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The soil production function: A brief history and its rediscovery

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Abstract

In 1877, G.K. Gilbert reasoned that the rate at which bedrock is converted to soil reaches a maximum under an optimal soil depth that facilitates contact between bedrock and water such that freeze–thaw and chemical weathering are maximised. In doing so, he outlined the functional dependence of soil production (bedrock weathering) on local soil depth. However, the concept of a soil production function does not appear to have been utilised until well into the following century when Carson and Kirkby (Carson, M.A., Kirkby, M.J., 1972. Hillslope Form and Process. Cambridge University Press, Cambridge, 475 pp) expressed it as a notional relationship. They also noted that at depths less than optimum, instability exists that will either drive soil depth to the optimal weathering depth or to zero depth. More recent work has also described a declining exponential soil production function in which the highest rate is at zero soil depth. Despite dealing with a fundamental issue in soil science, viz. soil formation, the soil production concept has been applied mostly to landscape evolution studies. The situation is ripe for its use in soil science and developments in techniques such as cosmogenic nuclides will assist this.

Keywords: Pedogenesis; G.K. Gilbert; Soil production function; SPF; Weathering; Soil formation

"The domain of pedology … … … may come to engross a considerable portion of dynamic geology." Robinson (1949, p5)

1. Introduction

One theme that has gained considerable attention over the past decade and especially the last 5 years has been a forced discussion on defining an appropriate soil production function (SPF), i.e. the relationship between soil production and soil depth. The demand for this stems from a need to incorporate soil production into models of slope development and thus landscape evolution. Not surprisingly the impetus for this has come from geomorphologists and geologists. Yet the issue is of considerable interest to soil science since it is an attempt to tie soil formation back to the landscape and thus incorporate the weathering of rock and the movement of particles to and from the developing soil material. It is, therefore, germane to pedogenesis. Considered at a more pragmatic level, the notion of soil tolerance levels depends on knowing the rate of soil production which is known at best in general terms and mostly for depositional sites rather than upland soils. The purpose of this note is to discuss the origin of the SPF and trace its path through the earth sciences.

2. Gilbert and the origin of the soil production function

In what was to become a landmark study in the earth sciences, Gilbert (1877; Fig. 1, Appendix A) espoused the ideas behind the functional dependence of soil production on soil depth, and recognised the coupling of soil production, soil depth, surface slope and soil transport. In his *Report of the Geology of the Henry Mountains*, Gilbert writes:

> Weathering is not directly influenced by slope, but it is reached indirectly through transportation. Solution and frost, the chief agents of rock decay, are both retarded by the excessive accumulation of disintegrated rock. Frost action ceases altogether at a few feet below the surface, and solution gradually decreases as the zone of its activity descends and the circulation on which it depends becomes

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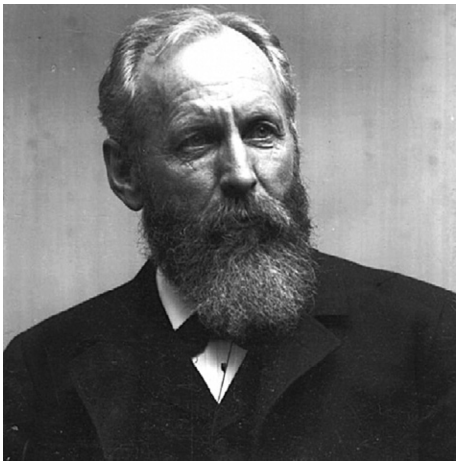

Fig. 1. Grove Karl Gilbert (1843–1918). Date of photo unknown. Sourced from the Geomorphology Specialty Group, Association of American Geographers.

> more sluggish. Hence the rapid removal of the products of weathering stimulates its action, and especially that portion of its action which depends upon frost. If however the power of transportation is so great as to remove completely the products of weathering, the work of disintegration is thereby checked; for the soil which weathering tends to accumulate is a reservoir to catch rain as it reaches the earth and store it up for the work of solution and frost, instead of letting it run off at once unused. p.97

These ideas suggest freeze–thaw and solutional processes, together or separately, produce soil only when soil is present. When a regolith cover is lacking, the water essential to both processes is unavailable and soil production stalls. At depths beyond which soil production is maximised (hereafter d_m), soil production is self limiting as thicker soil progressively buffers the underlying bedrock from weathering. This description depicts a "humped" function (Cox, 1980) (Fig. 2 curve 'a').

3. The missing years

Thereafter the idea of a SPF appears to have disappeared from mainstream geological texts including those dealing with soil. It is difficult to suggest why this occurred as there are a myriad of possible reasons. But it is intriguing to examine the accounts of three American geologists that one might assume to have been aware of Gilbert's writings as they were contemporaries and had a stated interest in soils: Nathaniel Southgate Shaler, George P. Merrill and William Morris Davis.

An early account by Shaler (1891) is famed for providing a general explanation of soils that departed from strictly geological perspectives in that he recognised the message from Darwin (1881) on the role of earthworms in creating humic soil material. Shaler's treatise is a *tour de force* with several diagrams indicating a keen eye for detail that were reused by others in subsequent publications, including Merrill (1906). His account is especially applicable to the American eastern states, but very few references are provided. Thus, there is no clear evidence that any of Gilbert's ideas were used let alone known. One possible exception is where Shaler uses the absence of soil to discuss those conditions where transportation greatly exceeds soil production:

> One of the most noteworthy features of soils is their wide extension over the surface of the lands. It is only in a very small portion of the land area that they are absent. The nature and origin of these fragmentary and on the whole insignificant soilless areas should be noted, for the facts are very instructive. pp. 225–226

This may be a reference to transport versus supply limitations. Even though Shaler clearly distinguished between soil mantles that had or had not been affected by recent glaciations there is little discussion on what controls the supply and rate of movement i.e. the basis of soil production might be recognized but not its controls.

Subsequently a more forthright statement appeared in a popularist text directed at conservation (Shaler, 1905):

> In the naturally adjusted surface of the earth the decay of the rocks beneath the soil steadfastly and effectively provides for the renewal of the coating.………The plants act on the bed-rocks in ways that tend to disrupt them and to bring the materials into the finely divided forms in which they, along with decayed organic matter, form a life-sustaining earth. Until the soil attains a certain depth, the roots of even the lesser plants attain to the bed-rock, their slender fibrils enter into its crevices and, expanding there, seem to wedge the stone apart. As the coating becomes thicker, only the stronger trees reach down to their basement, and so this disruptive action becomes less.………The deeper this work goes, the less effective it becomes, so that it too is limited in its extension. The result of these checks on the process of soil formation is that the layer of broken-up rock which only needs to be mingled with the waste of plants to form a true soil is commonly of no great depth.……… not more than a yard in thickness. pp. 121–122

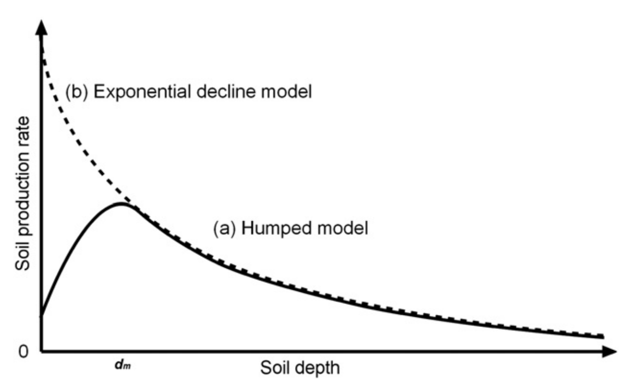

Fig. 2. Schematic representation of soil production function described by Gilbert (1877), first depicted graphically by Carson and Kirby (1972, Fig. 5.5) as curve 'a', the "humped" function. Curve 'b' depicts an inverse exponential function reported in several recent studies.

This statement more clearly recognizes a weathering limited system and a humped type weathering relationship but again there is no indication as to whether any of this was derived from the influence of Gilbert or arose independently.

In contrast to Shaler's generalised accounts Merrill's (1906) text is more comprehensive and adopts a compendium style. As a consequence it tends to emphasize the unusual as well as variability, sometimes at the expense of synthesis. Nevertheless, Merrill's account is a formidable treatment of rock composition and the alteration of rock to soil, and his term 'regolith' on p. 287 is symptomatic of this. Not surprisingly, the references to Gilbert are limited to particular features including alluvial cones (p. 50), glacial striations (p. 159–160), wind blasting (p. 164), desert varnish, (p. 244), and gypseous sand (p. 366). There is no formal acknowledgment of Gilbert's ideas relating to soil production but similar ideas are expressed in the last section of Part III (The Weathering of Rocks), 'Time considerations'. In this section ten factors that influence the rate of weathering are addressed: four address texture and composition, another three consider climate, and the others deal with soil depth. Of the latter it is the sub-section on the "Rate of weathering influence by position" that is relevant:

> It naturally follows, therefore, that a purely chemical decay will progress more rapidly where the rock mass is covered by such a layer of vegetable soil as shall keep the surface moist and give rise to decomposing solutions. Hence, ……, decomposition will keep on at an ever-increasing rate to a depth concerning which we have at present no data for calculation. It must not be too hastily assumed from this that rocks thus protected do in reality break down more rapidly than those on bare hillsides, since, in the latter case, where physical causes predominate, the loosened particles are removed as fast as formed, and new surfaces for attack are being continually exposed. Moreover, in assuming that rocks decay rapidly where covered by vegetation, we must not overlook the fact that the character of the overlying soil may be such as to protect rather than otherwise. pp. 257–258

This statement amplifies a previous one, also in Part III, that "The decomposing forces early lose their active principles and become quite inert at depths comparatively insignificant" p. 151. These statements would seem to imply that Merrill has recognized both humped and inverse SPFs. What is in less doubt is that Merrill viewed soil production as a weathering driven phenomenon that operated slowly: "Nevertheless, it is the slow process of superficial weathering that we owe a very large share of the apparent rock decomposition and incidental soil formation." p. 151.

Davis' work on landscape evolution also developed during this period. It was Davis (1892) who suggested soil creep as an answer to a paradox identified by Gilbert (1877) on hillslope convexity (Gilbert, 1909), a theme that is well known in geomorphic literature. The core of a soil production concept is provided by Davis in 1899 in a far reaching geomorphic study *The geographical cycle*. In a section titled 'The development of graded valley sides' Davis contends that the bulk of the work on valley sides is a product of weathering and slow transport:

> When the graded slopes are first developed they are steep, and the waste that covers them is coarse and of moderate thickness; here the strong agencies of removal have all they can do to dispose of the plentiful supply of coarse waste from the strong ledges above, and the no less plentiful supply of waste that is weathered from the weaker rocks beneath the thin cover of detritus. In a more advanced stage of the cycle, the graded slopes are moderate, and the waste that covers them is of finer texture and greater depth than before; here the weakened agencies of removal are favored by the slower weathering of the rocks beneath the thickened waste cover, and by the greater refinement (reduction to finer texture) of the loose waste during its slow journey. In old age, when all the slopes are very gentle, the agencies of waste removal must everywhere be weak, and their equality with the processes of waste supply can be maintained only by the reduction of the latter to very low values. p. 496–497

Davis seems to acknowledge that soil production is inversely proportional to soil depth and is also dependent on the degree of comminution of the weathering particles. However, there is no direct reference to Gilbert on this issue, and given that Davis was not averse to openly publishing contrary comments it might be assumed that this part of the *Report on the Geology of the Henry Mountain*s was overlooked by him. Nevertheless, Davis makes it very clear that there is a depth control and a particle size effect and it might rightly be stated that he was the first to make this link. We were unaware of this latter point until noticing the Davis quote in Carson and Kirkby (1972, p. 370) in a chapter where Davis' work is discussed in the context of slope evolution and not soil production. This latter theme appears in an earlier chapter. This separation between geomorphic and pedogenic themes remains widespread today especially within text books.

From this limited treatment we conclude that Gilbert's (1877) ideas on soil production were not openly recognised nor explicitly commented upon by three noted contemporaries and this indifference may have been widespread. Alternatively, it is possible that the same basic ideas began to emerge independently though in different contexts. We will probably never be able to resolve this. Certainly, however, the absence of any account of SPFs in popular geological texts in North America would not assist the concept being developed in the newly emerging field of soil science. An obvious reason for this was the emphasis on agriculture (especially on productivity within the USDA), soil mapping, and classification (Paton and Humphreys, in press). Soil formation was initially viewed as part of rock weathering (e.g. Whitney, 1909; Marbut et al., 1913) — a commonly accepted viewpoint at this time. The subsequent embrace of climatic determinism (e.g. Coffey, 1912; Marbut, 1928) after being influenced by Russian ideas on soil genesis (Paton and Humphreys, in press) is likely to have further removed the need to consider soil production.

Within the domains of soil science the closest inklings came from C.C. Nikiforoff. He argued that soil weathering could reach a steady state via dynamic equilibrium where the level of inputs matched outputs but the system remained in a state of perpetual flux (Nikiforoff, 1942, 1959). If this did not occur soils would eventually become inert media which clearly did not occur (Nikiforoff, 1942). This line of reasoning is also evident in consideration of his treatment of "noncumulative soils" i.e. soils on upland settings, because such a soil develops in balance with the lowering of the landscape (Nikiforoff, 1949). In none of these papers is the work of Gilbert referred to though Shaler's and Merrill's accounts of soils are. Nevertheless, Nikiforoff's ideas greatly influenced Hack's (1960) pioneering attempts to place geomorphology on a non-cyclical (i.e. non-Davisian) footing by advocating a dynamic equilibrium approach.

4. Soil production functions re-discovered

In qualitative examinations of weathering and transport on slopes, both Culling (1965) and Jahn (1968, first published 1954) imply an inverse relationship between soil production and soil depth. The 1960s witnessed an explosion of quantitative hillslope form and process studies founded on the mass balance equation (e.g. Ahnert, 1967, 1976; Armstrong, 1976; Kirkby, 1976) — an area of inquiry that dates to at least Lehmann (1933 — cited in Culling, 1965) and continues to the present. Ahnert (1967) modelled declines in soil production with increasing soil depth and commented that chemical weathering is maximised under a finite soil cover, an idea better developed by Ahnert in 1976 (Fig. 2). In the meantime, M.J. Kirkby diagrammatically expressed what Gilbert (1877) had outlined in words — a SPF with a maximum under a non-zero soil thickness (Carson and Kirkby, 1972, Fig. 5.5). The schematic relationship of soil production rate against soil depth and the accompanying evaluation of the instability that occurs for soils thinner than that where soil production is maximised (d_m), established important geomorphic concepts such as transport- and weathering-limited slope transport – also referred to by Gilbert (1877) – and spurred further speculation on the form of SPFs by various processes (e.g. see Cox, 1980 for a brief review).

A decade or so after Cox's (1980) review, hillslope-scale soil production rates were estimated using ^{14}C chronologies of colluvial fills (Reneau et al., 1989; Reneau and Dietrich, 1990), and soon after using fall-out cosmogenic ^{10}Be (Monaghan et al., 1992; McKean et al., 1993). However, the tools to reliably estimate local (sub-slope) soil production for a range of soil thicknesses, were yet to be developed.

Dietrich et al. (1995) raised the *ante* in a hillslope evolution study by estimating soil production for two soil depths (30 and 150 cm) using morphometric analysis for the former, and soil bulk density profiles combined with observations on the depth limit of biogenic disturbance (bioturbation) for the latter. The authors fitted an exponential decay and Gilbert-type SPF with $d_m = 25$ cm and employed a DEM to model soil thickness evolution to steady state (i.e. soil production equals erosion for each cell). The humped function, as a result of its instability, lead to a modelled landscape with a large proportion of bare rock associated with the most convex crests, in contrast to the exponential decay function (Fig. 2 curve 'b') which produced less modelled outcrop. As the latter was more consistent with the field situation it was accepted. This was the first real attempt to discriminate between the applicability of two SPFs.

5. The last decade

Until the measurement of small quantities of terrestrial *in situ* produced cosmogenic nuclides (TCN; e.g. ^{10}Be and ^{26}Al) in bedrock became possible, a better defined SPF was difficult to achieve. A hint of this was provided by Granger et al. (1996) who estimated the average erosion rates from 15 sub-catchments using TCN, the results of which may be interpreted as spatially-averaged soil production rates. However, the first substantial empirical description of the SPF came from the same study site of Dietrich et al. (1995), when Heimsath et al. (1997, 1999) confirmed the exponential decrease in soil production with increasing soil depth, using eleven soil production estimates from saprolite underneath soil cover ranging from 0 to 60 cm depth. Subsequently, the same or similar technique has been employed at five other study sites by a small range of authors (Small et al., 1999; Heimsath et al., 2000, 2001a,b; Wilkinson, 2005; Wilkinson et al., 2005) and there remains support for both Gilbert's humped SPF and an exponential decay function at various sites, although unequivocal field evidence of a SPF as envisage by Gilbert (1877) is still absent (Wilkinson and Humphreys, 2005). Nevertheless, Gilbert's ideas have resonated with Anderson (2002), who modelled frost shattering of crystalline bedrock using a humped SPF, with $d_m = 20$ cm; soil production was coupled to a transport law relating frost creep to soil depth, local slope, distance from the divide and climatic variables. This resulted in a modelled landscape with low diffusion rates on shallow soils whereas other modelling studies employ a constant diffusion parameter for the entire hillslope. If soil transport were similarly modelled in other studies and exhibited depth dependence, perhaps driven by biogenic creep, the morphologic signature of a humped SPF may not involve as much rock outcrop as modelled by Dietrich et al. (1995). Anderson's model successfully replicates details of the alpine slopes at his study site, except when he substitutes an exponential decay SPF for the original humped function. Unfortunately, constant soil thickness at this site prevents a nuclide-based determination of the SPF (Wilkinson and Humphreys, 2005). Most recently Minasny and McBratney (2006) have explored the humped function and found that a d_m of 20 cm applies well to existing TCN derived denudation rates from south-eastern Australia and used this result to model soil depth changes over time to produce spatial patterns that seemingly mimic reality despite a closed-system assumption and other constraints.

Numeric modelling by Furbish and Fagherazzi (2001) confirmed the qualitative analysis of Carson and Kirkby (1972), i.e. there is positive feedback in that part of a humped function where soil production increases with increasing soil depth, d, (i.e. $0 \le d \le d_m$), with stability existing beyond the peak (i.e. $d > d_m$). However it has been suggested a Gilbert-type humped SPF does not result in instability when soil transport is modelled as discrete events rather than a continuous process (M. Gabet, pers. comm.). This idea, coupled with that suggesting strong feedbacks between soil production and soil transport may lead to unstable soil depths for negative exponential SPFs (Phillips, 1993, 1995; Minasny and McBratney, 1999, 2001, 2006), infers that morphologic signatures may be more complex than previously conceived.

6. The future

A remaining challenge is to test the applicability of the existing two SPFs and as yet unknown forms to different kinds of situations. The declining exponential function to date has worked best under steady state landscape conditions and is most convincing where soil thickness changes with curvature. There is also an immediate need to quantify the SPF in field sites that exhibit a humped function, probably utilising TCN. Such sites might display a potential morphologic signature of a humped SPF (i.e. outcrop and few if any local soil depths with $0 \le d \le d_m$), or be sculptured in lithologies highly susceptible to weathering by hydrolysis, frost shattering, or bioturbation. Even if the dominant transport process operating can be modelled satisfactorily by linear diffusion at the target site there remains a need for morphologic disequilibrium (Heimsath et al., 1999) so that slope curvature and its co-variable, soil depth, vary spatially. However, at the same time as soil thickness is adjusting, there is the dilemma that soil depth must be relatively constant within the period under which average conditions are to be maintained, which for TCN measures is 10^4–10^5 years in the subsoil (Wilkinson and Humphreys, 2005). But these ideal conditions do not always occur. In addition transport functions often exhibit non-linear behaviour (e.g. Roering et al., 1999; Gabet, 2000; Yoo et al., 2005a) and this creates additional challenges.

7. Conclusion

An aim of this paper was to highlight the importance of the SPF to the soil science community. We hope that this will be achieved. The recent work on this theme, largely driven by studies in landscape evolution, also represents an emerging research theme in soil science. This challenge is being taken up. Thus, Yoo et al. (2005b) link slope dependent transport to soil carbon cycling and Minasny and McBratney (2006) seek to account for variation in soil thickness across the landscape as a form of pedogenetic systematics. Future texts on soils should feature the basic ideas of soil production even if only to better explain how soil erosion tolerance levels can be determined. It is also apparent that the results of such work may challenge existing ideas on soil formation and soil age, especially on upland sites that until recently proved difficult to explore. This issue was identified by Nikiforoff (1959) but remains largely unresolved except under special circumstances. The development of terrestrial cosmogenic nuclide measurements to determine soil production represents a significant breakthrough (Wilkinson and Humphreys, 2005). The results and implications of such studies are likely to be profound.

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Appendix A. A brief biographical note on Grove Karl Gilbert

Gilbert had a distinguished career in the US Geological Survey. A brief account of this is provided by Pyne (1980) and, also, by J.S Aber at: http://academic.emporia.edu/aberjame/histgeol/gilbert/gilbert.htm#23abstract.

Gilbert is honoured today in two ways: via an annual meeting and via a prize. The *Gilbert Club*, which began in 1985, is a one-day conference in geomorphology and is convened after the American Geophysical Union Meeting each December in San Francisco. Details are provided at the following site: [http://ist-socrates.berkeley.edu/~geomorph/gilbert.htm]. The *Geomorphology Specialty Group* (GSG) of the Association of American Geographers (AAG) issues the "The Grove Karl Gilbert Award for Excellence in Geomorphic Research" which is presented to the author(s) of a significant contribution to the published research literature in geomorphology during the past three years. Details are provided on the following site: [http://www.aag-gsg.org/awards.shtml].

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