, steep, humid continental	settling basin	4.0	0.1	0.01
<i>Meybeck</i> [1982]	global data	river sampling	2–50	...	...
<i>Malcolm and Durum</i> [1976]	Brazos River, Texas; lowlands, mixed uses	river sampling	2.2	...	...
<i>Stallard</i> [1998]	uplands, semi-arid	calculated with data from other sources	3–11	...	...
<i>Smith et al.</i> [2001]	Pacific southwest, USA	various methods	24	...	...
<i>Lowrance and Williams</i> [1988]	coastal Georgia, agricultural fields	rainfall simulations	574–251	...	...
<i>DeBano and Conrad</i> [1976] ^b	southern California chaparral; 50% slopes	troughs on hillslope plots	...	0.5	0.1
<i>Walling et al.</i> [1997]	Britain, steep to lowlands, agricultural to pasture	river sampling	...	0.6–2.8	0.6–1.4

^aThe \pm represents 1 s.e. propagated from soil analyses.

^bValues are calculated by assuming a fire recurrence interval of 81 years.

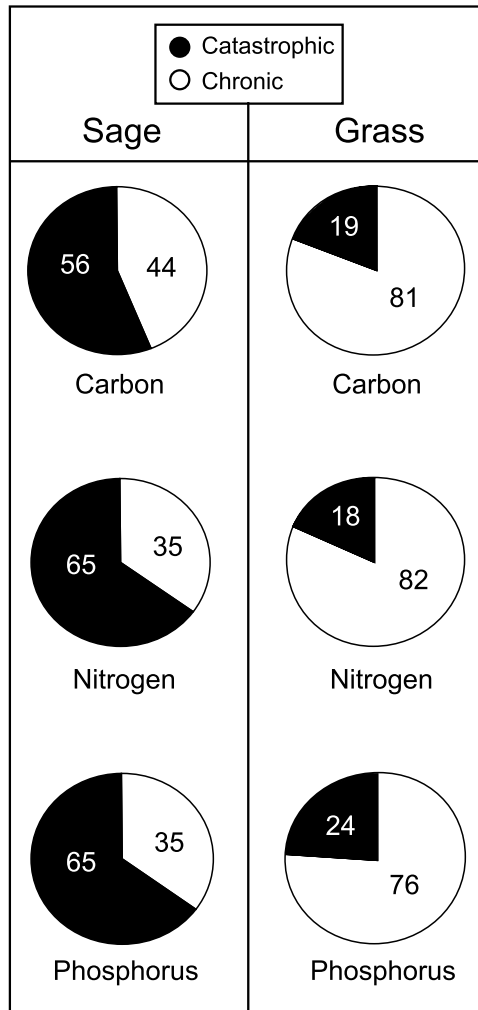


Figure 7. Percentages of nutrients delivered by catastrophic versus chronic processes according to vegetation community. Nutrient delivery from the sage scrub is dominated by large, infrequent pulses whereas nutrient delivery from grasslands is more regular.

coastal sage are likely to be correct. Our model indicates that the loss of SOC from sage scrub hillslopes is nearly twice that from grasslands, despite lower average sediment yields from sage hillslopes. Therefore changes in vegetation community from grassland to sage scrub (or vice versa) may have a dramatic effect on the total export of C from similar semi-arid landscapes. Furthermore, in the grasslands, 81% of the total particulate C is transported by soil creep, a chronic process, with the balance delivered by shallow landslides, a process that occurs on the timescale of centuries to millennia (Figure 7). In contrast, approximately half (53%) of the C in the sage is delivered by thin debris flows, a process that occurs on a decadal timescale. In landscapes where sediment has the potential to become quickly buried (e.g., coastal watersheds), SOC that is delivered in large pulses may have a greater likelihood of becoming sequestered than SOC delivered chronically.

[25] Of course, the net C balance for a given hillslope is going to be a function of C inputs (primarily via photosynthesis) and C outputs. In this study, we examine only one

component of the C balance, namely losses of insoluble C from the hillslope. Without information on the rates of plant-derived C additions and the rates of gaseous C losses from the two soil types, we are unable to determine how the different rates of SOC loss affect the total amount of C stored in the soils under the two vegetation types. With the exception of the top 10 cm of the soil profiles, C concentrations are roughly similar in the grassland and sage scrub soils (Figure 5) suggesting that the increased erosion of SOC on sage scrub hillslopes may be offset by either higher net inputs of plant-derived C, or lower gaseous losses of C (primarily as CO_2), in the sage scrub versus the grassland soils.

[26] Although the total yields of N and P from both vegetation types are similar, there is an important difference in the magnitude and frequency of delivery events. Grassland hillslopes have chronic losses of N and P while nutrient transport from sage scrub hillslopes is characterized by large, infrequent pulses (Figure 7). The chronic versus catastrophic nature of particulate-bound nutrient transport in the two different vegetation types has important implications for ecosystem biogeochemistry. Large pulses of N and P may overwhelm the ability of waterbodies to process these nutrients, leading to a rapid decrease in water quality after these infrequent geomorphic events.

6. Conclusion

[27] By including measurements of soil C, N, and P within a numerical model of sediment transport, we are able to predict annual yields of particulate C, N, and P in a hilly, semi-arid landscape vegetated by coastal sage scrub and gopher-rich grasslands. Although no data exist to test the model results, the general patterns of nutrient delivery predicted by the model are likely to be robust. From the model results, we conclude that, although the grasslands have higher sediment yields, the highest yields of particulate C are from the coastal sage scrub. In addition, we find that vegetation community strongly controls the magnitude and frequency of particulate C, N, and P delivery. Nutrient delivery from sage scrub hillslopes is catastrophic and arrives in large infrequent pulses whereas, for grass covered hillslopes, nutrient delivery is chronic. In watersheds with a relatively short distance between sediment source and sink, the differences in the tempo of nutrient delivery between the two vegetation communities may affect eutrophication potential as well as the amount of C deposited and sequestered.

[28] **Acknowledgments.** We thank the two anonymous reviewers and the associate editor for their helpful suggestions. Supplies and salary for E. Gabet were supported by a U.C. Regents Fellowship, U.C. Water Resources grant UCAL-W-1917, and a Mildred Mathias Grant. Computer modeling supported in part by National Science Foundation grant CDA96-01954 and by Silicon Graphics.

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