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HORSE POWER

Wheat, oats, maize, and the supply of cities

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Abstract

Lack of draft animals is often considered to have been an impediment to urban growth in Mesoamerica. Transport, however, was only one of several factors that influenced the growth of cities. This paper contrasts the effects of energetic efficiency differences between horses and human porters with productivity differences between European and Mesoamerican agricultural systems. Depending on strength and nutritional requirements, horses may be from one to five times as efficient as human porters. Furthermore, horses compete with humans for food. Where the horse played a major transport role, one-third of available, arable land was devoted to oat production. With this in mind, I compare maize versus wheat productivity to show that a unit of land in Mesoamerica could support up to twice as many people as the same unit of land in Europe. Thus, the transport advantage enjoyed by European cities is essentially offset by a more intensive agricultural system in Mesoamerica.

Investigators of pre-Hispanic urban development in Mesoamerica frequently point out that human portage is a remarkably inefficient way to move goods. The forced reliance on human labor would have acted to restrain development of city networks relative to Old World draft-animal-based systems. According to this view, a city cannot grow beyond the capacity of its agricultural supply zone, and an inefficient transport system severely limits the size of this productive hinterland (Drennan 1984; Hassig 1985; Sanders and Santley 1983; Santley and Alexander 1992). While not disagreeing with the above statement in general, I take issue with the specific assumption that draft-animal power greatly increases the ability of a system to provision its population. A comparison of animal versus human energetics and wheat versus maize productivity demonstrates that other factors may significantly outweigh the possible economic advantage of draft animals over human land transport.

I would like to make two major points. First, it is not conclusive that transport based on draft animals is vastly more efficient than human transport, as many archaeologists have been quick to assume. Second, the productivity of maize in Mesoamerica may have been much greater than that of wheat in Mediterranean and northern Europe. Indeed, the need to produce feed for horses diverted considerable land areas from wheat production, thus exacerbating the productive disadvantage of European agriculture.

HUMAN VERSUS EQUINE LABOR

Clearly, a horse can carry or pull considerably more than can a human porter in one load. It has been suggested that an average load for human porters was 30 kg (Drennan 1984). On the other hand, a horse can pull 300 kg in a wagon (von Thünen 1966:13). Using these rough estimates, Table 1 shows the number of loads required to provide 1,000 people with a year's supply of maize, assuming the daily nutritional requirement per capita to be 2,000 kcal; maize provides 3,565 kcal/kg, and 80% of the diet is provided by maize. The number of human porter loads is compared with the number of wagon loads required. The superiority of horse transport over human portage seems clear.

This superiority, however, becomes less obvious when energy requirements are considered. Estimates of the energy requirements of human porters are available in the literature (Drennan 1984; Sanders and Santley 1983). The more conservative (less efficient) figures provided by Sanders and Santley are used here (Table 2). The human porter carried an average load of 23 kg an average daily distance of 30 km. Daily nutritional requirements for an adult male performing hard work were approximately 3,600 kcal, or about one kg of maize, so a porter would consume his load in 23 days, after 690 km of travel. Thus, the maximum round-trip journey would be about 345 km each way (Sanders and Santley 1983:246). This would be the energetic maximum distance from which grain could be imported to a city.

My own research in early modern Europe indicates that landlocked cities there were likewise seriously restricted in the distance from which grain could be imported (Batten 1993). An examination of the energetic requirements of horses leads to some interesting conclusions. Von Thünen performed some of these calculations in 1826. A horse pulls 300 kg a distance of 37 km in a day, and will eat 9 kg of oats per day (von Thünen 1966:13). Von Thünen calculated that transport costs would then consume the entire value of a wagon load of grain at a distance of 375 km. Franz (1960) suggests that freight wagons traveled about 20 km per day, that horses consumed 10 kg of feed daily, and that a wagon pulled by two horses would carry a maximum of 1,000 kg. Thus, the horses would consume their entire load on a round trip of 500 km each way (Franz 1960:22–23).

The roads in von Thünen's part of Germany in the 1830s may have been better than in medieval and early modern Europe, as his

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Table 1. Relative capabilities of human porters and horses

	Human	Horse
Weight per load (kg)	30	300
Loads maize/1,000 persons/year	5,460	546

figure of 37 km travel per day seems optimistic. As noted, Franz assumes an average daily wagon journey of about 20 km (Franz 1960:22). Hassig (1985:283) reports that pack mules in tropical climates can travel 20–32 km per day in the dry season, 8–10 on a good day in the rainy season. On the other hand, a horse can pull one-eighth to one-tenth of its weight (tractive pull) 10 hours per day at a rate of 2.5 miles per hour or nearly 42 km per day (Potter 1917:273). Of course, the softer the road surface, the lighter the wagon would be loaded to keep the tractive pull manageable. For now, von Thünen's 37 km per day can be allowed to stand, although one must recognize that in rainy conditions and soft roads the pace would drop markedly. At 37 km per day, a horse eating 9 kg of oats per day would consume the contents of a 300-kg load after a round trip of about 615 km each way, not considering the food requirements of the driver (see Table 2).

A measure of the energetic cost per unit of weight and distance more clearly demonstrates the relative efficiency of horse and human (Table 3). Given the energetic requirements mentioned above, and given that a kg of oats provides 2,850 kcal, then a horse pulling a 300-kg load will use 2.31 kcal/kg/km. I recently calculated a reasonable range of loads hauled by horses (Batten 1997). A horse may pull between 200 and 700 kg of load on a wagon, depending on size of horse, topography and ground surface, construction of wagon, etc. Subject also to a wide range of factors, a horse was fed between 12 and 19 kg of oats and hay per day (Batten 1997). Given these inputs, energetic costs range from a maximum efficiency of 1.03 kcal/kg/km to a minimum efficiency of 5.79 kcal/kg/km (Batten 1997). A human porter will require 5.22 kcal/kg/km based on Sanders and Santley's estimates, or 3.20 kcal/kg/km based on Drennan's figures (Drennan 1984; Sanders and Santley 1983). Thus, the energetic efficiency of horse and human transport systems are of the same order of magnitude.

It is unlikely that the animals pulling the least weight would be fed the most, as is implied by the table of maximum and minimum efficiency figures. A more reasonable range of energetic efficiency might be estimated by coupling the maximum strength with the maximum energy-requirement figures. The resultant range of 3.61–1.65 just overlaps the range for human porters (Table 4).

Table 2. Maximum journey of human porters versus horse and wagon

	Human	Horse
Weight carried (kg)	23	300
Distance traveled per day (km)	30	37
Energy intake per day of maize/oats (kg)	1	9
Energetic limit (days)	23	33
Energetic limit (km)	690	1,230
Maximum one-way journey (km)	345	615

Table 3. Energetic requirements of humans and horses

	Humans[a]	Humans[b]	Horses[c]	Horses[d]
Weight carried (kg)	23	30	200	700
Distance traveled per day (km)	30	36	37	37
Daily energy requirements (kcal)	3,600	3,456	42,900	26,700
Energy efficiency (kcal/kg/km)	5.22	3.20	5.79	1.03

[a]Sanders and Santley.
[b]Drennan.
[c]Minimum.
[d]Maximum.

It appears that, in terms of energy expended, horses are not appreciably more efficient than humans. Of course, the relative energetic efficiency of horse and human transport may change considerably depending on the initial values used. My point is not that human porters are more efficient than draft animals at transporting goods, but that the superiority of draft animals has been overstated. Even if horse transport is twice as efficient as human portage, the assumption of dramatic energy savings through use of the horse must be questioned.

One might argue that horses do not compete with humans for food, and therefore the costs of horse transport are not incurred by the social system. This objection is not borne out by historical data. Although all draft animals can obtain nourishment from grass growing on the sides of roads, horses and mules must receive supplemental grain when working. Oxen require about half as much as do horses (Slicher van Bath 1963:22), and can apparently perform adequately without supplements. Indeed, oxen were preferred on the Oregon Trail because they did better on natural graze with no supplemental feed (Keith 1980). Turn-of-the-century U.S. Army feeding rations included 9 pounds of oats for mules and 12 pounds for horses, plus 14 pounds of hay per day (Hassig 1985:283). I will return to this issue after an examination of the relative productivity of Mesoamerican maize and European wheat agriculture.

STAPLE GRAIN PRODUCTIVITY

Mexican maize productivity varied from a low of 400 kg/ha on the piedmont without irrigation to a maximum of perhaps 2,250 kg/ha in irrigated areas. In fact, *chinampas* (raised gardens) could

Table 4. An alternative way of estimating an energetic efficiency range for horses

	Minimum	Maximum
Weight carried in kg	200	700
Distance traveled per day in km	37	37
Daily energy requirements in kcal	26,700	42,900
Energy efficiency in kcal/kg/km	3.61	1.65

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produce more than 3,000 kg/ha (Sanders 1976:144). The proportion of land devoted to each method undoubtedly varied considerably, but the larger cities probably made use of considerable permanent or floodwater irrigation (Sanders and Santley 1983; Sanders et al. 1979).

The variability was much less in Europe, in part because irrigation was rarely a factor. In interior Spain, wheat yields averaged only 480 kg/ha in 1840 (Blum 1961:330). The best recorded yields in preindustrial Europe were no better than 1,100 kg/ha, and these were exceptional (Biddick 1989:68; Blum 1961:330). Thus, maize agriculture in Mexico was potentially much more productive than wheat agriculture in Europe. The maximum yields in Europe barely attained the minimum productivity of intensive agricultural practices in Mexico.

The seed-to-yield ratio is a critical element. This determines how much seed must be set aside from each year's harvest for next year's seed, and thus, how much is available for consumption. Maize and wheat differ considerably in this regard. Compared to yields, the amount of maize that had to be set aside for the next year's planting was negligible. Seeding rates among traditional Mesoamerican agriculturists range from 10 kg of seed per ha for extensive gardens to 12 or 15 kg/ha for *chinampa* plots. This compares with yields of approximately 1,100 and greater than 3,000 kg/ha, respectively (Sanders cited in Hassig 1985:275; Steggerda 1941:96–97). Seed-to-yield ratios are accordingly around 1:110 and 1:200, respectively. Hassig (1985:18) reports seed-to-yield ratios of 1:30, which would mean seeding rates of greater than 30 kg/ha for yields of 1,000 kg/ha. This is an improbably high seeding rate for maize, but I use it in my comparisons to avoid overestimating the contrast between wheat and maize productivity.

Wheat seed-to-yield ratios provide a stark contrast. Seeding rates changed little in Europe throughout the centuries. According to the Roman authors Columella (1960:145 [Book II, IX]) and Varro (1954:275 [Book I, XLIV]), the Romans sowed about 5 *modius* to the *jugerum*, or 130 kg/ha. Seeding rates of from 115 to 230 kg/ha are reported for medieval and early modern Europe (Biddick 1989:68; Braudel 1981:121; Jacquart 1974:170). I use the figure of 130 kg/ha, near the low end of the range, in order to compare the maximum European productivity with the minimum Mesoamerican productivity. At an optimistic average yield of 800 kg/ha, a seeding rate of 130 kg/ha works out to a seed-to-yield ratio of 1:6, slightly better than the generally accepted figure of 1:3 to 1:5 for all of preindustrial Europe. Thus, in direct contrast with the seeding requirements for maize, an enormous portion of each year's harvest had to be set aside for the next year's planting (Braudel 1981:120–121; Le Roy Ladurie 1974:21; Slicher van Bath 1963: 18–23).

In order to clarify the effects of the different land use and productivity factors, I have calculated average productivity figures for the two regions. A very generous estimate of average productivity in much of preindustrial Europe would be about 800 kg/ha (Abel 1980:41; Braudel 1981:121). Average productivity estimates for Mexico would have to take into account the different types of land use, including irrigation. Assuming that cities would not have developed in the absence of reliable water, I use an average productivity for pre-Hispanic highland Mexico of 1,000 kg/ha.

During periods of high population density, such as the Late Horizon in Mesoamerica and the medieval and early modern periods in Europe, land would not usually have been left fallow for more than one year (Braudel 1981:114–115; Sanders et al. 1979:238, 376; Slicher van Bath 1963). Table 5 depicts the different land area requirements at average productivity for each region, assuming one year of fallow for every year of grain production, vastly different seed-to-yield ratios, and the somewhat lower nutritional value of wheat (3,333 kcal/kg) than that of maize. Note that it takes one and one-half times as much land area to feed 1,000 people in the European system as in the Mesoamerican one.

THE THREE-FIELD SYSTEM

The three-field system was in use in much of preindustrial Europe, broadly coincident with the use of horses for draft. The two-field system was sufficient where oxen provided most of the draft power, but horses required about twice as much supplemental feed as oxen (Jacquart 1974:172; Slicher van Bath 1963:22). In the three-year rotation, bread-grain production was followed by oat production, which, in turn, was followed by fallow (Braudel 1981:114–115; Le Roy Ladurie 1974:46; Slicher van Bath 1963:59). Thus, one-third of the available land was dedicated to spring grain production (usually oats), meaning that for every hectare in wheat production during a given year, 2 ha were not producing wheat.

However, not all the oats produced in the three-field system were fed to horses. Oats were an important food source for the poorer of Europe's rural residents (Braudel 1981:136), but preindustrial oat productivity rarely exceeded 500 kg/ha, with seed-to-yield ratios hovering around 1:3 (Braudel 1981:121; Slicher van Bath 1963:22). Using that moderately high figure of 500 kg/ha yields and an improbably low seeding rate of 100 kg/ha (1:5 seed-to-yield), the annual yield of spring oats from 1 ha divided into three fields would sustain only .65 persons. The thankless and probably fruitless effort to estimate the proportion of oats eaten by people and horses can be sidestepped by simply providing the limits of the argument. If all oats were consumed by people, the land area required to produce grain for 1,000 people would be 520 ha; if all oats were consumed by horses, the land area required would be 785 ha; if half of the oats produced were fed to horses, the requisite land area figure would drop to 630 ha (see Table 5).

Horses do compete with humans for food, and their consumption rates would probably fall in the upper, rather than the lower, half of the range. Looked at another way, given the same land area,

Table 5. Provisioning potential of land under maize and wheat agriculture

Grain	Rotation	Oats to horses	Hectares/ 1,000 people	People/ 10,000 ha
Maize	2-field		340	29,600
Wheat	2-field		525	19,100
Wheat	3-field	all	785	12,700
Oats	3-field	none	1,540	6,500
Wheat/oats	3-field	none	520	19,300
Wheat/oats	3-field	$\frac{1}{2}$	627	16,000

Note: Assuming 1,000 kg/ha maize productivity in Mesoamerica, 800 kg/ha wheat, and 500 kg/ha oat productivity in Europe, and one-year fallow in both systems. Seeding rates used are 30 kg/ha maize, 130 kg/ha wheat, and 100 kg/ha oats. The average individual energy requirement is 2,000 kcal/day, of which 80% is provided by staple grains. Maize provides 3,565 kcal/kg, wheat provides 3,333 kcal/kg, and oats provide 2,850 kcal/kg.

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a much larger population could be fed in Mexico than in Europe. In Europe, closer to 13,000 than to 19,000 people could be fed from the produce of 10,000 ha of land, whereas in Mexico 29,600 people could be fed. Clearly, if the size of the hinterland limits the size of cities, Mesoamerica was not at a disadvantage with respect to Europe. The type of crop, its productivity, and demographic and geographic attributes that influence intensity of production are at least as important to city supply as is the type of land transport available.

CONCLUSION

This paper does not consider some other advantages of horse power and the wheel. For example, with horse and wagon, it was possible to transport much heavier loads. Thus, such very heavy objects as monolithic stones, which could not be broken up into pieces manageable by human porters, could be carried by wagon. The horse was not used solely for transportation, but also as power for such farm tasks as plowing. Moreover, the manure from horses and cattle was an important component of the productive system; that is, it helped to regenerate land made poor in nutrients by hundreds of years of farming. While clearly important advantages of draft animals, the effects of these factors on the maintenance and growth of city populations remains unquantified.

The specific results of these rough calculations should not be given too much weight. The variability both in staple grain production and the hauling capabilities of individuals, whether human or animal, are too complex to be easily reduced to arithmetic means. Different initial conditions (e.g., weight carried, amount eaten, distance traveled, kilograms produced per hectare) will greatly affect the outcome of these calculations. Although I have tried at nearly every juncture to use contrastingly low and high estimates in order to stack the deck against my argument, rather than for it, any estimates of average values are subject to considerable error. The lesson to be learned is that it is unwise to too readily accept the apparent superiority of a horse-based transportation system. Sanders and Santley (1983:391) have rightly pointed out that the dominant transport mode and the surplus capacity of the food production regime were critical factors in determining the nature of urbanization. It must be remembered when comparing Old World with New World urbanization, however, that land-transportation advantages gained by the Old World reliance on draft animals may have been offset by the greater surplus potential of maize over wheat agriculture.

RESUMEN

La falta de animales de carga es frequentemente considerado haber sido un impedimento para el crecimiento urbano en Mesoamérica. Sin embargo, el transporte fue uno de varios factores que afectaron el crecimiento de las ciudades. Este artículo contrasta los efectos de las diferencias en las eficiencias energéticas entre caballos y transportes humanos con las diferencias productivas entre los sistemas agrícolas europeos y mesoamericanos. Dependiendo de la fuerza y los requisitos de nutrición, los caballos pueden ser de una a cinco veces tan eficientes como los transportes humanos. Mas aún, los caballos compiten con los humanos por alimentos. En aquellos lugares en que los caballos jugaron un papel importante como transporte, una tercera parte de la tierra cultivable fue utilizada para la producción de avenas. Con ésto en mente, yo comparo la producción de maíz y trigo para demostrar que una unidad de tierra en Mesoamérica pudo haber mantenido más del doble de las personas que una unidad de la misma tierra en Europa. Así pues, la ventaja en el transporte que disfrutan las ciudades europeas es esencialmente contrabalanceado por un sistema agrícola más intenso en Mesoamérica.

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