On the history of humans as geomorphic agents

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ABSTRACT

The human population has been increasing exponentially. Simultaneously, as digging sticks and antlers have given way to wooden plows, iron spades, steam shovels, and today's huge excavators, our ability and motivation to modify the landscape by moving earth in construction and mining activities have also increased dramatically. As a consequence, we have now become arguably the premier geomorphic agent sculpting the landscape, and the rate at which we are moving earth is increasing exponentially. As hunter-gatherer cultures were replaced by agrarian societies to feed this expanding population, erosion from agricultural fields also, until recently, increased steadily. This constitutes an unintended additional human impact on the landscape.

Keywords: humans, geomorphic agents, earth moving, landscape modification.

INTRODUCTION

Humans move tremendous amounts of soil and rock. By some measures, the amount of earth that we move exceeds that of any other geomorphic agent (Hooke, 1994). Some of this earth is moved intentionally in mining and in various construction activities; still more is moved unintentionally as a by-product of agriculture. Herein, building on earlier work by Nir (1983) and myself (Hooke, 1994), I examine the history of this human earth-moving activity, first qualitatively and then quantitatively.

A BRIEF HISTORY OF HUMAN EARTH MOVING

Paleolithic

Prior to and during the first 4 m.y. of human evolution, there is little evidence that primates moved earth in any systematic way. By ca. 400 ka, however, in the early to middle Paleolithic, *Homo erectus* was making sizable seasonal dwellings with walls supported by small boulders moved into place for the purpose, and with foundations and floors built from stone rubble (Berreman et al., 1971; Leakey, 1981). By this time, humans had become geomorphic agents.

These Paleolithic humans discovered that stone tools were useful for hunting and food processing. The best tools were made of special types of rock like flint. In places where flint was present on the ground surface, people found that more of it could be had by digging, using tools made of bone and antler. Thus, in the late Paleolithic or early Mesolithic in western Europe, human earth-moving activities expanded to include mining. Some mine shafts from this period were over 10 m deep, and galleries from them were up to 10 m long (Bromehead, 1954).

Mesolithic to the Bronze Age

In the middle Mesolithic, ca. 9 ka, hunter-gatherer cultures gave way to farming and herding. This change may have been a response to population pressures, as more people can be fed by farming (Cohen, 1977). In any case, village life appeared. With the stability thus provided, people were inclined to build more permanent dwellings constructed of sun-dried bricks (Bradford, 1954; Hodges, 1972). Mud for the bricks was excavated by using wooden hoes and shoulder blades of oxen. Similar tools were used to till the soil for planting, and of course, this tilling led to unintended soil erosion.

As villages expanded into cities, it became necessary to import water for both drinking and irrigation. This need motivated large-scale earth-moving activities, such as construction of canals and dikes (Drower, 1954; Hodges, 1972).

In the late Mesolithic, somewhat before 5 ka, humans learned that copper could be melted; by the end of the Neolithic, ca. 3.5 ka, it was discovered that the addition of a small amount of tin to the copper made a much harder alloy: bronze (Forbes, 1954; Hodges, 1972). These advances motivated searches for copper and tin and for techniques to mine and mold these metals. It was a simple step to move from brick molds to molds for casting metal. In an early example of the priority accorded the military, the first castings were weapons. The cost of socially useful tools, such as spades and hoes, was prohibitive.

Wealthy individuals of this time also arranged the construction of larger earth or stone structures as memorials or, in some cases, to provide themselves with a lifestyle beyond the grave comparable to that to which they had become accustomed. The pyramids of Egypt are the most ambitious such constructions, but burial mounds in Ireland were composed of as much as 200 000 tons of earth and rock (O'Kelly, 1982). These mounds covered passage graves that normally contained remains of several individuals. Copper and later bronze tools facilitated quarrying of the stone blocks used for some such structures.

Invention of the wheel, about 5000 yr ago, facilitated transport of geologic materials, both ore and stone, as well as other trade goods. Because loads in carts cannot be moved efficiently over rough terrain, roads were invented to make maximal use of the increased hauling capacity provided by the wheel. To make roads, then as now, humans moved earth. Some of these early roads were only graded tracks; others consisted of grooves intentionally cut in rock to guide the wheels of carts (Goodchild and Forbes, 1956, Fig. 457). Thus, invention of the wheel led to further earth moving on a significant scale.

Iron Age

About 2500 yr ago, iron came into use. Iron was a more "democratic" metal than bronze; it was more abundant and therefore cheaper. Thus, it was available to common people (Forbes, 1954). Iron tools had a great impact on earth moving. Iron blades were fitted to wooden spades. Plows, formerly made of wood, were fitted with iron shares. Miners and stone masons used iron hammers, picks, chisels, and wedges (Forbes, 1954; Bromehead, 1956).

With the advent of these tools, and driven by the desire for trade goods and the necessity of providing for increasing populations concentrated in cities, more ambitious projects were conceived. More canals were dug to drain lakes and to connect water courses for transportation. The Egyptians, for example, had already constructed the first canal linking the Mediterranean and the Red Seas. It was nearly 160 km long and was used for over 1000 yr. By about 600 B.C., it was 60 m wide and 13 m deep (Forbes, 1958). Buildings, from small storage rooms to multistory tenements to huge temples, were also constructed, as were imposing elevated aqueducts to bring water to cities. Roads were extended, and sophisticated road construction practices emerged, involving multiple layers of sand, crushed stone, gravel, rock slabs set in mortar, and so forth

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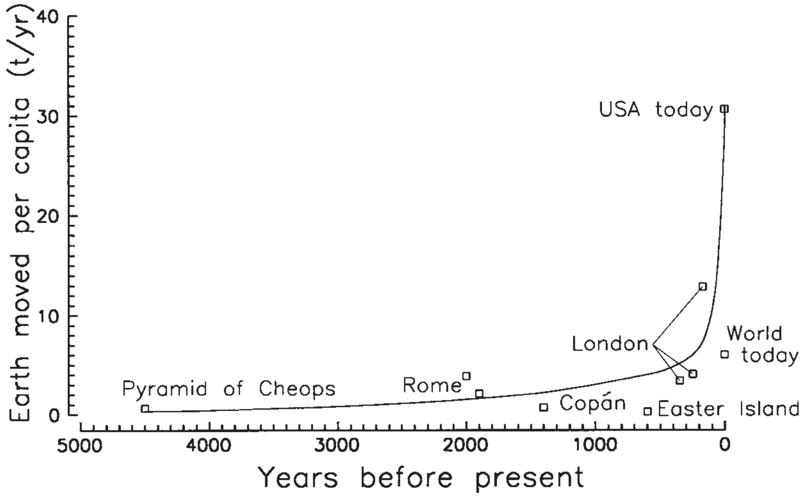

Figure 1. Estimates of amount of earth, including both soil and rock, moved per capita intentionally annually, by certain relatively advanced societies in the past; t is tons.

(Goodchild and Forbes, 1956; Forbes, 1958). Over a period of ~400 yr, the Romans paved nearly 300 000 km of roads and major highways (Forbes, 1958, p. 76). Some of the earliest lime-based cements were developed for use in this road construction. After about 100 B.C. concrete also became a common building material (Briggs, 1956).

During all of this time, agriculture was expanding, as was the erosion associated with it.

In the millennium following the Roman period, the principal new advances were in engineering (Hodges, 1972). Simple machines were invented for tasks such as ventilating mine shafts and pumping water from these shafts. Cranes, utilizing block and tackle, facilitated lifting the rocks used in construction. Water power was harnessed to drive some of these machines.

Industrial Revolution

The next major development in human earth moving came in the early 1800s, during the Industrial Revolution, when steam power became available. Steam engines required fuel, and after readily available wood supplies were exhausted, coal became the fuel of choice. In England, coal production increased rapidly from 50 000 tons in 1550 to 3 million tons in 1700 and 17 million a century and a quarter later (Forbes, 1958). Coal mining is still one of the most significant human earth moving endeavors, accounting for ~30% of the mineral production in the United States in 1988 (Hooke, 1994) and ~25% today (U.S. Bureau of the Census, 1999, p. 705).

At first, steam engines were fixed in place. Later, mobile steam shovels increased the rate at which we could move earth and rock, and explosives, first used for blasting in 1689 but not widely so until the middle of the nineteenth century (McGrath, 1958), facilitated the process. The internal combustion engine soon replaced steam, however, and the development from steam shovels to the humongous excavators of today was rapid. Today, some excavators can, with five scoops, load trucks with capacities of 70 m^3. And some trucks and excavators used in mining are more than twice these sizes.

QUANTITATIVELY, HOW MUCH EARTH DID HUMANS MOVE IN THE PAST?

Let's now try to put this development into perspective. Milestones in human ability and motivation to move earth occurred in the Mesolithic with the development of agriculture, at the start of the Bronze Age, then the Iron Age, then with the advent of steam, and finally with the appearance of the internal combustion engine.

At the present, in the United States, humans move ~30 tons of earth per capita annually. Worldwide, the figure is ~6 tons (Hooke, 1994). To estimate rates of human earth moving in the past, we need a mass of material moved, a time span, and an estimate of the local population. For example, the Mayan city of Copán in western Honduras was constructed over a period of ~400 yr by a population thought to have been ~20 000 individuals. The mass of material moved to build this city is ~5.3 million tons (Stuart, 1997). Thus, its construction required the movement of 665 kg of earth per capita annually. Of course, not all of the people were involved in this construction, but the figures, like those of today, reflect a combination of the available technology and motivation. Other estimates are shown in Table 1, and details of the data sources and calculations are given in the Appendix.

Several of the cases in Table 1 include only some of the intentional earth-moving activities in which people are engaged today (Hooke, 1994). To take into account these other endeavors, I have multiplied the mass moved by a multiplier chosen with consideration for the probable importance of the neglected activities at the time in question relative to their importance today (Table 1). For examples that do not include mineral production, this multiplier is 1.2. If neither mineral production nor roads are included, the multiplier is 1.5. Multipliers are used only when the activity excluded is one in which people are likely to have been engaged. The results of these calculations are plotted in Figure 1.

At any given time, some societies are not as technologically advanced as others. For example, the Copán and Easter Island civilizations should be compared with that of Egypt 4000 yr ago rather than with their contemporaries in Europe. Thus, if the points in Figure 1 were normalized in some way to take the relative state of technological development into account, these two points would lie nearer the left side of the diagram. Consequently, the curve in Figure 1 is drawn to reflect the earth-moving activities of the most advanced cultures at any given time.

To obtain an estimate of the *worldwide average* amount of earth moved by humans in the past, rather than of the amount moved by more advanced societies, I scaled the curve in Figure 1 by multiplying each point on it by the ratio of the per

TABLE 1. RATES OF HUMAN EARTH MOVING IN THE PAST

Time (ka)	Location	Mass moved (10^6 t)	Time span (yr)	Population	Multiplier	Mass moved per capita (kg/yr)
4.5	Egypt	6.3	20	1 000 000	2.0	625
2.0	Roman roads	5 350	420	50 000 000	1.0	355
2.0	Rome	2 330	800	1 000 000	1.2	3 495
2.0	Rome + roads	-	-	-	-	3 850
1.9	Rome	290	200	1 000 000	1.2	1 735
1.9	Rome + roads	-	-	-	-	2 090
1.4	Copán	5.3	400	20 000	1.0	665
0.6	Easter Island	1.0	600	6 200	1.0	260
0.35	London	0.9	100	388 000	1.5	3 365
0.25	London	2.0	100	738 000	1.5	4 040
0.175	London	13.0	50	1 630 000	1.5	12 860
0.0	United States	7 600	1	250 000 000	1.0	31 000
0.0	Worldwide	35 000	1	5 900 000 000	1.0	6 000

Note: Details of calculations are given in the Appendix.

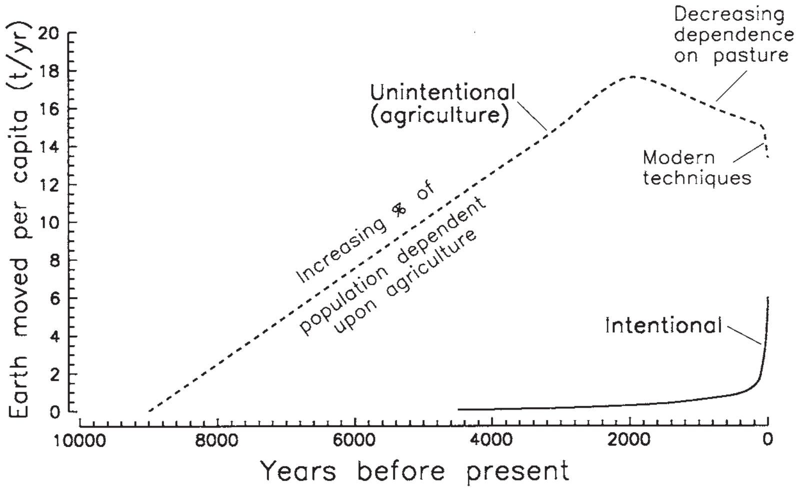

Figure 2. Estimates of the average amount of earth moved per capita at various times in the past, both intentionally as in house and road construction and mineral production (solid line) and unintentionally as in agriculture; t is tons.

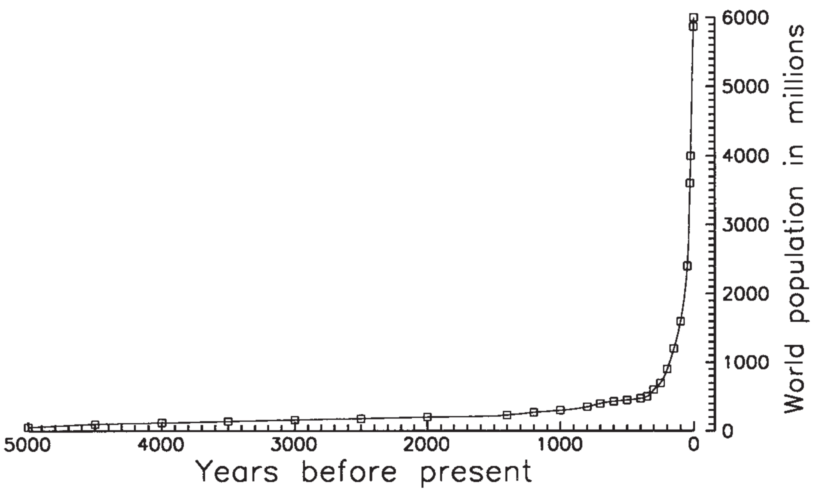

Figure 3. World population at various times in the past. After Thomlinson (1976).

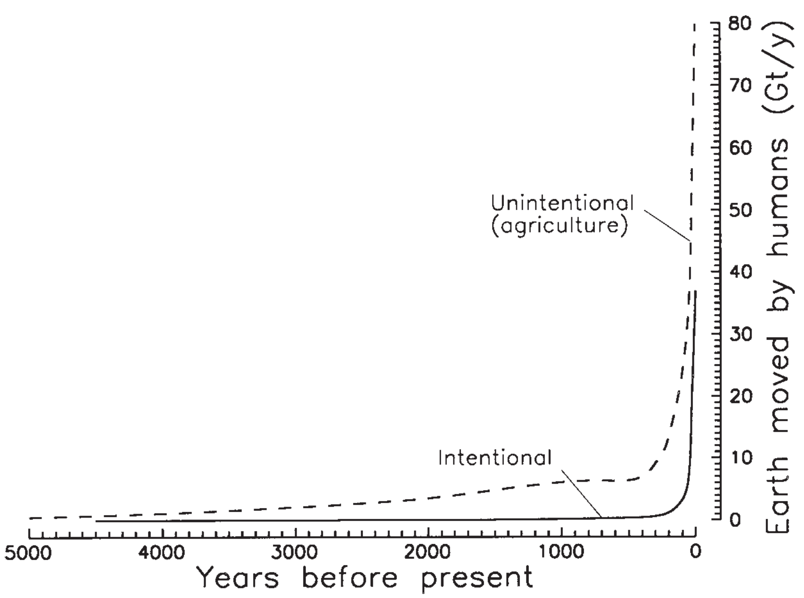

Figure 4. Estimate of total amount of earth moved annually by humans at various times in the past. Curves were obtained by multiplying earth moved per capita (Fig. 2) by population (Fig. 3).

capita estimate for the world, 6 tons/yr, to that for the United States, 31 tons/yr. The result is shown as the curve labeled "Intentional" in Figure 2.

ROLE OF AGRICULTURE

Let us now turn to the impact of agriculture on earth movement. Clearing for fields is known to result in accelerated erosion. The products of this erosion are, however, moved only a short distance. They accumulate as colluvium on slopes and as alluvium on floodplains downstream from the fields (Trimble, 1981, 1983; Trimble and Lund, 1982). I've designated these movements as "unintentional" because they are an unwanted by-product of agriculture rather than an end in themselves.

To estimate the impact of agriculture in the past, we need to know the annual sediment loss from croplands and pasture, the number of hectares of each needed to support a single person, and the number of people thus supported. In the developing world, croplands lose an average of about 35 t/ha every year (Pimentel et al., 1995). Losses from pasture are about 10 t/ha (U.S. Department of Agriculture, 1989). At present, we feed the world with about 0.3 ha of cropland and 0.6 ha of pasture per person (D. Pimentel, 1999, written communication). In the middle Holocene, it probably took about 0.25 ha of cropland and 0.75 ha of pasture to feed each person who was dependent upon agriculture (D. Pimentel, 1999, written communication). By using these figures and assuming that the percentage of the population dependent upon agriculture increased linearly between 9000 and 2000 yr ago and has remained at 100% since that time, we obtain (Fig. 2) an estimate of the amount of soil per capita displaced unintentionally by agricultural activities as a function of time. The gradual decline in the past 2000 yr is due to the presumed decrease in dependence on pasture, and the more precipitous decline in the past 50 yr is due to implementation of modern soil conservation practices in the United States and Europe.

THE BOTTOM LINE

If we multiply the per capita values in Figure 2 by the population at the respective times in the past (Fig. 3), we obtain the estimate of the total amount of earth moved, both intentionally and unintentionally, shown in Figure 4. The total earth moved in the past 5000 yr would be sufficient to build a 4000-m-high mountain range, 40 km wide and 100 km long. The astonishing increases in both intentional and unintentional human earth moving in the past few decades are a consequence of the exploding world population and, in the case of the intentional activities, to technological developments. If current rates of increase persist, we could double the length of our mountain range in the next 100 yr. One may well ask how long such rates of increase can be sustained, and whether it will be rational behavior or catastrophe that brings them to an end.

APPENDIX
Details of Calculations in Table 1

Egypt

Most data are from Hodges (1972, p. 118). I estimated the population on the basis of interpolation of an exponential curve fit to data in Shaw (1993, p. 24–25).

Roman Roads

This calculation is based on data and figures in Forbes (1958) and Goodchild and Forbes (1956). I estimated that an average road was 6 m wide and that in its construction 0.6 m of material was removed and replaced by 1.2 m of sand and stone.

Rome

Lanciani (1897) noted that the city of Rome is built on a rubble layer between 5 and 65 m thick. In my first calculation, I assumed an average thickness of 35 m and that this phase of construction of Rome lasted 800 yr.

Lanciani (1897, 1909) also gave detailed data on the area of various zones in Rome at the time of greatest prosperity, the number and typical size of tenement houses and patrician dwellings in each zone, and the thicknesses of walls. On the basis of his descriptions and diagrams of the respective types of structure, I estimated that a four-story tenement house would collapse into a pile of rubble 7.4 m thick and a two-story patrician dwelling would collapse into a pile half as thick. On the basis of Briggs (1956), I assumed that this phase of construction lasted 200 yr.

Copán

Data for this calculation come from Stuart (1997).

Easter Island

Van Tilburg (1994) and Conniff (1993) gave detailed information on the number of statues, statue bases, stone hats for statues, houses, and earth ovens. On the basis of illustrations and numbers in these references, I estimated the average mass of each of these types of construction, summed them, and divided by the population.

London

Finlay (1981, p. 51 and Fig. 3.4), Hern (1990), and Schwarz (1992, p. 126) gave populations and maps of London at various times in the past. From the maps, I obtained the rate of increase in area. I assumed that the construction material was largely stone, and on the basis of diagrams showing thicknesses of walls of buildings, I estimated that construction required moving (importing or excavating) 5 m of stone with an average density of 2350 kg/m^3 per square meter of city area.

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