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Yaks, yak Dung, and prehistoric human habitation of the Tibetan Plateau

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Abstract

This paper explores the importance of yak dung as a source of fuel for early human inhabitants of the Tibetan Plateau. The wild and domestic yak is introduced, followed by a discussion of yak dung production, collection, and energetic return. Yak dung is compared with other products such as milk, pack energy, and meat, demonstrating its high energetic value while emphasizing that various yak products serve different, complementary, and nonfungible purposes. Following this review of yak dung energetics, issues related to the early peopling of the Tibetan Plateau become the paper's focus. Availability of yak dung as a fuel was a potentially critical factor for colonization of the high Plateau, where other fuel sources are largely lacking. The patchy distribution of dung on the landscape may have required the development of various strategies for ensuring an adequate supply during foragers' travels in the high Plateau. Meeting fuel needs may have led to the integration of the wild yak into human settlement systems and may have contributed to behaviors that resulted in the yak's domestication.

> "No yak, no Tibetan people."
> Lobsang Trinley Lhundrup Choekyi Gyaltsen
> 10th Panchen Lama (Wu and Wu 2004)

1. Introduction

People living on the Tibetan Plateau rely for survival upon the yak, the region's native cattle. The yak is the load-packer for pastoralists on the move in the Plateau's high pastures and the wagon- or plow-hauler for farmers on the fringes. Yaks give daily sustenance in the form of milk, butter and cheese, yoghurt and whey, and occasionally meat and blood and fat. The long strong outer hairs of the yak's coat furnish ropes, tent cloth, pack bags, and ornamentation (Hollywood has lately discovered what Tibetan women have long known, that they are ideal human hair extenders). The yak's fine wooly underfur is made into yarn, felt, clothing, and blankets. Yak leather goes into bags, belts, boots, bundles, binding, bridles, bellows, boat hulls, breastplates, and beyond. Pastoralists trade yaks and yak products with neighboring farmers, merchants, and lamaseries for the essentials and luxuries not available locally – tea and oil, barley and peas, spices and snuff, pots and pans, tea bowls and prayer wheels, tent poles and needles, silk brocade and silver plate, rifles and binoculars. In the spiritual realm, the yak is godly, its skulls and horns and butter fashioned into icons to be revered. Yak butter keeps firelight alive in lamps religious and secular.

More prosaically, yak dung serves nearly all heating and cooking needs in a land where people require ample fuel but where wood or coal are scarce or nonexistent. Traditional Tibetan pastoral economy is fueled mainly by dung of yak, sheep, and goat (Goldstein and Beall, 1990). Each year, the yak produces three to four times its own weight in dung, a load that goes into cooking and heating, plaster and manure, construction of fences, walls, shrines, and storage rooms and is sometimes traded or sold to obtain other needed commodities. Over the course of its life, the typical domestic yak yields a greater potential energetic contribution through its dung than through milk, transport energy, or meat. Resident Tibetan and Mongol pastoralists have relied on yak dung for several thousand years, and Paleolithic hunters striving to live in the Tibetan high country before pastoralism probably also depended on yak dung. Indeed, one may speculate that the yak's domestication was initiated and sustained as much by people's need for dung fuel as by the use of other products such as meat, hair, or hide; and that other benefits of yak domestication, such as pack energy and milk, must have come as secondary benefits later in the process. To know how people settled in the inhospitable Tibetan Plateau as hunters or pastoralists, it behooves us to understand the energetics of yak dung.

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2. The Yak (*Bos [Poephagus] grunniens*)

Phylogenetically the yak is grouped with the Bovini, closely related to wild cattle and bison, but its nearest congener is not clear: some place it with *Bos* (Groves, 1981; Ritz *et al*., 2000), others *Bison* (Geraads, 1992; Verkaar *et al*., 2004; Lai *et al*., 2004). The yak is typically considered a subgenus of *Bos* (e.g., Wilson and Reeder, 1993; Nowak, 1999), but anatomical and genetic differences may justify its separation into its own genus *Poephagus* (cf. Olsen, 1990; Olsen, 1991; Wiener *et al*., 2003, p. 18; Han, 2003, p. 432). Genetic evidence suggests the yak diverged from other cattle lineages 1–2 million years ago (Tu *et al*., 2002), as the Tibetan Plateau was rising in elevation.

2.1 Wild Yak

The wild yak reigns in alpine habitats of the high Tibetan Plateau above 3000 m altitude, where other cattle fare poorly. Wild yaks were widespread and abundant in the Plateau and other high mountain ranges in central Asia before modern hunters decimated their numbers in the late twentieth century (Hoffmann, 1991; Lu, 2000). Currently, wild yaks are highly endangered with an estimated population of 15,000 or less, restricted to the remote Changtang region of the northern Tibetan Plateau and the Qilian Mountains (Schaller and Wulin, 1995; Schaller, 1998; Lu, 2000). Wild yaks are protected by law but still illegally hunted and their numbers appear to be declining overall, though populations in some protected areas have recently been on the rise (Harris and Loggers, 2004).

Wild yaks are massive, with great black upward- and backward-curving horns and long shaggy black to brown pelage covering the body including the tail. Pronounced sexual dimorphism characterizes the wild species. Adult males (called *drong* or *aBrong* in Tibetan) can be 2 m high, over 3 m long, and typically weigh 600 to as much as 1200 kg (Lu, 2000), while females (*dri* or *aBri*) are considerably smaller, weighing only 300 kg on average. Compared to domestic cattle, yaks possess large lungs and heart, a short wide trachea permitting rapid respiration, expansive sinuses, high hemoglobin concentration and red blood cell count, thick fur, and few sweat glands, all adaptations to the low level of oxygen, high solar radiation, and extreme cold of their high-altitude homeland.

Two wild ecotypes are recognized (Lu, 2000). One, called *Gaxi* by Tibetans, is restricted to alpine meadows in the western Qilian Shan and Aerjin Shan mountains. The *Gaxi* is a relatively gracile form, bulls weighing up to 600 kg and reaching 170 cm height at withers with 210 cm chest girth. The *Gaxi* possesses a prominent shoulder hump, long legs, long face, small muzzle, short ears, no dewlap, a fluffy broom-like tail, and horns curving gracefully backward. Pelage is brown-black with a gray nose, eye ring, and back line. These beasts are timid and do not aggressively attack people or other animals.

The other ecotype is the Kunlun yak (called *Hengde*, or “snow hill wild cattle”), found on alpine meadows in the upper reaches of Yaluzangbu River, the Kunlun Mountains, and across the Changtang in northern Tibet. These yaks are much larger than the *Gaxi* type, bulls ranging up to 1200 kg and reaching 205 cm height at the withers with a 270 cm chest girth. The head is massive, with horns having a basal circumference greater than 50 cm (nomads use them as containers to store milk or home-brewed barley beer). The shoulder has a prominent tuberous projection, legs are stocky, and the face is short with a wide expressive forehead marked with gray-white nose and eye rings. Pelage is black to black-brown with grayish back line; the hair is long on the top of the head as well on the shoulder, belly, and legs, long enough to nearly sweep the ground. Kunlun yaks are wary and usually flee at first sight of people, but if cornered or surprised at close quarters (or if they are shot), they may become very aggressive and are widely known to attack people, animals, and occasionally land rovers (Wellby, 1898; Schaller, 1998). The Swedish explorer Sven Hedin noted that yaks and other large game which lived in remote areas not usually inhabited by hunters or herders, were unafraid of people (Hedin, 1905, pp. 469, 478, 501).

Yaks graze on alpine sedges, grasses, forbs, lichens, and mosses. Their specialized tongues, covered with small thorny tubercles, allow them to easily lick up low-lying forage (Schaller and Wulin, 1995). Forage in the high country flourishes from mid-May to late August, followed by a long winter during which time yaks resort to wilted or dead herbage, a period of starvation that may result in 25–30% loss of body mass and frequent deaths (Long *et al*., 1999).

Yaks form separate male and female groups most of the year, bulls remaining solitary or forming groups up to 10–12 individuals. Females, calves, and some young males herd up from a dozen to two hundred. During the breeding season in late summer and early fall, bulls join the female herds and compete for mates, often violently. Females typically calve beginning at 4–5 years and every other year thereafter, giving birth in early summer. Wild yaks may live to 25 years, but their reproductive span is thought to be about 15 years.

The seasonal foraging movements of wild yaks are not well documented and may vary from region to region depending on local availability of forage, seasonal temperature, and presence of hunters or herders. Yaks may begin the summer growing season in lower elevation valleys, meadows, and Plateau plains, taking advantage of the early-season pastures there, but as summer warms up, they move to developing late-season pastures near snowline and on higher mountains. During winter, they may drop down to lower elevations or remain in the higher mountains. Yaks are well insulated and tolerate cold temperatures better than summer heat, and their movements reflect this preference.

2.2 Domestic Yak

Wild yaks are presently critically endangered, but their domestic descendants (Fig. 1) are abundant in central highland Asia. Some 14–15 million domestic yaks serve as

*Fig. 1. Typical domestic yak (*Bos *or* Poephagus grunniens*), Qinghai Province, China.*

major herd animals through much of the Tibetan Plateau and neighboring Qinghai, Sichuan, and Gansu provinces in China, in bordering highland countries such as Nepal, India, Bhutan, Mongolia, and Russia, and in much smaller numbers in Europe and North America. Domestic yaks differ from the wild stock in size, temperament, and coloration, the domestic varieties often showing white or piebald coats and lacking the gray-white muzzle hairs characteristic of the wild yak. The domestic yak is about 1.5 m tall, with males ranging from 300 to 500 kg weight and females between 200 and 300 kg (Buchholtz, 1990; Wiener *et al*., 2003). It shares with its wild ancestor many of the physiological and anatomical traits that adapt yaks so well to the cold and harsh environments of the Plateau (Zhang, 2000a). There are two main types, the Qinghai-Tibetan Plateau ("Plateau" or "grassland") type common to the broad meadows and steppes of the Tibetan Plateau and the so-called Henduan or Alpine type of the montane valleys primarily in western Sichuan and Gansu, each with several locally recognized "breeds" (Cai, 1989; Wiener *et al*., 2003, p. 17; Lai *et al*., 2004; Zhong *et al*., 2004). A rich literature on domestic yak production focuses on growth performance, milk yield, hair output, and other measures of productivity of different breeds (see Wiener *et al*., 2003, for an encyclopedic summary).

Wild and domestic yaks can easily interbreed, though such interbreeding usually does not occur in nature because the two species rarely comingle. In certain situations where wild and domestic yak herds do comingle, solitary wild bulls are sometimes observed hanging around the domestic herds (Lu, 2000), and domestic females sometimes wander off with the wild herds (Harris and Loggers, 2004). In some cases, herdsmen deliberately attempt to cross their females with wild bulls (Weiner *et al*., 2003, p. 45). On the other hand, wild bulls have been reported to occasionally attack and even kill domestic yak (Buchholtz, 1990). Crossbreeds tend to be larger, fiercer, and more intractable, but they are often preferred by herdsmen for their better growth and more protective nature (Wiener *et al*., 2003, p. 11). Domestic yaks and cattle also crossbreed, but the male progeny are sterile and subsequent backcrosses are genetically unstable, so breeding of these crosses typically stops at the first generation (Wu, 1998; Weiner *et al*., 2003, pp. 33–59). These yak–cattle hybrids, called *dzo* in Tibetan and *pian niu* (犏牛) in Chinese, are highly regarded by herders and farmers at the lower elevation range of the yak. The *dzo* are larger, produce more milk, work as pack or draught animals better than purebred yak, and are well suited to an elevation niche between the upper limit of cattle and the lower limit of the purebred yak, roughly 2500–3500 m.

2.3 Yak Domestication

As to the domestication history of the yak, very little is known (see Flad *et al*., this volume; Palmieri, 1976; Clutton-Brock, 1981; Olsen, 1990). According to Zeng and Chen (1980), yaks were originally hunted on the Tibetan Plateau and in mountains of Shangxi and Hubei Provinces in China, until they were tamed and domesticated by the Qiang people. The Qiang (羌, a term meaning "shepherds;" Lattimore, 1940, p. 215) refers to non-Han ethnic groups inhabiting the Tibetan borderlands in Sichuan, Gansu, and Qinghai Provinces, including the Qinghai Lake area (Hoffman, 1990). "It is believed that the yak was tamed and domesticated by the ancient people of Qiang (the supposed ancestors of the tribes of Tibetan, Qiang, Yi, and Naxi) in Changtang of northern Tibet about 5000 years ago (during the Longshan Culture period)," note Wu and Wu (2004).

> Since then, the yak and the ancient Qiang people co-existed and the yak became a sign and totem of the tribes, and was used to name the tribes or places. It is recorded that a clan of the Qiang people once migrated south to Kangding of Ganzi in western Sichuan and established the historically famous country, "the Yak State", during the Han Dynasty. A number of different clans like "the yak Qiang" or "the yak clan" was recorded in the historical literatures of the Han Dynasty. They were engaged in the yak keeping, the area where they stayed was administratively called "the yak country," and the mountain and the river where their yak grazed and drank was named as "the yak mountain or the yak river" (Wu and Wu, 2004).

Trade routes involving domestic yak were recorded as early as the dynasties of Qin (221–206 BC) and Han (206 BC to AD 220), and crossing of yaks with Chinese yellow cattle to create the hybrid *dzo* is described in ancient writings (Zeng and Chen, 1980). Zhang (2000b) notes that "systematic crossing of yak with other cattle has been recommended and practiced for many years; ancient documents indicate that yak have been crossed with common cattle (*Bos taurus*) for at least 3000 years. Documents from eleventh century China (Zhou Dynasty [1040–771 BC]) suggest that crossing of yak with cattle by the Qiang people gave benefits now recognized as heterosis. From the earliest times, the name 'Pian Niu' (and other variants) has been used to describe these hybrids. These crosses find a special niche with herdsmen, usually at a somewhat lower altitude than typical yak country. Crossbred females are an important source of milk and dairy products. Since males cannot be used for breeding, they are used as draught animals or are slaughtered for meat. These hybrids are very suitable for work as they are easily tamed and have better heat tolerance than pure yak."

Bailey *et al*. (2002) examined mitochondrial DNA from domestic yaks in Bhutan, Nepal, China, and Mongolia to identify two distinct haplogroups, hypothesizing that yak domestication occurred twice, similar to other cattle (Loftus *et al*., 1994) and other ungulates (Bradley, 2000). Bailey and her colleagues used a "molecular clock" estimate to suggest that divergence from the wild stock took place about 5000 years ago, cautioning about a wide latitude for error. This estimate corresponds generally with limited available archeological and historical records (Olsen, 1990; Flad *et al*., this volume).

3. Importance of Yak Dung

Dung of various herbivores, called *argol* from the Mongol word for "animal droppings," is widely used as fuel in central Asia, just as it is in other parts of the world lacking adequate supplies of wood (see, e.g., Winterhalder *et al*., 1974; Wright, 1992). The importance of dung fuel in central Asia was recognized by the nineteenth-century Lazarist missionary Abbé Evariste-Régis Huc (1898, pp. 89–90) whose pioneering survey, brief as it is, deserves reiteration for a modern audience:

> The luxurious variety of combustibles which the civilized nations of Europe enjoy, have exempted us from the necessity of making very profound researches into the divers qualities of argols. Such has not been the case with the shepherd and nomadic peoples. Long experience has enabled them to classify argols, with a perspicuity of appreciation which leaves nothing to be desired in that particular respect. They have established four grand divisions, to which future generations will scarcely be able to apply any modification.
>
> In the first rank are placed the argols of goats and sheep; a glutinous substance that enters largely into its composition, communicated to this combustible an elevation of temperature that is truly astonishing. The Thibetans and Tartars use it in the preparation of metals; a bar of iron, placed in a fire of these argols, is soon brought to white heat. The residuum deposited by the argols of goats and sheep after combustion, is a sort of green vitreous matter, transparent, and brittle as glass, which forms a mass full of cavities and very light; in many respects, closely resembling pumice stone. You don't find in this residuum any ash whatever, unless the combustion has been mixed with foreign matter. The argols of camels constitute the second class; they burn easily, and throw out a fine flame, but the heat they communicate is less vivid and less intense than that given by the preceding. The reason of this difference is, that they contain in combination a smaller proportion of glutinous substance. The third class comprehends the argols appertaining to the bovine species; these, when thoroughly dry, burn readily, and produce no smoke whatever. This is almost the only fuel you find in Tartary and Thibet. Last come the argols of horses and other animals of that family. These argols not having, like the others, undergone the process of rumination, present nothing but a mass of straw more or less triturated; they throw out a great smoke when burning, and are almost immediately consumed. They are useful, however, for lighting a fire, filling the office of tinder and paper to the other combustibles.
>
> We perfectly understand that this rapid and incomplete essay on argols is not of a character to interest many readers; but we did not feel justified in either omitting or abridging it, because it has been an object with us to neglect no document that might be of assistance to those who, after us, might venture upon nomadic life for awhile.

Huc's appreciative and absorbing account contains very little concerning "argols appertaining to the bovine species …almost the only fuel you find in Tartary and Thibet." Wild yak fecal productivity and use are equally poorly measured by modern science. Dung production of the domestic yak may help to illustrate the productivity and utility of the dung of its wild ancestors, given proper allometric and environmental allowances.

3.1 Dung Production

The amount of dung produced by a yak is a function of feed intake and quality of diet, which vary with season and grazing conditions, as well as animal size. Long (2003a, p. 391) notes that an adult grazing yak will consume "18–25 kg fresh forage in summer to 6 to 8 kg per day, or even much less, of wilted grass in cold-season grazing conditions." These are fresh forage values; dry matter (DM) intake is a preferable measure for assessing dung fuel production since moisture content can vary so much and since dung fuel is burned dry. On a DM basis, an adult yak will consume "4–5 kg DM per day in summer and autumn, and be reduced to 1–1.5 kg DM per day, or even less, during late winter and early spring" (Long, 2003b, p. 369). During the summer "the energy and protein intakes are adequate to meet maintenance, work and production, but in the later parts of the winter and early spring they fall below the requirements. Yak then lose weight and condition" (Wiener *et al*., 2003, p. 80).

Liu *et al*. (1997, cited in Long, 2003a) report that a 2-year-old yak consumes 3.4% of its body weight in DM each day under premature summer grazing conditions and 3.0% in mature growing period conditions; 3-year-olds consumed slightly more, 3.9 and 3.5%, respectively. Chen *et al*. (1994) report a slightly lower figure, ~3.16 kg DM per 100 kg body mass each day. Of this amount, 69.7% is digestible, meaning that 30.3% (0.96 kg per 100 kg body mass) is nondigestible DM that is excreted as feces.

If an amount of DM equaling ~3.5% of body weight is consumed per day and ~30% of that DM is excreted as feces, then ~1.6% of body weight is excreted as feces per day. If these proportions apply to wild stock, then a 500 kg bullock may eat 17.5 kg DM per day and yield as feces 5.25 kg DM per day, ~1916 kg per year, about 3.8 times its body mass. Obviously, a really big bull of 1000 kg will produce much more. The smaller wild cow, at 300 kg, leaves about 3.1 kg per day and 1150 kg per year.

The quality of forage has an important influence on the amount of dung produced. Summer range forage digestibility may range 65–70% (Cincotta *et al*., 1991), but is often less than 50% especially during the long winter and spring "starvation" months. If in winter a yak eats only 2 kg of standing dead forage per 100 kg body weight per day, with an average digestibility of 50%, then a 500 kg bullock would deposit 5 kg of dry weight dung each day and a 300 kg cow would leave 3 kg each day or about 3.65 times their body weight if computed on an annualized basis. Schaefer *et al*. (1978) used experimental conditions with controlled feed at a digestibility of 49.3%, and obtained essentially similar values, ~3.5 times body weight per year.

This prodigious amount of dung turns out to yield a considerable amount of energy. We measured caloric fuel content of dung of domestic yaks and other main domestic herbivores common in central Asia (Table 1). Samples were collected in the Qaidam Basin, gathered in the field, so no information is available about the diet of the participant animals; dung fuel content of animals on different diets and during different seasons merits further study.

By weight, the gross caloric values of dung from different animals are quite similar, probably reflecting a similar grass and herb diet (the camel sample may reflect a greater proportion of browse). By volume, however, the samples vary considerably in caloric value as a function of density and particle size. These structural differences, the result of distinctive digestive processes, account for the variation in fuel behavior noted by Abbé Huc and others. Sheep, yaks, and camels are ruminants, with a multichambered foregut to facilitate fermentation and breakdown of cellulose. Sheep and goat dung is dense and composed of very finely divided particles of organic matter, while yak dung is less finely divided and more open in structure. Horses are hindgut digesters, with an enlarged cecum and colon to process large amounts of low-quality fibrous feed, and their dung is very coarse. Variation in feces particle size probably has as much significance for its utility as fuel as it does for understanding the feeding ecology of different herbivores (Clauss *et al*., 2002).

Our specific results indicate that yak dung yields about 3307 kcal of heat energy per kg or about 900 kcal per liter of dried dung flakes. By way of comparison, if a kilogram of yak dung was converted (with perfect efficiency) into electrical energy, it could operate a typical personal computer for 9.6 h or a 60-W light bulb for 2.67 days. A liter of yak dung will bring a liter of ice-cold water to boil at 5000 m if it is burned in a typical cast-iron stove with an energetic efficiency of ca. 9.6% (water boils at 85° C at this altitude). Assuming that yak dung is identical to cow dung in its burning efficiency, it burns in an open fire with ~3–5% efficiency; for reference, wood burns with 5–8% efficiency and contains about twice the heat energy of dung (UNESCO, 1982). A liter of yak dung burning in an open campfire would therefore yield about 27–45 kcal of usable heat for cooking, enough to boil 0.3–0.5 l of ice-cold water.

This heat energy value suggests that a wild yak bullock of 500 kg, having an average feed intake of 3 kg per 100 kg body weight and an average feed digestibility of 50%, resulting in 7.5 kg of dung per day, would yield 24,802 kcal of total fuel energy per day, or some 9 million kcal per year. A female 300-kg yak on the same diet would give 4.5 kg of dung and 14,882 kcal of fecal fuel energy per day, or 5.4 million kcal per year. Depending on technology, 3–10% of this heat would be usable for cooking, with the rest of the energy lost to the immediate environment. This potential heat energy is, of course, scattered in the pasture and around camp and requires collection and processing for use.

3.2 *Economics of Yak Dung Collection and Use*

Yak dung collection and use was investigated in Qinghai Province, China, where dung fuel remains a critical

Table 1. Energy content of different herbivore dung samples, Qaidam Basin, Qinghai Province, China. Gross energy measured by calorimetric bomb by Atlantic Dairy and Feed Institute, Fredericton, New Brunswick, Canada.

Fuel	Gross energy (kcal/kg)	g/l	kcal/L
Yak	3306.6	270.0	892.8
Sheep	3771.1	236.1	890.4
Camel	3660.4	207.8	760.6
Horse	3634.6	132.7	482.3

Table 2. Daily work calendar of the Madam Cuotou (Age 53) Family, Jianshe Township, Dari County, Qinghai Province, China. Redrawn from Liu et al. 2001, Table 7.4.12.

<table>
<tr><th>Hour</th><th colspan="2">Husband</th><th>Son</th><th colspan="3">Wife</th><th>Daughters</th></tr>
<tr><td>5</td><td></td><td></td><td></td><td>Get up</td><td></td><td>Milk</td><td></td></tr>
<tr><td>6</td><td></td><td></td><td></td><td></td><td>Pick up Dung</td><td></td><td></td></tr>
<tr><td>7</td><td>Meal</td><td></td><td rowspan="9">Herd sheep</td><td>Cook and meal</td><td></td><td></td><td></td></tr>
<tr><td>8</td><td></td><td rowspan="10">Herd horses, drop in other herds, diagnose animal illnesses, process sheep leather</td><td></td><td></td><td>Process milk</td><td rowspan="9">Two daughters herd yak in turn</td></tr>
<tr><td>9</td><td></td><td></td><td></td><td>Make cheese</td></tr>
<tr><td>10</td><td></td><td></td><td rowspan="2">Dry dung</td><td rowspan="9">Herd calves and milk</td></tr>
<tr><td>11</td><td>Lunch</td><td>Cook and meal</td></tr>
<tr><td>12</td><td></td><td></td><td rowspan="7">Pick up dung and transport dung</td></tr>
<tr><td>13</td><td></td><td></td></tr>
<tr><td>14</td><td></td><td></td></tr>
<tr><td>15</td><td></td><td></td></tr>
<tr><td>16</td><td>Tea</td><td>Rest</td><td></td></tr>
<tr><td>17</td><td></td><td rowspan="4">Herd sheep</td><td></td><td>Milk</td></tr>
<tr><td>18</td><td rowspan="3">Spare time</td><td></td><td></td><td rowspan="3">Herd yak</td></tr>
<tr><td>19</td><td></td><td></td><td rowspan="3">Gather and store dry dung</td><td></td></tr>
<tr><td>20</td><td rowspan="2">Tie down horses</td><td></td><td></td></tr>
<tr><td>21</td><td>Supper</td><td></td><td rowspan="2">Supper and to bed</td><td></td><td></td></tr>
<tr><td>22</td><td>To bed</td><td></td><td></td><td></td><td></td><td></td></tr>
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commodity among both herders and village dwellers alike. Collection of yak dung may be sustained or sporadic, depending on situation and need. Dung collection is done primarily by women and children, particularly for day-to-day use. Women will typically spend 2–3 h per day collecting and processing dung, but this task may be accomplished while conducting other tasks such as herding (Table 2). Men take part in dung collection on special foraging trips when large quantities are gathered, for commercial ventures, or when they are alone herding. Several situations observed in the field or in the literature are discussed below.

1. An extended Tibetan family of 13 was observed living near the village of Heima He, south of Qinghai Lake, in a typical three-room mud-brick house about 15 m long by 5 m wide. For fuel they relied entirely on *niufen* (牛糞), the Chinese term for yak dung, which they collected themselves. The dung was stored outside the house in large heaps; such heaps can be seen throughout the Tibetan Plateau, next to these permanent houses (Fig. 2). Each heap was roughly 2 m wide, 3–4 m long, and 1 m high, rounded and with a hard dry dung coat to repel rain. A heap took about a month of intermittent work to collect, mainly during autumn. A heap, roughly 8000 l, resulted in about 16,050-l bags of dung. The family used a heap every 2 months in the summer (about 133 l per day), one every month in the winter (about 260 l per day), or about 10 piles per year. The annual total amounts to about 80,000 l of dung, perhaps 22,000 kg total, the output of about 12 yak each contributing 5 kg per day. Energetically,

Fig. 2. Dung piles next to permanent Tibetan home.

this amounts to 6.4 million kcal per year, or about 494,000 kcal per person per year.

2. A group of three adults who lived in a cinder block house in Heima He were observed wheeling a barrow holding six large burlap sacks filled with moist yak dung they had just collected from nearby pastures. Each sack, carrying an estimated 350 l, could be filled in about 10 min. One member of the group said that each bag lasted about 10 days (about 35 l per day), for cooking and heating needs. This group thus spent a couple hours of collection time to gather about 2 months' fuel supply (travel included, but processing time for drying the wet dung is extra). Thirty-five liters per day is considerably less use than the previous case, and it is not known what other fuel sources were available to this small family. However, the time spent in collecting dung was apparently well rewarded and not a limiting factor to its use. If a full day's work was spent in drying the dung and the volume decreased by 50% (both conservative guesses), then a caloric return of about 950,000 kcal in ~15 h would be the result, or about 63,000 kcal per hour.

3. A woman herder living in a tent camp during the rainy summer season collected the night's crop of yak dung in the early morning after milking, spreading it on the ground to dry it in mid-morning (Fig. 3). She raked up the dried flakes before the afternoon rains and stored it in rice bags for the next day's fuel (Liu *et al*., 2001). Two to three such bags, each holding about 60 l of dung flakes, sufficed for the day's heating and cooking needs. Therefore, daily summer fuel use in a cloth or hair tent with an earthen firebox amounted to 120–180 l of dung. This amount of fuel is somewhat higher than the first case described above, possibly because the tent she and her family lived in was more poorly insulated than the substantial house of the first group. At roughly 900 kcal per liter, fuel use amounts to 108,000–162,000 kcal per day in the summer. Given approximately 2 h per day the woman spent in collecting and processing dung, she obtained roughly 54,000–82,000 kcal of fecal energy per hour.

Fig. 3. Drying yak dung for daily fuel.

Fig. 4. Hui dung collector, Qinghai Province.

4. A group of Hui dung collectors who lived in a farming village near the Yellow River brought two small trucks to a well-used highland pasture 50 km away. They made this trip a few times each year to collect yak dung in any open pasture, supplementing coal and wood supplies for the winter. One young man collected dung by himself, carrying on his back a loose conical wicker basket (53 cm deep and 62 cm in diameter) that held approximately 75 l. Walking around the pasture, the young man found a moderately dry, collectable dung patty every few paces and flipped it into the basket using a wooden pitchfork (Fig. 4). He gathered 65 such patties in 13 min, until the basket was loosely filled, then he returned to dump the basket into the truck; total time for each collecting bout was about 20 min. (Three or four such baskets, properly dried, would be a day's fuel use in a summer tent camp as depicted in case 3, above.) A second dung-collecting pair consisted of a young woman with a large basket on her back (~145 l), into which an older man shoveled wet dung patties. Another man stood in the truck and packed down the basket loads as they came in.

Each truck carried approximately 1800 l, or about eight of each of the large and the small basket loads, but the dung in the truck was packed more tightly than in the basket, so each truckload probably counted for 12 of each basket load. Assuming 20 min per collecting bout, each truckload could be gathered in 4 h of work by the four collectors. By the time we had met this group, they had already worked 4 h and had one truck filled (Fig. 5). Thus, one good day's work would supply several months' worth of fuel, though fuel still required processing and drying.

Again, the limiting factor in dung fuel use does not seem to be abundance or the time spent in collecting, at least in pastures well used by domestic yak herds. The most time-consuming effort is probably involved in drying and processing. Nevertheless, yak dung appears to have been sufficiently economical a fuel to warrant special collecting trips from at least 50 km away. Though this group indicated

Fig. 5. A large load of fuel collected by four people in 4 h.

the dung would be used for fuel, it could also have been gathered to fertilize gardens or fields, if the farmer lacked other manure sources for that purpose.

5. A Mongol herdsman lived with another herder in a small camp near Xidatan, not far from Kunlun Pass, in Qinghai Province (Fig. 6). The young men occupied a canvas wall tent about 4×5 m in dimensions, with a small cast-iron stove for heating and cooking (Fig. 7). He used about 8 l of dry crumbled yak dung flakes to stoke a fire sufficient to boil one or two large kettles of water, about a liter of fuel for every liter of water boiled. This he would do two or three times a day, during meals. He collected from around the camp whenever he needed fuel and kept no more than a few days' supply stored up, at least while we were there in the summer. He said that in the winter he used about 30–40 l of dung each day to keep warm and cook. He mainly used yak dung, but sometimes he added sheep dung as well because it burned hotter. A bit of rubber from a tire tube worked the same. In all, if he used a base amount of $\sim$24 l of

Fig. 6. Mongol herdsman in tent, near Xidatan, Kunlun Pass area, Qinghai Province.

Fig. 7. A small cast-iron stove fueled with dung serves all heating and cooking needs.

dung per day for meals and an additional $\sim$12 l for warmth in the cold months (October–May), this herdsman in his small canvas tent would need about 11,700 l (3160 kg) of dung each year. Assuming that this man's estimate is correct, and given the small size of his domicile and the bitter cold of a Tibetan winter, this daily amount of fuel appears surprisingly small; it suggests that the fuel is used mainly for cooking rather than maintaining a comfortable indoor air temperature, as noted by other investigators (Goldstein and Beall, 1990).

6. An additional interesting case was provided in 1852 by Abbé Huc (Huc, 1898, p. 89). He wrote:

> We observed, also, flocking to Tchogortan, another class of Lamas not less interesting than the Mongols; they always arrived at daybreak; their garments were tucked up to the knees, and on their backs were large osier baskets; all day long they would traverse the valley and the adjacent hills, collecting, not strawberries and mushrooms, but the dung which the herds of the Si-Fan [yak] deposit in all directions. On account of this particular occupation, we named these Lamas Lama-Argoleers, from the Tartar word argol, which designates animal excrement, when dried and prepared for fuel. The Lamas who carry on this class of business, are in general idle, irregular persons, who prefer vagabondizing about on the hills to study and retirement; they are divided into several companies, each working under the direction of a

> superintendent, who arranges and is responsible for their operations. Toward the close of the day, each man brings the portion he has collected to the general depot, which is always situated at the foot of some well, or in the hollow of some valley. There the raw material is carefully elaborated; it is pounded and molded into cakes, which are placed to dry in the sun, and when completely desiccated, are symmetrically piled, one on the other, the stack, when formed, being covered with a thick layer of dung, to protect it from the dissolving action of the rain. In the winter, this fuel is conveyed to Kounboun, and there sold.

7. One final case, from Waddell (1906, p. 103), illustrates the value placed on stores of yak dung by Tibetan communities and their colonial antagonists:

> A curious illustration of the monetary value of fuel in this arctic region, where the only available material, namely, yak-dung, is a life necessity, came to light, when, owing to our telegraph wire having been cut near Phari, a fine was inflicted on the town of dried yak-dung fuel, as this was badly required by our troops. A fine of fifteen tonnes of cakes of this material was imposed, which at local barter rates represented in money about L15 sterling. So effectual was the fine, in this local coinage of the country, that they willingly paid half of it in Indian rupees, to escape parting with this invaluable article, and the line was never cut again. Without this commodity all human life in this barren part of Tibet would be impossible. As it is, the Tibetans seldom warm themselves at fires, but trust to thick clothing and animal food to keep themselves warm, and use fuel only for cooking. The yak are indeed a godsend in these barren regions. They are never given any food by their owners, but are sent adrift to forage for themselves, yet in return they work as beasts of burden, give milk for butter, and their own flesh for food, and also bestow the indispensable fuel daily. This arrangement recalls the extensive use of a similar article for the same purpose in India, where firewood is scarce, and where its substitute is gratefully called by the Indian peasantry "the gift of the cow" (go-bar).

These few cases, mixing anecdotal evidence and fairly rough measures of time spent in collecting dung, the amount of dung used for various cooking and heating purposes, and the caloric return of the dung utilized, highlight four main points. Most important, a modest amount of time expended in dung collection can result in a very substantial return of fuel, sufficient for all cooking and (in many cases) significant heating needs. In places where yaks graze, the availability of dung is not a limiting factor in collection. However, the amount of time and effort needed to dry and process enough dung to maintain a sufficient daily store in the rainy summer season may be a limiting factor in dung use. Finally, considerable variation in the use rates of dung fuel is notable in these few cases, probably reflecting situational flexibility. More detailed investigations of dung collection and use rates are warranted to further explore the energetics of this traditionally important fuel source.

4. Energy of Other Yak Products

Dung is just one product among many. It is worthwhile to compare its energy value with some of the yak's other contributions.

4.1 Milk

Milk and milk products are among the most important contributions of domestic yak. As Wiener *et al*. (2003, p. 136) note, "milk yield is closely related to pasture growth and quality and, in general terms, the amount of milk produced by the yak cow is considered as no more than the amount needed for the normal growth and development of its calf. In this respect, the milk yield of yak is more akin to that of animals in the wild than to the milk yield of dairy cattle." Yak cows typically have a lactation period of 150–180 days, with average daily yield ranging from 1 to 3 kg (Wiener *et al*., 2003, p. 138), depending on breed, condition, whether the cow has calved (which typically occurs every other year), milking strategy (e.g., once or twice daily), and time of year. Milking twice daily can increase yield by about one-third. Yak–cattle hybrids, or yak cows that were the progeny of wild yak–domestic yak crosses, may produce substantially more milk than purebred yak cows.

In general, a purebred yak cow of the Plateau type can be expected to produce an annual yield of 150–250 kg of milk. The milk is dense and sweetish, about as rich as ewe's milk and richer than a dairy cow's, with 15–18% milk solids, fat content averaging about 5.5–7.0%, protein and lactose approximately 4–5.5% each, and total energy about 850–1000 kcal per kg (Wiener *et al*., 2003, p. 148). If a yak cow produces 200 kg annually, she may yield up to 200,000 kcal of milk energy.

By comparison, over the year that same cow can easily produce 1500 kg of dung, resulting in a total dung energy yield of nearly 5 million kcal, some 25 times the energy content of her milk. Of course, milk energy in the bucket is already captured, whereas the dung must be collected; much of the dung, probably most of it, will remain in the pasture to fertilize next year's herbage. More important, yak milk is directly consumed and digested by people, whereas dung is not. Nonetheless, this example indicates the relative magnitude of energy available from dung and milk.

4.2 Pack and Draught Energy

Known as the "ships of the plateau," yaks are highly valued for their sure-footed capabilities in packing large loads over long distances, and they are safer than horses for riding in swampy ground, through rivers, or on steep rocky slopes. Farmers at lower elevations use yaks to plow fields and haul carts or other loads. Steers typically serve as pack and draught animals. Yaks can pack loads of 60–80 kg for 20–30 km per day without difficulty, sometimes for periods exceeding a month (Wiener *et al*., 2003, pp. 165–167). Loads of over 300 kg (over 85% of body weight) have been carried for shorter distances, at altitudes exceeding 4000 m. A plow weighing 390 kg can be pulled by a yak steer of about the same weight.

A pack yak that carries a load of 70 kg for a distance of 25 km at a rate of 4 km per hour ($=7.78 \times 10^7$ g-cm/s) yields about 0.763 kW of power or about 10.9 kcal per minute. Over the total trip of 6.25 h, the resulting energy outlay is approximately 4100 kcal. If the pack animal makes such a trip 100 days per year, the annual pack energy output would be 410,000 kcal, a very significant and highly valued energetic contribution. For comparison, the same pack yak would leave on the trail about *six times* that amount of energy in the form of burnable dung. The two forms of energy serve very different purposes, however, and are not easily convertible.

4.3 Hides and Hair

These products have an important energetic role, primarily to reduce heat loss to the environment through use as clothing, blankets, tents, and the like. Yak hair, especially down, can make excellent wool with good heat-retention properties, and though the hair has poor felting qualities, it can be combined with sheep or camel hair to create felt. The felt that goes into traditional Tibetan robes and as insulation in yurts and tents is an excellent thermal insulator.

The yield of hair and down varies considerably depending on age, sex, and breed (Wiener *et al*., 2003, pp. 156–163). Tibetan Plateau breeds yield relatively little, between 0.5 and 2.0 kg per animal per year; other breeds yield between 2 and 4 kg; the very furry male Jiulong yak, bred for its fiber, may yield as much as 25 kg per year (Wiener *et al*., 2003, p. 157). Down accounts for about 40–50% of the total yield in 2–4-year-olds.

An example of the heat-retention capacity of traditional fiber products can be gleaned from a study of the yurt, the Mongol portable house (Manfield, 2000). Multiple thick layers of felt (mainly sheep and goat) give the yurt its great thermal efficiency: the *R*-value (a measure of resistance to heat flow) of 20 cm of felt is calculated to be 5.12 $W/m^2 \cdot$ C, the equivalent of about 4 cm of fiberglass batting. Total heat flow from the yurt was a low 54 W/m^2 and required a relatively low heat input (4.5 kW) to maintain a comfortable indoor temperature of 15° C when the outside temperature was about 35° C below that. This estimate suggests that a comfortable ambient temperature inside the yurt can be maintained using 4.5 kW every hour or about 3870 kcal per hour. That is equivalent to 1.17 kg or 4.3 l of dung per hour (about 100 l a day), assuming that all heat energy stays within the yurt (which it does not).

The yurt has limited distribution on the Tibetan Plateau, being used mainly by Mongol herders at lower elevations in the Qaidam Basin to the north. Among traditional Tibetan pastoralists, the "black tent" (Manderscheid, 2001) is more common, in part because "the black tent is such an important symbolic marker of nomadic Tibetan cultural ethnic identity that the people are loath to abandon them" (Barfield, 1993, p. 187; see also Ekvall, 1968, pp. 61–65). Barfield notes that while "a Tibetan black tent may seem superficially similar to those found in Arabia or Afghanistan, it is sturdier…its panels are made of woven yak hair rather than goat hair…the resulting cloth has a much tighter weave and provides more insulation than the black tents of the arid zones" (Barfield, 1993, p. 187). Over time the panels become infiltrated with smoke from dung fires until they are essentially waterproof (Manderscheid, 2001). Yak-hair tents are by no means as thermally efficient as the yurt and are often freezing cold inside during the long winter (Goldstein and Beall, 1990), but they do cut the wind and keep the stove's heat close by. The *R*-value for the traditional yak hair 'black tent' apparently has not been measured but can be estimated to range between 0.5 and 1.0 $W/m^2 \cdot °$ C.

Traditional clothing was estimated to have a thermal resistance or insulating value of up to about 1.6 clo (Manfield, 2000, p. 13). The clo unit is used to describe clothing's insulating capacity (Gagge *et al*., 1941) and is $\sim$0.155 $W/m^2 \cdot$ C. One clo is roughly the insulating value of a man's underwear and lightweight business suit, or "a heavy top coat alone." The Tibetan long felt robe is roughly equivalent to a heavy top coat, perhaps slightly heavier. The traditional winter fleece-lined sheepskin robe is much thicker, each one requiring eight to ten tanned sheepskins, weighing up to 15 kg (Ekvall, 1968); it may have a clo value of 3–4, near the practical clo limit.

These figures give some idea of the potential heat-saving value of yak hair, though traditionally most clothing and felt products were made from sheep wool and skin, not yak hair. Yak hair, wool, and especially hides are commodities that can be traded for food or other necessary articles.

4.4 Meat

Despite Buddhist prohibitions against killing, the yak is an important source of meat for herders and their families (see Ekvall, 1968; Palmieri, 1976, pp. 117–130; Goldstein and Beall, 1990; Olsen, 1990, for discussions of this issue). Meat usually comes from castrated steers and sterile male cattle–yak hybrids, surplus males, and females at the end of their milk-producing and reproductive careers (though they can still produce valuable dung!).

Wiener *et al*. (2003, pp. 151–152) report that "live weights at slaughter varied with breed and location (and age at slaughter) from 116–576 kg. Dressing percentages ranged from 40–62 percent." The dressing percentage (carcass weight/live weight) tends to range from about 38% for younger animals to over 50% for animals aged 5 years or more. Eighteen-month-old yak with average live weight of 117.7 kg yielded an average carcass weight of 54.3 kg (46% of live weight) and 42.3 kg of meat (35.9%) (Wiener *et al*., 2003, p. 152). Goldstein and Beall (1990, p. 82) reported a figure of 80–125 kg of meat from a yak carcass. The meat is finely textured, relatively lean, and very tasty. Protein runs about 23%, fat content is ∼2.5–3.5%, and the energy content is about 1200 kcal/kg. Assuming a meat to live weight ratio of 0.36, a 300-kg animal would yield 108 kg of meat or 129,600 kcal of energy. The much larger wild yak might produce two to three times that amount of meat, enough for the needs of several families for a winter.

This meat energy is of course a one-time contribution, bringing to an end the living yak's yield in milk, dung, and hair. Some animals are valued and kept alive for their dung and their meat value is "banked" until needed. In this regard, it is worth noting that the same 300 kg animal would yield the same caloric value through its dung in less than 10 days.

Yet the "same caloric value" is obviously not the same at all. We humans cannot eat and bodily assimilate the caloric value of yak dung. Moreover, yak meat may be scarce, but if yaks live nearby then yak dung will be bounteous. These factors must be considered in weighing the relative importance of different energetic commodities.

4.5 *Offspring*

Calves are obviously another important contribution, both to perpetuate the herd and for sale or trade. Typically, a female yak will produce a calf every 2 years between the ages of four and five until 15 or so, yielding between five and seven offspring in her reproductive career. Yak–cow crosses are especially valuable as objects of sale to farmers. Stevens (1993, p. 149) noted that among the Khumbu Sherpa of Nepal, "the breeding and sale of *nak*-cattle crossbreed calves has historically been so lucrative that it was probably the most important factor in the regional prominence of *nak*," as female yak are named in the local language.

4.6 *Social and Spiritual Energy*

One final source of "energy" is the social importance and spiritual or godly aspect of the yak, particularly its "wild" avatar (Olsen, 1990; Wiener *et al*., 2003, pp. 12–13; Wu, 2003). This energy cannot be discounted, particularly in considering the yak's long-term interactions with people that resulted in its domestication. Tibetan society is often considered to be a yak culture, and the term often used for yak, *nor*, refers to wealth. The wild yak is widely revered as the embodiment of the spirit force of Tibet. Tibetan religion and folklore is rich in legends about the yak (Cayla, 1976; Olsen, 1990).

In light of the yak's spiritual energy, Palmieri (1976) suggested the yaks may have been domesticated for religious purposes, specifically cult sacrifices: "desire to obtain sacrificial bovines for cult purposes in high-altitude Tibet and the Nepal Himalaya thus may well have motivated man to domesticate the indigenous yak in imitation of common cattle" (Palmieri, 1976, p. 279). Following Simoons's (1968) study of the mithan, an Indian ritual ox, Palmieri suggested that the process of domestication involved convincing wild yaks to trust humans via a salt tie, linking the presumed desires of wild yak for salt with humans' abilities to provide it. Herders commonly feed salt to domestic yak in some areas of Tibet and Nepal, making the animals more docile and tractable; herders may also capture and tame wild yak calves for subsequent breeding with domestic yak (Palmieri, 1976, pp. 280–281). According to this hypothesis, "young wild yak/dri, taken by hunters or agricultural folk, could have been brought back to a settlement, where they were given food and salt to bind them to man. Later, when matured, these 'wild' yak/dri could have been allowed to range freely. Occasionally, man would visit his free-ranging animals both to re-establish the salt-tie and to choose animals for sacrifice." Tibetan folk stories support this hypothesis, where the search for salt transforms cattle into yaks or where salt is used to coax wild yaks into submission. Palmieri noted that such a tie would have been unsuccessful on the Tibetan Plateau, where natural salt lakes and other salt sources are common. He suggested that this salt tie must have occurred off the Plateau, on the southern flank of the Himalaya, where salt was largely absent and people and yaks may have interacted for long periods.

The idea of a salt tie in the connection between people and yaks toward domestication remains speculative, as is the proposed place of domestication of the yak, but the spiritual energy connecting the wild yak and Tibetan people is certainly real (Olsen, 1990). The yak's spiritual energy cannot of course be translated into fuel or food energy, but in the Tibetan spiritual world order, yak energy is "good to think" (Levi-Strauss, 1963).

Increasingly, the wild yak is also an important emblem in biological conservation (Miller *et al*., 1994; Miller and Schaller, 1997; Schaller, 1998; Harris *et al*., 1999). Now limited to its last stronghold in the remote Changtang, the wild yak population holds on to survival by virtue of geographic isolation, wariness of people, and the Chinese government's attempts to control illegal poaching, which continues despite strong penalties because some individuals are willing to pay large sums to "bag one." The wild yak now survives as a totem for Tibetan society and for conservation efforts worldwide.

5. Fuel Availability on the Tibetan Plateau

The previous case studies provide evidence for the importance of domestic yak dung as a fuel in modern Tibetan pastoralist society. Energetically, dung ranks high in the potential contributions of the yak, though different yak products (fuel, food, transport, heat conservation, and spiritual power) all play very different and complementary roles in supporting Tibetan people. Yak pastoralists live nearby their herds so they have easy access to abundant dung; the limiting factor to its availability, evidently, is the time it may take to process and dry it, especially in rainy summer months, but a family's needs appear to be rather easily met.

Arguably, hunters and other foragers who first occupied the harsh and wood-less Plateau environment before pastoralists must also have depended on dung as fuel (see Rhode *et al*., 2003, for a similar argument regarding Late Pleistocene settlement of high-latitude western Beringia). Unlike yak pastoralists who bring their fuel producers with them, these foragers may have encountered constraints to dung availability in the places where they hunted and camped. It is worthwhile to consider the availability of wild yak dung on the Plateau, if hunters did not bring with them their own herd of dung providers. This issue is addressed in two ways, considering temporal and spatial variability in the availability of fuels on the high Tibetan Plateau, respectively.

Virtually all of the Tibetan Plateau today is covered with treeless and shrubless meadow, grassland, alpine desert, or cushion-plant vegetation (Kingdon-Ward, 1947; Chang, 1981), hence the importance of yak dung as an essential fuel for pastoralists living there (Fig. 8). Forests and shrublands do occur on the lower margins of the Plateau and in the major river canyons draining the high country along the southeast and southwest margins; a few hills and mountains on the outer edge of the Plateau also support isolated stands of trees (juniper or spruce) or shrub communities in a few places up to ~4500 m altitude. The distribution of trees and shrubs differed in the past, however. Charcoal and pollen records from the Tibetan Plateau and Qinghai Lake basin indicate that trees and shrubs grew more commonly and at higher elevations during the Holocene optimum, 6000–8000 years ago, than they occur at present (Yan *et al*., 1999; Kaiser *et al*., 2006; Ji *et al*., 2005; Kaiser *et al*., 2007). People first made sustained forays into the interior of the high Tibetan Plateau (>4000 m) during this same period, as indicated by archeological evidence (Brantingham *et al*., this volume). Miehe *et al*. (2006) report that anthropogenic deforestation occurred in southern Tibet during the Late Holocene and suggest that the region would today be covered in forest rather than desert pastures, were it not for heavy grazing of sheep and goats. A similar argument can be made for the Late Holocene decline of woody shrubs and trees in the Qinghai Lake basin, on the northeast margin of the Plateau (Liu *et al*., 2002; Ren, 2000; Shen *et al*., 2005), a time when pastoralism probably began to be established in this region. Woody fuels were therefore more widely distributed on the Plateau, and especially along its margins, during the period of earliest sustained human occupation and into the later Holocene. Yet even during the Holocene climatic optimum, most of the vast high-elevation Tibetan Plateau would have lacked such fuels and dung would have been the major, if not only, option for these early human colonists.

The types of fuel used by prehistoric foragers occupying the Tibetan Plateau must be confirmed archeologically. Our work in the mid-elevation (~3200 m) Qinghai Lake Basin indicates that local trees and shrubs (*Populus* and possibly *Potentilla*) were commonly utilized for fuel in Late Upper Paleolithic and Epipaleolithic sites dating before 9000 Cal yr BP (Madsen *et al*., 2006; Rhode *et al*., 2007). Dung was apparently used for fuel at one site (Heimahe 3) as revealed by charcoal and ash analysis (Rhode *et al*., 2007; cf. Miller, 1984; Canti, 1997; Hastorf and Wright, 1998). At present, we have no information about the types of fuel sources used by early foragers on the high Plateau.

Spatial variation in the availability of yak dung across the Plateau landscape can be examined via records of various adventurers, religious sojourners, and soldiers who

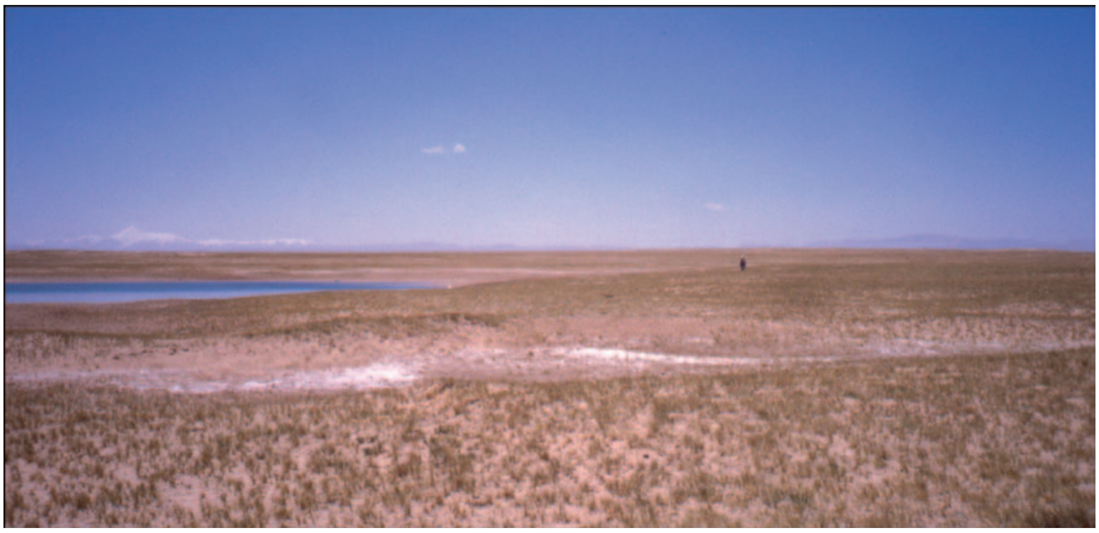

Fig. 8. Typical view of vast treeless plain on the high Tibetan Plateau, south of Kunlun Pass, Qinghai Province.

passed through the region in the late nineteenth and early twentieth centuries. Expeditionary accounts refer repeatedly to wild yaks, yak dung, and its distribution along their routes. For example, William Woodville Rockhill, crossing Tibet in 1891–1892, made numerous notes in his diary about the distribution of yak dung and its importance as fuel (Rockhill, 1894):

[May 30, p. 194] "Fortunately we brought with us several bags full of argols, for there were none to be found anywhere about camp. In this country it is always well to carry a small supply of dry dung, it weighs but little and may often prove invaluable and save one's boxes or pack saddles from being used as fuel."

[June 4, p. 199] "On the way up [a pass] I noticed six yak feeding on the side-hills. The ground was everywhere covered with their dung, so I fancy they are quite numerous in these hills…from the great quantities of yak droppings on this, as on the north side of the range, I fancy that this must be a fine place for a sportsman…"

[June 10, p. 205] "Bunches of yak were on every hill, and that readily accounted for the shortness of the grass in the neighborhood. It is wonderful what huge quantities of grass these animals eat, a herd of a hundred would, I believe, find barely enough on a good, rich meadow three miles square. Fortunately their droppings supplied us with an abundance of much needed fuel, and we were able to keep a big fire burning continually, a thing we have not done for many a day."

[July 4, p. 226] "The ground was soaked, the argols too wet to burn, the only water we could get was muddy and brackish. It was a poor place for a camp, bleak beyond description, the only thing which commended it was the grass. We broke up one of our packing boxes to start a fire and dry some argols for fuel…"

[July 15, p. 243] "The constant heavy rains at this season of the year make traveling in these parts slow, wearisome and difficult, for, to add to the fatigues of the journey, fuel (dung of course) is very scarce, as nearly all is soaked by the rain."

[July 19, p. 247] "Near where we have camped I noticed old fireplaces and other signs that people inhabit this country at some season of the year; it is the highest inhabited spot we have yet met with, its altitude is not less than 16 200 feet above sea level…No dry argols are to be had to-night, and we have had to burn one of our pack saddles…"

[July 20, p. 248] "We passed by quite a number of old camps and pulled down some of the dung walls to get dry fuel. Yak dung is the principal substance used in domestic architecture among the Drupa Tibetans. Besides being used to make low walls around the tents, as is also customary in K'amdo, the people here build little dome-shaped structures about five feet high and six feet in diameter with a small opening in the south side. In these they keep dry sheep's droppings and yak dung for fuel; they also put away in similar storehouses, of which there are a number around each tent, such as their belongings as they don't care to keep inside their dwelling."

Similar tales are recorded in Bower (1893, pp. 388, 394, 398), Bonvalot (1892, pp. 180, 189, 200–201, 206, 208, 231–2, 309–310), Hedin (1905, pp. 100, 142, 405, 424, 429, 444, 459, 465, 474–478, 500–504), and others who traversed Tibet during this period. Wild yak and other native large animals (the kiang, chiru, gazelle, wild sheep, and others) were widespread and often exceptionally abundant, particularly in those large areas of the central Plateau (e.g., the Changtang) where people were scarce (Schaller, 1998). These animals roamed selectively depending on their seasonal habitat preferences, and many parts of the Plateau were not preferred habitat. In some places, large yak herds covered hillsides and pastures with dung, making an argol-collector's as well as hunter's paradise. But long stretches of travelers' trails lacked yaks or yak dung, and the incautious explorer risked burning his pack saddle, boxes, tent poles, whatever, to stay warm. In the rainy season, obtaining quantities of dung dry enough to burn may have entailed prolonged processing. Prudent long-term survivors on the Tibetan Plateau made sure they had sufficient fuel available to them wherever they happened to be. Foragers coping with spatial discontinuities in dung fuel may have ensured an adequate supply of this essential resource by "mapping on" to likely dung-rich areas, e.g., by following yak herds and their trails or by focusing on yak's preferred habitats; or by using various logistical strategies to bring fuel to their camps, e.g., collecting and drying yak dung to carry with them, transporting dung fuel to base camps for processing and use, or bringing captive yaks with them – the last of these a potential step that may have helped to initiate the yak's domestication.

6. Yak Domestication and Yak Dung

6.1 How and Why Were Yak Domesticated?

As noted above, little is known concretely about the process of yak domestication, even the specifics of place or time (Palmieri, 1976; Clutton-Brock, 1981; Bonnemaire, 1984; Olsen, 1990; Flad *et al*., this volume). Why the wild yak gave rise to a domestic stock is itself something of a mystery, as with other cattle (Clutton-Brock, 1981, p. 66). Most species of mammals are unsuited to domestic life, and only a very few have become successfully domesticated (Baskin, 1974; Diamond, 1997). These few domesticates tend to possess physiological and behavioral characteristics that fit well in a human–animal mutualistic relationship, including relatively high productivity (somatic or reproductive), generalized and usually herbivorous feeding behavior, gregariousness, nonterritorial mating systems, hierarchical group structure, and polygamy (Walther *et al*., 1983; Garrard, 1984; Rowley-Conwy, 1986). At first sight, the wild yak would seem to make a poor candidate for domestication: it is very large and reproduces slowly, is generally unruly and flighty around people, and can be very dangerous (cf. Diamond, 1997, pp. 168–174). It inhabits one of the most isolated and least hospitable places on earth for human occupation, affording little opportunity for close and sustained interactions with humans or for the development of human social, demographic, and ecological factors that appear to promote domestication (e.g., moderate to high population density, settled communities, territoriality, and overhunting around settled communities; Hayden, 1995). So why, then, were yaks domesticated?

Despite their shortcomings, several characteristics of the wild yak must have facilitated domestication. One is social structure: yaks form close-knit herds of cows, calves and young males with a well-defined dominance hierarchy but are not strongly territorial (Schaller, 1998). This trait gives individual animals a sense of herd membership or social "place" that can be exploited by people to control captured animals. Like other cattle, cows and calves also exhibit strong interanimal imprinting (Schaller, 1998; Wiener *et al*., 2003), a behavior trait that can also be manipulated by herders to advantage. Captured animals with this set of social rules may become imprinted onto a person as the dominant herd leader or may be readily fitted into the established hierarchy of a domestic herd (Diamond, 1997, pp. 172–174).

Another behavioral characteristic is that yaks instinctively tend to bunch up in stressful situations to protect themselves against predators or while traveling together along narrow trails; such "bunching" behavior may make captive animals better suited to confinement in corrals or pens. If social structure and behavior were central to the yak's domestication, then the wild yak was most likely to have been domesticated when people who already managed domestic herds entered the Tibetan Plateau. The social structure established between herders and their herds would have most easily been able to incorporate captured wild yaks.

A third characteristic promoting domestication may be the wild yak's isolation. Genetic segregation of a breeding population must have been essential to the yak's domestication, and selective forces leading to domestication could not be sustained without segregation from wild herds. We should therefore expect that yak domestication required separation from the main distribution of wild yaks, where genetic isolation of small breeding populations could be effectively maintained. This probably occurred on the fringes of the Tibetan Plateau, below the optimal altitude range of wild yaks, but not so low that domesticated yaks would lose their adaptation to high altitudes (whether wild yaks brought to lower elevations become more tractable and docile is not known). Alternatively, captive yaks may have been effectively segregated from breeding with free wild yak by the wild yak's apparent wariness when people are around.

Most importantly, yak domestication should have become important only when people made sustained settlement of the Tibetan high country, where yaks are eminently adapted for survival and domestic cattle are emphatically not. Yaks have a reputation for not thriving below 3000 m (though many populations of domestic yaks do exist below this altitude; see Weiner *et al*., 2003, pp. 337–346). In competition with domestic cattle, yaks would not be selected for at low elevations. Yaks would only be preferred at higher altitudes where they outperform cattle (e.g., above 2500–3000 m elevation) and would only be preferred if people had opted for sustained occupation at those high altitudes themselves. It is likely that this preference occurred in the context of the development of farming and herding communities on the margins of the Tibetan Plateau during the Mid-Holocene, such as the Zongri complex in the upper Huanghe (Yellow River) drainage (Chen *et al*., 1998; QSWG/HZMB, 1998; Chen, 2002; cf. Aldenderfer and Zhang, 2004; Rhode *et al*., nd; Aldenderfer, this volume).

Yak domestication must have occurred under conditions in which the benefits of conserving yak for future use outweighed the immediate gains of hunting them (Alvard and Kuznar, 2001). In this shift from hunting to animal husbandry, "we went from exploiting the somatic potential of other organisms to co-opting and increasing their reproductive potential" (Alvard and Kuznar, 2001, p. 295). The costs associated with animal husbandry increases for large animals and those with low reproductive rates: future gains simply do not outweigh immediate payoffs, given opportunity and discount costs. With their great size and slow intrinsic rate of population increase, wild yak find themselves firmly in the "hunt" category (a feature they share with most major domestic animals). Mitigating factors must have made yak husbandry more beneficial than yak hunting, including the need for products such as dung or transport energy (so-called secondary products; cf. Sherratt, 1981), reduction of risk (Mace, 1993), or longer-duration planning for the future (Alvard and Kuznar, 2001, p. 306). Of these, the utility of secondary products such as dung and transport may have had the most immediate benefit to occupants of the Tibetan Plateau. If a kept animal "earns its keep" by delivering other important products besides its meat and skin, then the opportunity and discount costs of keeping it alive are reduced, and husbandry becomes as profitable as hunting. Behaviors that reduced risk may also have been strongly favored in the unpredictable Plateau environment, particularly during the Mid- to Late-Holocene transition ca. 4500 BP when the Tibetan environment became significantly colder and harsher. One such risk-reducing behavior may have been to ensure that a steady supply of fuel was available by keeping one's own fuel-producing herd near to hand.

6.2 *Was Yak Dung a Factor in Domestication?*

Could yak dung have played a role in the development of a mutualistic bond between yaks and people, eventually leading to the domestic yak and yak-pastoralist? Before yaks were domesticated, wild yaks could supply people with dung, meat, hides, and hair, and occasionally live calves that might be captured for pets (Serpell, 1989) or to lure other wild yaks to congregate near hunters (as was once suggested for domestic reindeer; Hatt, 1919). Contributions such as milk or transport could not be expected from wild yak. Of the two main critical commodities, meat and fuel, yak dung was the most abundant and most likely to be obtainable on a regular basis. From a purely energetic point of view, yak dung could have been as important as any other product obtainable from the wild yak.

To compensate for the patchy distribution of dung on the Plateau landscape, people could pursue one or more solutions: (a) bring yak dung or other fuels with them on their travels through areas that lack yak; (b) follow the herds using yak dung as they trail along, and avoid areas where yak do not go; and (c) procure and maintain wild yaks to produce dung wherever they camp.

If people used only option (a) and carried dung or other fuels with them, no domestication relationship should be expected since people would not develop a reliance on either yaks or yak dung, and yaks would develop no mutualistic tie to people. As Rockhill (1894, p. 194) advised, prudent foragers would carry some dried yak dung to tide them through places where other fuel sources were not expected to occur. Light as dried yak dung may be, it can be bulky, and carrying around significant quantities without effective means of transport (i.e., pack animals) appears unlikely. If it takes 2–3 l of dung to boil 1 l of water over an open fire (see above), the volume of dung that a person would need to carry for even short trips of a few days in fuel-less terrain could quickly become unwieldy, though not especially heavy. Similar problems attend transport of other energy-rich but voluminous resources: small amounts are ideal, but large quantities are prohibitive for pedestrian foragers (e.g., Madsen and Kirkman, 1988; cf. Jones and Madsen, 1989; Metcalfe and Barlow, 1992).

If people followed the herds (option b), they might become dependent on yaks and yak dung, but no reciprocal reliance would develop on the yak's part, any more than in other predator–prey relationships (cf. Wilkinson, 1972). Wild yak herds would experience no selective pressures to become attached to humans; indeed, human predation would most likely exert selective pressures on wild yaks to flee fast and far, as they do nowadays in response to hunting pressures (cf. Hedin, 1905; Schaller, 1998).

If people used option (c), however, captured wild yaks could have been kept as camp animals (Olsen, 1990, p. 89) to provide dung, carry loads, and eventually to provide other products such as hair and milk. In short, people who settled in the high Plateau may have relied on yak dung as fuel and in the process became yak followers, which afforded opportunities to capture and isolate wild yak individuals that would serve as a reliable source of dung and, later on, other useful products.

These scenarios are of course not mutually exclusive. They highlight the evident conclusion that yak domestication must have required capture and reproductive isolation of wild stock in some manner. They implicate yak dung as one main product that could be obtained in early phases of an emerging human–yak mutualistic relationship.

Counterarguments against the notion that yak dung was an important element in the yak's domestication can of course be mounted. Most obviously, merely following the herd will not by itself result in domestication, even if individual animals were occasionally captured and kept. There is no necessary reason that collecting yak dung by itself significantly alters the selective landscape sufficient to force significant changes in the behavior, morphology, or genetics of the yak.

Second, other fuel might be available. In some areas, wood from small shrubs and bones or horn splinters were usable as fuel (Rijnhart, 1901; Hedin, 1905, p. 444, 468), but the historical records and our observations of high Plateau vegetation suggest that these fuel sources are less abundant than wild yak dung. Other herbivores produce large serviceable quantities of dung, notably the wild ass or kiang, but kiang dung is less suitable for fuel than yak dung, as Abbé Huc noted long ago. Wood was available on the Plateau's margins and may have been more common during the early period of human occupation, but as noted before, most of the Plateau would have been woodless even during the Holocene climatic optimum. Sheep dung may have been a useful and abundant fuel, if the traveler was a shepherd with flock. Sheep pellets are commonly used as fuel in parts of the Tibetan Plateau, burning hotter than yak dung but requiring a bellows to stay ignited in the thin oxygen of the high plateau (Goldstein and Beall, 1990, p. 35). It is harder to collect than yak dung, unless the sheep are penned or confined to close quarters. Sheep droppings would not be a ready option for hunters or pre-pastoralists, of course.

Third, it may be argued (from an intentionalist perspective) that yak dung was not the reason for occupying the high Plateau and therefore not for domesticating yaks while there. People would not have made the arduous journey to the high Plateau solely for the purpose of collecting yak dung (though some people do so nowadays): hunters would have traveled there in search of wild game, pastoralists in search of luxuriant meadows for their herds, bandits in search of hunters or pastoralists to attack. Despite these intentions, however, all of these people would have required fuel to stay on the high Plateau for any appreciable length of time, and yak dung was one of the best fuels available in the high country.

Fourth, there is no evidence that processes resulting in the domestic yak involved selection for enhanced dung production. Quite the opposite: dung production is tied to body size and diet, and the process of yak domestication selected for a reduction in body size along with increased docility and tractability, which probably resulted in lower individual dung production rates. Overall usable dung production could have been enhanced with a domestic herd, thereby raising the unit of selection from the individual to the group; but it is difficult to imagine a successful group-selectionist domestication process involving a herd of unruly wild yaks, selected as a herd for the purpose of enhanced dung production. More likely, increased dung production would have been the outcome of selection favoring yaks that could live in domestic settings (docility, adherence to a dominance hierarchy led by people or their herding dogs, etc.), which would have made greater quantities of dung more readily available close to peoples' camps.

Ultimately, the process of domestication entails a shift in emphasis from an interest in the dead animal (its meat or hide) to an interest in the maintenance of the living animal and, more important, its progeny (Meadow, 1989; Alvard and Kuznar, 2001). Keeping a stock of animals for whatever reason (and a ready supply of useful dung can be one very good reason) becomes an end in itself and better to keep a reproducing stock than to constantly replenish it from the wild. At that point, the importance of dung fuel as a driver in the relationship between yaks and people would become only one of several products that a kept herd could provide.

Given these considerations, yak dung collection may have been an important element linking people to yaks at an early stage in the process of yak domestication, but it is unlikely to have been fully responsible for that process. Yak dung can be seen as one important resource, one that people are likely to have depended on, preceding the use of other important resources such as milk and transportation. Considering yak dung in this light highlights the continuum of behaviors linking people to other animal species, ranging from simple to not-so-simple predator–prey dynamics, to capture-keeping relationships, to full-scale domestication (Wilkinson, 1972).

6.3 Yak Domestication and the History of Human Settlement of the Tibetan Plateau

Based on these considerations, a speculative model about the timing and context of yak exploitation and eventual domestication can be developed. As outlined in Brantingham *et al.* (this volume; also Madsen *et al.*, 2006), Upper Paleolithic foragers began to occupy the mid-elevation fringes (∼3000–3500 m elevation) of the Tibetan Plateau by ca. 15,000 Cal yr BP. These small mobile hunting parties, whose forays were probably limited seasonally, may have encountered herds of wild yaks (depending on the season of occupation of the mid-elevation step), but no evidence yet exists that they hunted yaks, let alone domesticated them. It is unlikely that yak domestication occurred in this context.

During the Early Holocene, Upper Paleolithic and Epipaleolithic hunters made sustained forays into the high Plateau (>4000 m), possibly as a result of competitive displacement by farming groups at lower elevations, possibly in response to expanded habitat during the Holocene climatic optimum (Madsen *et al.*, 2006; Rhode *et al.*, 2007; Brantingham *et al.*, this volume). These groups undoubtedly encountered wild yaks and likely used yak dung for fuel in the high country. Whether they hunted yaks or scavenged winter-killed yaks for food or became yak-herd followers is not known. Available site assemblages suggest a mobile foraging strategy with some evidence of residential bases at marginal elevations (e.g., Jiangxigou 2, near Qinghai Lake, and Layihai on the upper Huanghe; see Brantingham *et al.*, this volume; Gai and Wang, 1983; Rhode *et al.*, 2007). This initial sustained colonization of the high country could mark the inception of yak domestication, but evidence is currently lacking. No evidence of yak exploitation is known from these sites, and the keeping, transporting, and maintaining a genetically isolated breeding population of captured wild yaks appear unlikely.

During the Middle Holocene, small communities of mixed hunting and farming economic orientation began to appear on the margins of the high Plateau, as at Zongri (Chen *et al.*, 1998; QSWG/HZMB, 1998; Chen, 2002) and Karuo (CPAM, 1985; Aldenderfer and Zhang, 2004). These Neolithic villages, related to central Chinese Yangshao agricultural complexes but also derived from local Tibetan antecedents (Chen, 2002; Aldenderfer, this volume) contain substantial architecture, graves with grave goods, sophisticated ceramics and bone and polished stone tools, as well as evidence of domestic cattle and other domesticated plants and animals along with abundant remains of wild game presumably from local and higher-elevation contexts (Flad *et al.*, this volume). Yak remains are not known from these sites, but it is possible that at this time people captured wild yaks and transported them to settlements on the Plateau margin, gave them limited feed to reduce their size and make them dependent on people (Lu, 2000), and possibly plied with salt to tame them (cf. Palmieri, 1976), resulting in isolated populations in the first stages of domestication. If captive breeding occurred, then domestication would have been well under way. It should be reiterated, however, that evidence for yak remains at these sites is currently absent, so this scenario is entirely speculative.

Finally, toward the end of the Middle Holocene, pastoralists began to bring domestic sheep herds into the high Plateau pastures on a regular seasonal basis. The timing of the inception of sheep pastoralism in the high Plateau is not well established, but domestic sheep are archeologically known from northwest China dating to at least 4000–5000 BP (Flad *et al.*, this volume). The onset of sheep-herding in the high Tibetan Plateau was likely to have been a major impetus for yak domestication. Sheep-herders must have encountered wild yaks on the high Plateau and may have captured and tamed individual wild yaks, eventually segregating and taming a breeding population within their own herds (in keeping with the traditional historical accounts of the Qiang people). This process was likely facilitated by trading captured and tamed yaks to cattle-raising farmers at lower elevations, who may have crossbred them with yellow cattle to create hybrid *dzo*, and possibly raised purebred yaks as breeding stock.

Once yak were domesticated, the high Plateau opened up to human occupation in ways not possible before. Sheep pastoralism in the high country is viable seasonally but not year-round (Goldstein and Beall, 1990; Stevens, 1993). Yaks can survive in the high country year-round, so a more intensive pastoralist occupation of the high country was possible. Yaks are able to survive on the scant alpine vegetation better than sheep. Most important, yaks can carry much more equipment than sheep, including the heavy tents used for shelter. With the use of yaks as animals of traction, the long distances of the Plateau became manageable for people, and with their yak's help, they could bring what they needed to survive in the high country on a more permanent basis, including a ready supply of dung fuel. But whether yak domestication began during a pre-pastoral hunting mode of occupation of the Tibetan Plateau or during a subsequent pastoralist occupation of the Plateau must yet be determined through archeological investigation focusing on the nature and timing of early occupation of the Tibetan Plateau itself and of Neolithic farming and herding communities on its fringes (Huang, 1994; Chen *et al*., 1998; Brantingham *et al*., 2001; Chen, 2002; Brantingham *et al*., 2003; Aldenderfer and Zhang, 2004; Brantingham *et al*., this volume).

To recapitulate, our current evidence for the timing of yak domestication, limited though it is by the paucity of the Tibetan archeological record, suggests that it most likely occurred in the context of the occupation of the margins of the high Plateau by mixed farming/hunting groups who maintained herds of domestic cattle after ca. 6000 years ago, and especially in the context of the establishment of sheep pastoralism ca. 4000–5000 years ago. Much more archeological work is needed to clarify the processes, geographic distribution, and timing of yak domestication.

7. Summary

Yaks are a fundamental part of traditional Tibetan society and must have been crucial to the development of that culture in prehistory. One of the important products of yak is dung, used for a variety of purposes but especially as a fuel for cooking and heating. This paper described the energetics of yak dung and its contribution in relation to other products of the yak, demonstrating that dung is one of the largest energetic contributions the yak delivers. The importance of yak dung to Tibetan yak pastoralist society has been noted by nearly every visitor to the country, but yak dung was probably equally important to the hunters and foragers that preceded the yak pastoralists in settling the high Plateau. Indeed, yak dung may have been an important element in the early development of yak domestication. This domestication process may have occurred in the context of initial sheep pastoralism some time prior to ca. 4000 BP, but much is left to be learned about the history of pastoralism on the Tibetan Plateau and the yak's role in it.

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References

Aldenderfer, M. (this volume). Modeling the Neolithic on the Tibetan Plateau.

Aldenderfer, M., Zhang, Y., 2004. The prehistory of the Tibetan Plateau to the seventh century A.D.: Perspectives and research from China and the west since 1950. Journal of World Prehistory 18, 1–56.

Alvard, M., Kuznar, L., 2001. Deferred harvests: The transition from hunting to animal husbandry. Amer. Anthrop. 103, 295–311.

Bailey, J.F., Healy, B., Han, J., Sherchand, L., Pradhan, S.L., Tsenduren, T., Foggin, J.M., Gaillard, C., Steane, D., Zakharov, I., Bradley, D.G., 2002. Genetic variation of mitochondrial DNA within domestic yak populations. Proceedings of the Third International Congress on Yak, Lhasa, China, pp. 181–189.

Barfield, T.J., 1993. The Nomadic Alternative. Prentice Hall, Englewood Cliffs, NJ.

Baskin, L., 1974. Management of ungulate herds in relation to domestication. In: Geist, V., Walther, F. (Eds), The Behavior of Ungulates and Its Relationship to Management. International Union for the Conservation of Nature, Morges, Switzerland, pp. 530–541.

Bonnemaire, J., 1984. Yak. In: Mason, I.L. (Ed.), Evolution of Domesticated Animals. Longman, London, UK, pp. 39–45.

Bonvalot, G., 1892. Across Thibet. Translated by C.B. Pitman. Cassell Publishing Company, New York.

Bower, H., 1893. A journey across Tibet. The Geographical Journal 1, 385–404.

Bradley, D.G., 2000. Mitochondrial DNA diversity and the origins of domestic livestock. In: Renfrew, C., Boyle, K. (Eds.), Archaeogenetics: DNA and the Population Prehistory of Europe. MacDonald Institute for Archaeological Research. Cambridge, UK, pp. 315–320.

Brantingham, P.J., Ma, H., Olsen, J.W., Gao, X., Madsen, D.B., Rhode, D.E., 2003. Speculation on the timing and nature of Late Pleistocene hunter-gatherer colonization of the Tibetan Plateau. Chinese Science Bulletin 48, 1510–1516.

Brantingham, P.J., Olsen, J.W., Schaller, G.M., 2001. Lithic assemblages from the Chang Tang region, northern Tibet. Antiquity 75, 319–327.

Brantingham, P.J., Gao, X., Olsen, J.W., Ma, H., Rhode, D., Forman, S.L., Zhang, H., Madsen, D.B. (this volume). A short chronology for the peopling of the Tibetan Plateau.

Buchholtz, C., 1990. True cattle (genus Bos). In: Parker, S. (Ed.), Grzimek's Encyclopedia of Mammals 5. McGraw-Hill, New York. pp. 386–397.

Cai, L., 1989. Yak of Sichuan. Sichuan Nationality Publishing House, Chengdu, Sichuan, China.

Canti, M.G., 1997. An investigation of microscopic calcareous spherulites from herbivore dungs. Journal of Archaeological Science 24, 219–231.

Cayla, L., 1976. Some mythological aspects of yak in Tibet. In: Bonnemaire, J., Jest, C. (Eds), Le Yak: Son Rôle Dans La Vie Matérielle Et Culturelle Des Éleveurs D'asie Centrale. Ethnozootechnie 15. Société d'Ethonozootechnie, Paris, France, pp. 23–34.

Chang, D.H.S., 1981. The vegetation zonation of the Tibetan Plateau. Mountain Research and Development 1, 29–48.

Chen, H., 2002. A study of the Zongri remains. PhD dissertation, Peking University, School of Archaeology and Museology, Beijing.

Chen, H., Ge, S., Li, G., 1998. Preliminary discussion of the cultural character of the Zongri site. Kaogu 5, 15–26.

Chen, Y., Yuan, Y. *et al*., 1994. Estimation of feed intake and digestibility of adult female yak in cold season. Journal of China Yak 2, 29–32.

Cincotta, R.P., Van Soest, P.J., Robertson, J., Beall, C.M., Goldstein, M.C., 1991. Foraging ecology of livestock on the Tibetan Changtang: A comparison of three adjacent grazing areas. Arctic and Alpine Research 23, 149–161.

Clauss, M., Lechner-Doll, M., Streich, W.J., 2002. Faecal particle size distribution in captive wild ruminants: An approach to the browser/grazer dichotomy from the other end. Oecologia 131, 343–349.

Clutton-Brock, J. 1981. Domesticated animals from early times. University of Texas Press, Austin.

CPAM, 1985. Karuo: A Neolithic site in Tibet. Cultural Relics Publishing House, Beijing.

Diamond, J. 1997. Guns, Germs, and Steel: The Fates of Human Societies. W.W. Norton, New York.

Ekvall, R.B. 1968. Fields on the hoof: Nexus of Tibetan nomadic pastoralism. Waveland Press, Prospect Heights, IL.

Flad, R.K., Yuan, J., Li, S., (this volume). Zooarchaeological Evidence for Animal Domestication in northwest China.

Gagge, A.P., Burton, A.C., Bazett, H.C., 1941. A practical system of units for the description of the heat exchange of man with his environment. Science 94, 429.

Gai, P., Wang, G., 1983. Excavation report on a Mesolithic site at Layihai on the upper Yellow River. Acta Anthropologica Sinica 2, 49–59.

Garrard, A.N., 1984. The selection of south-west Asian animal domesticates. In: Clutton-Brock, J., Grigson, C. (Eds.), Animals and Archaeology, Vol. 3, Early Herders and their Flocks. BAR International Series 202, British Archaeological Reports, Oxford, pp. 117–132.

Geraads, D., 1992. Phylogenetic analysis of the Tribe Bovini (Mammalia:Artiodactyla). Zoological Journal of the Linnean Society 104, 193–207.

Goldstein, M., Beall, C. 1990. Nomads of Western Tibet: The Survival of a Way of Life. University of California Press, Berkeley.

Groves, C.P., 1981. Systematic Relationships in the Bovini (Artiodactyla, Bovidae). Zeitschrift Für Zoologische Systematik Und Evolutionsforschung 19, 264–278.

Han, J. 2003. Molecular and cytogenetics in yak – a scientific basis for breeding and evidence for phylogeny. In: Wiener, G., Han, J., Long, R. (Eds), The Yak (second edition). Regional Office for Asia and the Pacific, Food and Agriculture Organization of the United Nations, Bangkok, Thailand, pp. 415–432.

Harris, R.B., Loggers, C.O. 2004. Status of Tibetan Plateau mammals in Yeniugou, China. Wildlife Biology 10, 91–99.

Harris, R.B., Pletscher, D.H., Loggers, C.O., Miller, D.J., 1999. Status and trends of Tibetan plateau mammalian fauna, Yeniugou, China. Biological Conservation 87, 13–19.

Hastorf, C.A., Wright, M.F., 1998. Interpreting wild seeds from archaeological sites: A dung charring experiment from the Andes. Journal of Ethnobiology 18, 211–227.

Hatt, G., 1919. Notes on reindeer nomadism. Memoirs of the American Anthropological Association 6(2). Washington, DC.

Hayden, B. 1995. A new overview of domestication. In: Price, T.D., Gebauer, A.B., (Eds.), Last Hunters, First Farmers. School of American Research Press, Santa Fe, pp. 273–299

Hedin, S., 1905. Scientific Results of a Journey in Central Asia 1899–1902, Volume 3, North and East Tibet. Lithographic Institute of the General Staff of the Swedish Army, Stockholm.

Hoffman, H. 1990. Early and medieval Tibet. In: Sinor, D. (Ed.), The Cambridge History of Early Inner Asia. Cambridge University Press, Cambridge, pp. 371–399.

Hoffmann, R.S., 1991. The Tibetan plateau fauna: A high altitude desert associated with the Sahara-Gobi. In: McNeely, J.A., Neronov, V. (Eds), Mammals in the Palaearctic desert: Status and trends in the Sahara-Gobian region. Russian Academy of Science, Russian Commission, UNESCO Man and Biosphere Program, Moscow, pp. 285–297.

Huang, W., 1994. The prehistoric human occupation of the Qinghai-Xizang Plateau. Göttinger Geographische Abhandlungen 95, 201–219.

Huc, E.R., 1898. Travels in Tartary, Thibet, and China, during the years 1844-5-6. Translated by W. Hazlitt. Reprint of 1852 Edition. Open Court Publishing Co., Chicago.

Ji, S., Liu, X., Wang, S., Matsumoto, R., 2005. Palaeoclimatic changes in the Qinghai Lake area during the last 18,000 years. Quaternary International 136, 131–140.

Jones, K.T., Madsen, D.B., 1989. Calculating the cost of resource transportation: A great basin example. Current Anthropology 30, 529–534.

Kaiser, K., Miehe, G., Schoch, W.H., Zander, A., Schleutz, F., 2006. Relief, soil and lost forests: Late Holocene environmental changes in southern Tibet under human impact. Zeitschrift Für Geomorphologie. N.F. Supplement 142, 149–173.

Kaiser, K., Schoch, W.H., Miehe, G., 2007. Holocene paleosols, colluvial sediments in northeast Tibet (Qinghai Province, China): Properties, dating, paleoenvironmental implications. Catena 69, 91–102.

Kingdon-Ward, F., 1947. Tibet as a Grazing Land. The Geographical Journal 110, 60–75.

Lai, S., Liu, Y., Wang, L., Fu, C., 2004. Phylogenetic analysis of a few of Chinese yak breeds. In: Zhong, J., Zi, X., Han, J., Chen, Z. (Eds.), Fourth International Congress on Yak, 2004 – Chengdu, China. International Veterinary Information Service (www.ivis.org), Ithaca, New York.

Lattimore, O., 1940. Inner Asian Frontiers of China. American Geographical Society Research Series 21. New York.

Levi-Strauss, C., 1963. Totemism. Beacon Press, Boston.

Liu, S. *et al*, 1997. Study on the forage intake at different phenological periods in grazing yak. Journal of Qinghai Animal Husbandry and Veterinary Medicine 22, 17–18.

Liu, Y., Ni, H., Wang, J., Baas, S., 2001. Strengthening pastoral institutions in north-west China pastoral area to access improved extension services for risk management and poverty alleviation. Report IN0601a, Sustained Development Department. Food and Agriculture Organization of the United Nations, Bangkok, Thailand.

Liu, X., Shen, J., Wang, S., Yang, X., Tong, G., Zhang, E., 2002. A 16000-year pollen record of Qinghai lake and its paleoclimate and palaeoenvironment. Chinese Science Bulletin 47, 1931–1936.

Loftus, R.T., MacHugh, D.E., Bradley, D.G., Sharp, P.M., Cunningham, P., 1994. Evidence for two independent domestications of cattle. Proceedings of the National Academy of Science USA 91, 2757–2761.

Long, R.J., 2003a. Yak nutrition – a scientific basis. In: Wiener, G., Han, J., Long, R. (Eds.), The Yak (second edition). Regional Office for Asia and the Pacific, Food and Agriculture Organization of the United Nations, Bangkok, Thailand, pp. 389–414.

Long, R.J., 2003b. Alpine rangeland ecosystems and their management in the Qinghai-Tibetan Plateau. In: Wiener, G., Han, J., Long, R. (Eds.), The Yak (second edition). Regional Office for Asia and the Pacific, Food and Agriculture Organization of the United Nations, Bangkok, Thailand, pp. 359–388.

Long, R.J., Zhang, D.G., Wang, X., Hu, Z.Z., Dong, S.K., 1999. Effect of strategic feed supplementation on productive and reproductive performance in yak cows. Preventive Veterinary Medicine 38, 195–206.

Lu, Z.L., 2000. Reproduction and conservation of wild yak. In: Zhao, X.X., Zhang, R.C. (Eds.), Recent Advances in Yak Reproduction. International Veterinary Information Services (www.ivis.org), Ithaca, New York.

Mace, R., 1993. Nomadic pastoralists adopt subsistence strategies that maximise long term household survival. Behavioural Ecology and Sociobiology 33, 329–334.

Madsen, D.B., Kirkman, J., 1988. Hunting hoppers. American Antiquity 53, 593–604.

Madsen, D.B., Ma, H., Brantingham, P.J., Gao, X., Rhode, D., Zhang, H., Olsen, J.W., 2006. The Late Upper Paleolithic occupation of the northern Tibetan Plateau margin. Journal of Archaeological Science 33, 1433–1444.

Manderscheid, A., 2001. The black tent in its easternmost distribution: The case of the Tibetan Plateau. Mountain Research and Development 21, 154–160.

Manfield, P., 2000. A comparative study of temporary shelters used in cold climates. What can be learnt from the design of the yurt and the Scott tent to inform the future design of shelters systems for emergency relief? M.Phil. essay, Environmental Design in Architecture, Cambridge University, Cambridge, UK. http://www.shelterproject.org/downld/manfield1.pdf.

Meadow, R., 1989. Osteological evidence for the process of animal domestication. In: Clutton-Brock, J. (Eds.), The Walking Larder: Patterns of Domestication, Pastoralism, and Predation. Unwin Hyman, London, pp. 80–90.

Metcalfe, D., Barlow, K.R., 1992. A model for exploring the optimal trade-off between field processing and transport. American Anthropologist 94, 340–356.

Miehe, G., Miehe, S., Schlütz, F., Kaiser, K., Duo, L., 2006. Palaeoecological and experimental evidence of former forests and woodlands in the treeless desert pastures of southern Tibet (Lhasa, A.R. Xizang, China). Palaeogeography, Palaeoclimatology, Palaeoecology 242, 54–67.

Miller, D.J., Schaller, G.B., 1997. Conservation Threats to the Chang Tang wildlife reserve. Ambio 26, 185–186.

Miller, D.J., Harris, R., Cai, G. 1994. Wild yak, their conservation on the tibetan plateau. In: Zhang, R., Han, J., Wu, J. (Eds.), Proceedings of the First International Congress on Yak. Gansu Agricultural University, Lanzhou, pp. 27–34

Miller, N.F., 1984. The use of dung as fuel: An ethnographic example and an archaeological application. Paléorient 10, 71–79.

Nowak, R. 1999. Walker's Mammals of the World, 6th Edition, Volume II. Johns Hopkins University Press, Baltimore, MD.

Olsen, S.J., 1990. Fossil ancestry of the yak, its cultural significance and domestication in tibet. Proceedings of the Academy of Natural Sciences of Philadelphia 142, 73–100.

Olsen, S.J., 1991. Confused Yak Taxonomy and Evidence of Domestication. Illinois State Museum Scientific Papers 23, 387–393.

Palmieri, R.P. 1976. Domestication and Exploitation of Livestock in the Nepal Himalaya and Tibet: An Ecological, Functional, and Culture Historical Study of Yak and Yak Hybrids in Society, Economy, and Culture. PhD dissertation, Geography, University of California, Davis.

QSWG/HZMB (Qinghai Sheng Wenwu Guanlichu, and Hainan Zhou Minzu Bowuguan), 1998. Preliminary report on the excavations at the site of Zongri in Tongde County, Qinghai. Kaogu 5, 1–14.

Ren, G., 2000. Decline of the mid-to-late Holocene forests in China: Climate change or human impact. Journal of Quaternary Science 15, 273–281.

Rhode, D., Madsen, D.B., Brantingham, P.J., Goebel, T., 2003. Human occupation of the Beringian mammoth steppe: Starved for Fuel or Dung-Burner's Paradise? Current Research in the Pleistocene 20, 68–70.

Rhode, D., Zhang, H., Madsen, D.B., Gao, X., Brantingham, P.J., Ma, H., Olsen, J.W., 2007. Epipaleolithic/Early Neolithic Settlements at Qinghai Lake, Western China. Journal of Archaeological Science, 34, 600–612.

Rijnhart, S.C., 1901. With the Tibetans in Tent and Temple. Fleming H. Revell, Chicago.

Ritz, L.R., Glowatzki-Mullis, M.-L., MacHugh, D.E., Gaillard, C., 2000. Phylogenetic analysis of the tribe Bovini using microsatellites. Animal Genetics 31, 178–185.

Rockhill, W.W. 1894. Diary of a Journey Through Mongolia and Tibet in 1891 and 1892. Smithsonian Institution, Washington, DC.

Rowley-Conwy, P. 1986. Between cave painters and crop planters: Aspects of the temperate European Mesolithic.

In: Zvelebil, M., (Ed.), Hunters in Transition: Mesolithic Societies of Temperate Eurasia and their Transition to Farming. Cambridge University Press, Cambridge, pp. 17–32.

Schaefer, A.L., Young, B.A., Chimwano, A.M., 1978. Ration digestion and retention times of digesta in domestic cattle (*Bos tarus*), American Bison (*Bison bison*), and Tibetan yak (*Bos grunniens*). Canadian Journal of Zoology 56, 2355–2358.

Schaller, G., 1998. Wildlife of the Tibetan Steppe. University of Chicago Press, Chicago.

Schaller, G., Wulin, L., 1995. Distribution, status, and conservation of wild yak (*Bos grunniens*). Biological Conservation 76, 1–8.

Serpell, J. 1989. Pet-keeping and animal domestication: A reappraisal. In: Clutton-Brock, J., (Ed.), The Walking Larder: Patterns of Domestication, Pastoralism, and Predation. Unwin Hyman, London, pp. 10–19.

Shen, J., Liu, X., Wang, S., Matsumoto, R., 2005. Palaeoclimatic changes in the Qinghai Lake area during the last 18,000 years. Quaternary International 136, 131–140.

Sherratt, A., 1981. Plough and pastoralism: Aspects of the secondary products revolution. In: Hodder, I., Isaac, G., Hammond, N. (Eds.), Pattern of the Past: Studies in Honor of David Clarke. Cambridge University Press, Cambridge, pp. 261–305.

Simoons, F.J., 1968. A Ceremonial Ox of India: The Mithan in Nature, Culture, and History. University of Wisconsin Press, Madison.

Stevens, S.F., 1993. Claiming the High Ground: Sherpas, Subsistence, and Environmental Change in the Highest Himalaya. University of California Press, Berkeley.

Tu, Z.-C., Qiu, H., Zhang, Y.-P., 2002. Polymorphism in mitochondrial DNA (mtDNA) of yak (*Bos grunniens*). Biochemical Genetics 40, 187–193.

Verkaar, E.L.C., Nijman, I.J., Beeke, M., Hanekamp, E., Lenstra, J.A., 2004. Maternal and paternal lineages in cross-breeding bovine species: Has wisent a hybrid origin? Molecular Biology and Evolution 21, 1165–1170.

Waddell, L.A., 1906. Lhasa and its Mysteries, with a Record of the Expedition of 1903–1904. Books for Libraries Press, Freeport, NY [1972 Edition].

Walther, R.R., Mungall, E.C., Grau, G., 1983. Gazelles and their relatives: A study of territorial behaviour. Noyes Press, Park Ridge, New Jersey.

Wellby, M.S. 1898. Through Unknown Tibet. Fisher Unwin, London.

Wiener, G., Han, J., Long, R. 2003. The Yak (second edition). Regional Office for Asia and the Pacific, Food and Agriculture Organization of the United Nations, Bangkok, Thailand.

Wilkinson, P.F., 1972. Oomingmak: A model for man-animal relationships in prehistory. Current Anthropology 13, 23–44.

Wilson, D.E., Reeder, D.M. (Eds.), 1993. Mammal Species of the World (second edition). Smithsonian Institution Press, Washington.

Winterhalder, B., Larsen, R., Thomas, R.B., 1974. Dung as an essential resource in a highland peruvian community. Human Ecology 2, 89–104.

Wright, M., 1992. Le Bois De Vache II: This chip's for you too. In: Foster, J., Harrison, D. (Eds.), Alberta: Studies in the Arts and Sciences 3. The University of Alberta Press, pp. 225–244.

Wu, N., 1998. Indigenous knowledge of yak breeding and cross-breeding among nomads in western Sichuan, China. Indigenous Knowledge and Development Monitor 6-1. http://www.nuffic.nl/ciran/ikdm/6-1/ning.html.

Wu, N. 2003. Social, cultural, and economic context of yak production. In: Wiener, G., Han, J., Long, R. (Eds.), The Yak (second edition). Regional Office for Asia and the Pacific, Food and Agriculture Organization of the United Nations, Bangkok, Thailand, pp. 347–358.

Wu, K., Wu, C., 2004. Documentation and mining of yak culture to promote a sustainable yak husbandry. In: Zhong, J., Zi, X., Han, J., Chen, Z. (Eds.), Fourth International Congress on Yak, 2004 – Chengdu, China. International Veterinary Information Service (www.ivis.org), Ithaca, New York.

Yan, G., Wang, F.B., Shi, G.R., Li, S.F., 1999. Palynological and stable isotopic study of palaeoenvironmental changes on the northeastern Tibetan Plateau in the last 30,000 years. Palaeogeography, Palaeoclimatology, Palaeoecology 153, 147–159.

Zeng, W., Chen, Y., 1980. Yak in Ancient China. Journal of China Yak 1980(1), 71–74.

Zhang, R.C., 2000a. Ecology and biology of yak living in Qinghai-Tibetan Plateau. In: Zhao, X.X., Zhang, R.C. (Eds.), Recent Advances in Yak Reproduction. International Veterinary Information Services (www.ivis.org), Ithaca, New York.

Zhang, R.C., 2000b. Interspecies hybridization between yak, Bos taurus and Bos indicus and reproduction of the hybrids. In: Zhao, X.X., Zhang, R.C. (Eds.), Recent Advances in Yak Reproduction. International Veterinary Information Services (www.ivis.org), Ithaca, New York.

Zhong, J.C., Chen, Z.H., Deng, K.Y., 2004. The study on the classification of the Chinese Yak. In: Zhong, J.C., Zi, X., Han, J., Chen, Z.H. (Eds.), Proceedings of the Fourth International Congress on Yak: Yak Production in Central Asian Highlands. Sichuan Publishing House of Science and Technology, Chengdu, pp. 9–13.

Zhong, J.C., Zi, X., Han, J., Chen, Z.H., (Eds.), 2004. Proceedings of the Fourth International Congress on Yak: Yak Production in Central Asian Highlands. Sichuan Publishing House of Science and Technology, Chengdu, China.