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What place for livestock on a re-greening earth?

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ABSTRACT

Humanity is quickly encroaching upon the finite limits of the biosphere. As our numbers and appetites grow, food supplies become less secure, reserves of clean energy dwindle, pools of freshwater evaporate, the atmosphere's capacity to absorb our emissions diminishes and space for human and biotic habitat grows scarce. In response, some are now asking whether the biosphere can support our growing herds of domesticated livestock, notably ruminants. My aim in this review is to contemplate the place of these animals in a world in need of re-greening, in more ways than one. In addressing this objective, I advance the premise that the place of livestock is examined best from the vantage of 'land', broadly defined. Livestock have been implicated in many injurious processes: land use change, excess water use, nutrient excretion, fossil energy use, competition for food and emission of greenhouse gases. At the same time, they offer numerous benefits: producing food from human inedible sources, preserving ecosystem services, promoting perennials on croplands, recycling plant nutrients and providing social benefits. Thus livestock can be both stressors and benefactors to land and the aim of researchers should be to shift the net effect from stress to beneficence. To advance this goal, I offer seven questions, seen through the lenses of 'systems', 'place', 'time' and 'community', mostly to foster discourse. How do we better study whole systems? How do we better tune the systems to local land? How can we know long term consequences? How do we measure progress? How do we choose among trade-offs? How do we engage society? What will (or should) our successors' livestock systems look like? Humans and their livestock are intertwined to such an extent that their symbiosis will not likely soon be severed. Livestock offer many benefits to human society and often their place in ecosystems can be ecologically justified. But that does not mean that all ways of raising them are beneficial, nor that they necessarily fit everywhere. In coming decades, researchers, in concert with practitioners, consumers and policymakers, will need to show creativity, foresight and courage to envision new ways of melding animals into our ecosystems, not only to minimize harm, but to advance their re-greening.

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Abbreviation: GHG, greenhouse gas; CO_2-eqv, CO_2 equivalents; N, nitrogen.

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1. Introduction

For millennia, humans have lived symbiotically with their animals, offering them feed and refuge, in exchange for food, clothing, power and companionship (Schusky, 1989; Rollin, 2008). The bonds of this 'ancient contract' (Budiansky, 1989; Grandin, 1995) have long tied us to our domesticated animals, notably ruminant livestock – cattle, sheep, and buffalo.

But now, as our own numbers are climbing ever higher, and our appetite for animal products spirals upward, the ancient contract is under scrutiny (McAlpine et al., 2009; Broome, 2008; Gerber et al., 2010; Wirsenius et al., 2010). Faced with limits of land, water and energy, and the spectre of global change, some say our planet can no longer contain us and our growing herds without injury. "The livestock sector emerges as one of the top two or three most significant contributors to the most serious environmental problems" declared one prominent report (Steinfeld et al., 2006). "The more than 20 billion farm animals are an even greater burden for the Earth's biosphere than the 6 to 7 billion humans," claims Hahlbrock (2009). This has led some to ask whether we might be better off depending less on livestock and its products (*e.g.*, Jowit, 2008; Black, 2008; Garnett, 2010; Gura, 2010; Lal, 2010; Pelletier and Tyedmers, 2010).

My aim in this review is to ponder what place livestock might occupy in a coming world beset by mounting environmental stresses. Scientists are calling for a manifold re-greening of agricultural systems (Conway, 1997; Rockström and Karlberg, 2010). Where do livestock fit in such a venture? My underlying intent is more modest than this broad objective might imply – merely to invite further conversation on this urgent question, leading eventually to new research, re-tuned and re-directed, to face the coming stresses.

In these ruminations, I advance the following premise: that the place of livestock is examined best from the vantage of 'land'. This perspective, I propose, is critical for two reasons. Firstly, many of livestock's perceived environmental threats arise from their disconnectedness with land (Naylor et al., 2005). And secondly and perhaps more importantly, livestock's highest ecological merit, and its strongest rationale, may be their role in stewarding land. Whether or not livestock can be justified, and the choice of how to manage them wisely, distils to this question: Do livestock hinder or advance our aims to sustain the land in perpetuity?

By 'land', I mean more than surface soil – 'land' includes all living things, and their interactions with each other and their physical environment; in short, the ecosystem (Tansley, 1935). By this definition, 'land' also includes humans; indeed they are often the keystone species (O'Neill and Kahn, 2000), so that we are now, belatedly perhaps, studying ecosystems as social-ecological systems (Chapin et al., 2010).

2. Coming stresses

To reflect on the place of livestock in a future world, we need first to ask how that world will be. We see the future only dimly, but it seems safe to predict that intensified stresses are coming, driven largely by the still growing number of people, with expanding appetites, crowding ever more tightly into a finite biosphere (Wilson, 2002). Clever technologies, with supplemental fossil energy, have forestalled the dire forecast of Malthus (1798), but they do not free us from limits (Lamm, 2006), nor negate the risk of unhappy collision between growing demands and finite capacity (Orr, 2002). Among the worries are growing demands for food, water, energy, waste disposal sites and habitat, all potentially limited, and all bearing directly on the question of livestock's place in the future's biosphere.

2.1. Food

The world's farmers, equipped with more and better genotypes, fertilizer, and other innovations, have achieved astonishing gains in productivity in recent decades. In the past half-century, global yield of cereals has more than doubled, and production of meat has more than tripled (FAOSTAT, 2010). But yield of food may need to increase by 50% or more in the next half-century (MEA, 2005a; Royal Society, 2009; Godfray et al., 2010). To keep pace, rates of increase in cereals, the most important food source, may need to at least equal the impressive rates achieved in decades past (Tester and Langridge, 2010). The biggest challenge may be not merely increasing productivity, but achieving these higher yields while treading more gently on the land (Cribb, 2010; Baulcombe, 2010). Growing food may be constrained most, not by innate inability to increase yield, but by strict limits to the degree of damage our ecosystems will bear without impairing future productivity.

2.2. Water

A second challenge is the looming shortage of fresh water (Jury and Vaux, 2007; Morison et al., 2008; Rockström et al., 2009a; Vörösmarty et al., 2010). Water, says Solomon (2010), "is overtaking oil as the world's scarcest critical natural resource", a scarcity that impinges especially on agriculture which is by far the world's largest user of freshwater (Jury and Vaux, 2007; Morison et al., 2008; Passioura and Angus, 2010), and whose productivity depends so heavily on irrigation (Rosegrant et al., 2009). As demands from other sectors grow, available water may increasingly constrain agricultural output (Hightower and Pierce, 2008; Rockström and Karlberg, 2010; Carpenter and Biggs, 2010), making its wise use ever more critical.

2.3. Energy

A third approaching limit is the dwindling reserve of readily accessible energy. For decades, human prosperity has been spurred by fossil fuels, a one-time 'subsidy from the deep past' (Steffen et al., 2007) that allowed unprecedented economic growth (Orr, 2007). Vast reserves of fossil C still remain, but they are often accessible only with higher environmental cost and expenditure of energy (Hall et al., 2003; Homer-Dixon, 2007; Archer et al., 2009). Alternative energy sources – solar, wind, biofuel, hydroelectricity, nuclear, others – may either be insufficient to replace fossil fuels in the near term, or have their own attendant risks. With global energy use projected to increase further (IAC, 2007), suitable energy may become ever more scarce, also for agriculture which now relies heavily upon it (Heinberg, 2007; Schade and Pimentel, 2010).

2.4. Biogeochemical interferences

Related to the demand for energy is a fourth worry: the disruption of Earth's biogeochemical cycles. We have become a planetary force (Vernadsky, 1945); with our growing numbers and technological might, humans now increasingly re-arrange cycles of elements, notably that of C. Annual emissions of CO_2 from fossil fuel combustion and cement now exceed 8 Pg C (Canadell et al., 2007). About half of these emissions are absorbed by sinks on ocean and land, but still, atmospheric CO_2 increases by almost 2 ppmv/year, pushing concentrations now toward 400 ppmv, far above the pre-industrial level of 280 ppmv, with no immediate plateau in sight (Le Quéré et al., 2009; Raupach and Canadell, 2010). This rapid accrual threatens to disrupt not only climate, but also ocean chemistry (Kerr, 2010; Shi et al., 2010).

Beyond emitting CO_2, humans also release other greenhouse gases (GHG), especially CH_4 and N_2O (IPCC, 2007a). The latter arises, in part, from the massive infusion of industrially generated reactive N, mostly to fertilize our crops, the excess of which seeps into water and air (Galloway et al., 2008).

These biogeochemical disruptions, like the other listed stresses, are symptoms of our stretching Earth's limits: we are exceeding the planet's capacity to absorb our wastes – GHG and others – without jeopardizing processes critical to the biosphere's welfare, and thus our own (Kitzes et al., 2008; Rockström et al., 2009b,c).

2.5. Habitat

A last constraint is the shrinking space to support our growing numbers and aspirations. We occupy ever more land to grow food, fiber and fuel, and to support our expanding cities, highways, cultural and commercial enterprises. Further, we seek places uncluttered to play and roam, places still uninhabited to remind us of nature's magnificence (Mill, 1848; Haber, 2007). But in using the land as our larder, habitat and playground, we are squeezing out other biota. Losses of biodiversity have already occurred, and more species are threatened, partly by expanding, intensifying agriculture (MEA, 2005b; UNEP, 2009; Butchart et al., 2010). These losses are lamentable in themselves; but they may also carry a graver hidden cost: the diverse assembly of biota, connected through flows of energy and nutrients, keep our biosphere tuned for us, in ways not fully understood (Lovelock, 2006), and we cannot be sure how a biologically impoverished planet might function.

Our biosphere, and each of the ecosystems within it, has limits. We can extract from it only so much, and spew into it only so much before we exceed those limits, with consequences irrevocable and uncertain. All of these limits – impending shortages of food, water, energy, waste repositories, space – have a common thread; all are tied, in one way or another, to our use of 'land'. If we are to meet our own needs without impinging on others, including our descendents, then we will need to find ways of more wisely and gently using the land. And we cannot think about use of our lands without examining the place of livestock thereon.

3. Livestock's place on land

Domesticated livestock, especially ruminants, are now dominant creatures in the biosphere. Their global biomass exceeds our own, and dwarfs that of all mammalian wildlife (Smil, 2002a,b; Oenema and Tamminga, 2005). Their presence, already imposing, may increase further, as demands for livestock products grow. By mid-century, demand for milk and meat may as much as double, relative to 2000, driven by growing population and higher consumption spurred by affluence (McMichael et al., 2007; Garnett, 2009, 2010). Much of the new demand will be met by intensively raised livestock (Naylor et al., 2005; Gerber et al., 2010), and will occur in developing countries, in lands already vulnerable (Bruinsma, 2003; Steinfeld et al., 2006; Lal, 2007).

Livestock are now a dominant and growing user of land (Asner et al., 2004; Steinfeld et al., 2006; FAO, 2009), and so the continued functioning of global ecosystems cannot be understood without considering the place of livestock within them, forcing us to think deliberately about how, or even if, we can manage these larger herds without undue pressures on the biosphere. To do that, we need to consider how livestock influences land – the stresses they impose, but also their benefits.

3.1. Stresses of livestock on land

Recent reviews contend that current and future livestock herds may threaten the integrity of world ecosystems (Steinfeld et al., 2006; McMichael et al. 2007), leading some to suggest that consumption of livestock products be curtailed (Stehfest et al., 2009; Godfray et al., 2010; Popp et al., 2010; Stokstad, 2010; Lal, 2010). Stresses in which livestock are implicated include land use change, excretion of polluting nutrients, overuse of freshwater, inefficient use of energy, diverting food for use as feed and emission of GHG.

3.1.1. Land use change

Of all human land uses, raising livestock now occupies the largest share (Steinfeld et al., 2006; Steinfeld and Wassenaar, 2007). About 31.5 million km^2 of land, ~20–30% of the global total, is now used for grazing, and as much as a third of cultivated land area (total area ~15 million km^2) is used for feed and forage (Asner et al., 2004; Goldewijk and Ramankutty, 2004; Monfreda et al., 2008; Ramankutty et al., 2008). Often this presence is benign or beneficent – but not always, especially where it represents an incursion into other biomes. Particularly worrisome is loss of tropical forests in the Amazon, where a large share of the deforested area is used for grazing, and livestock are implicated as primary drivers of deforestation (Steinfeld and Wassenaar, 2007; Herrero et al., 2009; Nepstad et al., 2009; UNEP, 2009; Barona et al., 2010). Such land use change can cause long lasting detrimental effects including loss of habitat, biodiversity and C stocks.

3.1.2. Water use

Livestock systems use water in copious amounts, mostly to irrigate crops used as feed in intensive feeding operations (Naylor et al., 2005; Jury and Vaux, 2007; Herrero et al., 2009; Rosegrant et al., 2009). Though estimates vary widely, typical values are ~16,000 L of water/kg beef (SIWI, 2005; Hoekstra and Chapagain, 2008; UNEP, 2009; Carpenter and Biggs, 2010; Hoekstra, 2010). According to Falkenmark and Rockström (2004; cited by Jury and Vaux, 2007), consuming meat requires about eight times the water per kJ as a vegetarian diet. Although such estimates are tenuous and variable, livestock do consume substantial amounts of a scarce resource (Falkenmark et al., 2009), and projected increases in numbers may further tax the dwindling pools of available water. Livestock, further, may affect not only the amount of water used, but also the quality of water through release of contaminating nutrients (FAO, 2009; de Vries and de Boer, 2010).

3.1.3. Nutrient excretion

Already in 1970, Delwiche saw that of all recent human “interventions in the cycles of nature the industrial fixation of nitrogen far exceeds all the others in magnitude.” Since then, creation of reactive N has more than doubled, and anthropogenic inputs, mostly to nourish crops, now exceed natural inputs in terrestrial landscapes (Gruber and Galloway, 2008; Rockström et al. 2009c). Only a fraction of this added N ends up in food; much of it leaks into water and air, cascading through the ecosystems, inflicting successive injuries as the N passes among its various forms – ammonia, nitrate, N_2O, NO_x – before eventually returning to inert N_2 (Erisman et al., 2007; Galloway et al., 2008; Schlesinger, 2009).

Livestock are a primary source of reactive N loss to air and water (Erisman and Sutton, 2008). Most N ingested is promptly excreted. Globally, excreted N amounts to about 100 Tg N/year, broadly comparable to all fertilizer N applied (Oenema and Tamminga, 2005; Bouwman et al., 2009). Excreted N is especially vulnerable to loss; for example, as much as half or more of N ingested by feedlot beef can be lost to the atmosphere as NH_3 (McGinn et al., 2007; van Haarlem et al., 2008; Todd et al., 2008). Managing reactive N more efficiently is a foremost environmental challenge in coming decades (Rockström et al., 2009c). Livestock systems, because of their prominence in the N cycle, may need to be modified accordingly.

Livestock also excrete large amounts of P (Bouwman et al., 2009). Unlike those of N, P reserves are finite (Gilbert, 2009; Van Vuren et al., 2010); hence, losses not only cause environmental damage but also waste a depleting resource.

3.1.4. Energy use

Modern farming systems, like many industrial activities, depend heavily on supplemental energy. Indeed, modern agriculture has been defined as “the use of land to convert petroleum into food” (Bartlett, 1978). Use of animal products, by some estimates, increases dependence on extraneous energy. For example, by one estimate (cited by Hillel and Rosenzweig, 2008), about 35 kJ of fossil energy are required to produce 1 kJ of feedlot fed beef. While such estimates vary with assumptions and setting, fossil energy used in producing food is likely to receive increasing attention (Carlsson-Kanyama et al., 2003; Anon., 2010a), and livestock products merit scrutiny in such analyses.

3.1.5. Competition for human food

Much of the increase in livestock production is occurring in intensive (*i.e.,* ‘landless’) systems (MEA, 2005b; Gerber et al., 2010), using feed produced on arable lands that could be growing food crops. About 30 to 40% of cereals now grown globally are used as feed for livestock (Goudriaan et al., 2001; Myers and Kent, 2003; Ciais et al., 2007; Garnett, 2009; Godfray et al., 2010), and this fraction may increase to as much as 50% if projected consumption trends occur (UNEP, 2009). Much of the food energy in plant biomass is lost when it passes through animals, so that the number of people fed/ha of cropland declines when grain is diverted through livestock (Garnett, 2009; Godfray et al., 2010). “By 2050, on current trends, the world’s livestock will consume the equivalent of 4 billion people”, suggests (Tudge, 2008). According to UNEP (2009), constraining worldwide meat consumption in 2050 to levels in 2000 would free enough grain to feed 1.2 billion people. Such analyses may oversimplify – grain saved by eating less meat does not necessarily all become available to hungry people (Stokstad, 2010). Still, in the coming world, where we will need to feed billions more people on finite lands, any competition between feed and food cannot be easily discounted (Keyzer et al., 2005).

3.1.6. Greenhouse gas emissions

Perhaps the worry expressed most vociferously is the perceived threat of livestock to future climates through emission of GHG. Estimates of such emissions vary, depending in part on fluxes considered. Direct emissions, mostly as CH_4 from enteric fermentation and N_2O from excreted N, account for about 9% of global anthropogenic emissions, in CO_2-eqv (Gill et al., 2010). But when other emissions – notably CO_2 fluxes from land use change – are also ascribed to livestock, they account for about 18%, exceeding those from transportation (Steinfeld et al., 2006; McMichael et al., 2007; Gill et al., 2010).

Researchers have long sought to mitigate emissions from livestock, especially those of CH_4, which also represent losses of feed energy (Monteny et al., 2001; Lassey, 2007; Martin et al., 2010; Wall et al., 2010), but achieving quantum gains may be difficult because CH_4 emission seems securely entrenched in the ruminant digestive advantage (Gill et al., 2010). If projected increases in livestock numbers occur, emissions from livestock could easily increase further in coming decades (IPCC, 2007b).

Greenhouse gas emissions/kg product typically are higher for livestock products than for grain. In the UK, for example, emissions from beef amount to 16 kg CO_2-eqv/kg compared to 0.8 kg CO_2-eqv/kg of wheat (Garnett, 2009). Consequently, consuming less livestock product, at least in developed countries, is sometimes seen as a way of easing threats of climate change (McMichael et al., 2007; Bellarby et al., 2008; Stehfest et al., 2009; Garnett 2009; Popp et al., 2010).

3.2. Benefits of livestock for land

A litany of environmental ills has been ascribed to livestock. All of these are pertinent and merit attention, but livestock also have undeniable ecological benefits, sometimes overlooked: they create human food from inedible sources, conserve grassland ecosystems, promote use of land-preserving forages, help recycle nutrients and provide a host of social benefits.

3.2.1. Food from human-inedible phytomass

Although livestock can compete with us for food, they also furnish sustenance from sources we cannot use directly – notably from the vast grasslands that cannot, or at least *should* not, be cultivated (Garnett, 2009). Grasslands (or 'rangelands') cover about one third of global ice-free land (Ellis and Ramankutty, 2008; Wang and Fang, 2009), roughly twice the area of arable cropland. Their vegetative output is not directly edible for humans, but can be assimilated by ruminants, which convert it into high-quality human food (McMichael and Butler, 2005; Haber, 2007; Godfray et al., 2010). This advantage applies also to crop residues and other by-products of farms and industry (von Kaufmann and Fitzhugh, 2004; Garnett, 2009). Thus, by virtue of their physiology, livestock do not always compete directly with humans for food and, in fact, bolster human food supply by exploiting inedible biomass to produce protein-rich food "The food-chain argument. . ." says Smil (2000), "would be universally valid if our species had developed multiple stomachs or if our guts carried bacterial communities capable of digesting phytomass containing high shares of hemicellulose and cellulose."

3.2.2. Preserving ecosystem services

Managed poorly, livestock can deplete an ecosystem, but managed wisely they often maintain or enhance vital ecosystem services furnished by the land. For example, they can help sustain biodiversity (Steinfeld and Gerber, 2010). Increasingly, ecologists see that, to flourish, complex ecosystems such as grasslands need gentle continual disturbances. From this perspective, judicious grazing becomes an agent of restorative disturbance, an instrument of conservation and renewal (Hampicke and Plachter, 2010), sustaining not only the plant communities on these lands, but also the myriad other species, from microbes to mammals, that thrive therein (Collins and Barber, 1985; Milchunas et al., 1988; Willms et al., 2002; Dormaar and Willms, 1990; Spasojevic et al., 2010). A recent 'horizon scan of global conservation issues' pondered benefits of eventually producing meat synthetically, but worried justifiably about "an adverse influence on those vegetation types dependent on livestock grazing" (Sutherland et al., 2010).

Grazing lands also hold large reserves of soil C, which, if released to the atmosphere, would accentuate CO_2 emissions (Janzen, 2004). Indeed, improved grazing systems can sometimes enhance the amount of C stored, thereby extracting CO_2 from the atmosphere (Derner et al., 2006; Allard et al., 2007; Soussana et al., 2010). In some cases, such gains can offset other GHG emissions, at least for a time (Liebig et al., 2010).

Grazing and browsing animals have always been integral to many ecosystems. Domesticated animals, while not perfect analogues for the 'wild' species they displace, can still help sustain these ecosystems – if managed with the health of the land in mind.

3.2.3. Promoting perennials on arable lands

Perennial forage crops on arable cropland, grown either alone or in rotation with annual crops, can sustain or improve the land (Jordan et al., 2007). Because of their robust root systems, perennial grasses and legumes prevent erosion, reduce leaching of nutrients and replenish soil organic matter (Janzen et al., 1998; Glover et al., 2010). Indeed, planting perennial forages is often among the best practices for sequestering soil C to mitigate climate change (Gregorich et al., 2005). Furthermore, legume forages such as alfalfa can fix N thereby reducing economic and environmental costs of fertilizers (Wilkins, 2008).

The advantages of perennials have motivated a search for perennial grain crops (Glover et al., 2010), but agronomically viable cultivars are likely still decades away (Jackson, 2008). In the meantime, says Jackson (2008), we should look for other ways of 'perennializing the landscape', and the "most immediately practicable way of doing this is to go back to crop rotations that include hay, pasture and grazing animal" (Jackson and Berry, 2009).

The importance of livestock in preserving lands, partly through planting of restorative perennials, has long been lauded (Hanson, 1939; Mickey, 1945). For example, when soils of the Canadian prairies suffered extensive losses soon after initial breaking from sod, a recommended solution was to keep more livestock (Bracken, 1920; Anon., 1921). These advantages of mixed systems with perennial crops remain (Doran et al., 2007; Russelle et al., 2007). And if we are to grow perennial forages then we must have livestock to warrant planting them.

3.2.4. Recycling of nutrients and organic residues

Livestock in mixed systems have another benefit – they provide a conduit for efficient recycling of nutrients. Most of the N and other nutrients in diets are excreted by animals, a potential drawback if they pollute water and air. But a tight synchrony between crops and livestock can furnish a high quality output (milk or meat), while recycling the nutrients back to the land thereby reducing external inputs for the next crop. Indeed, raising of livestock was widely recommended historically to maintain soil fertility (Shaw, 1911). Shutt (1913), for example, wrote: "How, then, are soils to be maintained in a productive state and at the same time yield a profit for their working? First in the keeping of livestock; in the manure so obtained we have the opportunity of restoring to the soil eight-tenths of the plant food taken from it in crops they consume . . .. We do not keep sufficient livestock on our farms." In parts of the world where fertilizers are expensive or unavailable, recycling of nutrients via livestock remains a vital practice, particularly with use of N_2-fixing forage legumes (Wilkins, 2008). In future decades, when energy costs may limit use of synthetic fertilizers, livestock tightly coupled with crops may again offer a way of using and re-using nutrients efficiently.

Aside from recycling nutrients in feed, livestock also provide a way of returning to the land organic matter and nutrients in byproducts, such as crop residues, distillers' grain or food processing wastes (Garnett, 2009; Bremer et al., 2010). In this way, livestock extract value from such wastes before they are returned to the soil. By shunting most nutrients back to the land, livestock – wisely managed – create efficient loops where the same nutrients can be used over and over, furnishing valuable output in each cycle.

3.2.5. Social benefits

If 'land' includes all its inhabitants, then we need to consider also the many and diverse benefits that livestock provide to people. Foremost among these benefits may be nutritional advantages. When assessed strictly on a per kg or per kJ basis, livestock derived foods may fall short of plant derived food. But meat, milk and other animal products provide nutritional value beyond mere energy; they are high in protein, accounting for about a third of the protein consumed by humans globally (Steinfeld et al., 2006; Popp et al., 2010), and contain a complement of nutrients not always easily obtained by eating only plants, especially in developing countries (Barrett, 2001; von Kaufmann and Fitzhugh, 2004; Müller and Krawinkel, 2005; Godfray et al., 2010). Thus animal derived foods may carry a premium, negating simple comparisons with plant derived foods.

Beyond nutrition, livestock offer further societal benefits, highly diverse, and not easily quantified. They provide cultural richness, partly by the foods they produce, and generate livelihoods (Buller and Morris, 2007), accounting for 40% of agricultural GDP (Steinfeld et al., 2006). Domestic animals may be especially important in poorer countries, where they act as a 'savings bank' (Oenema and Tamminga, 2005), provide draft for farming and transportation, produce fuel, and yield non-food goods, such as leather and wool (Garnett, 2009, 2010; Tudge, 2010).

Even more difficult to quantify is the aesthetic value livestock contribute to landscapes. Aside from their own intrinsic appeal, animals enhance the aesthetic value of meadows and pastures that enthral residents and visitors to pastoral lands world wide. Goulding et al. (2008), for example, note that in rural areas of the UK, "the income from tourism . . . is perhaps 10 times that from farming" presumably, in part, from the livestock enhanced appeal of the countryside. One last benefit of livestock, perhaps least understood and quantified, is the subtle but powerful attachment of people to the animals themselves – the almost mystical bond of the "ancient contract". Rollin (2008), for example, reflected on how "ranch people often sit up all night for days with a marginal calf, warming the animal by the stove in the kitchen, and implicitly valuing their sleep at pennies per hour!". Cummins (2003), pondering the rewards of looking after livestock, wrote: "But when I start thinking about how our animals and crops and fields and woods and gardens sort of all fit together, then I get that good feeling inside. . .". Such examples, which presumably occur in countless ways worldwide, imply that humans and societies derive benefits from animals beyond mere monetary value.

Livestock are more than merely a means of producing milk, meat and money; more than resources furnishing products for consumption. They are now integral to our ecosystems, part of the biotic community in which we live, and many of their benefits to society might best be seen in that light.

3.3. Net stresses and benefits

Based on the preceding brief overview, are livestock stressors or benefactors, an asset or a liability in the re-greening of land? The answer, clearly, is that they are both. Even within individual facets they are both: they compete with us for food, but also give us food from sources not otherwise edible; they excrete polluting nutrients, but also help recycle them efficiently; they suppress biodiversity, but also help sustain it; they are emitters of GHG, but also help withhold soil C from the atmosphere.

Livestock can both hinder or advance the renewal of land. The aim of researchers then should be to find ways of shifting the overall effect to the right along the continuum from stress to beneficence. In this way, scientists can help restore livestock management as an instrument for a re-greening Earth, and re-affirm livestock managers as stewards of the land.

To advance that aim, what questions should researchers be asking? The following is a partial series of questions, offered to solicit the further essential conversation that might help advance the place of livestock on a re-greening Earth.

4. Questions for pondering the place of livestock on a re-greening earth

The question of livestock's place in a future world, as seen in preceding sections, has no simple ready answer. Producing livestock poses justifiable worries, but it also holds legitimate promise. Whether or not livestock belong, and the way they should best be managed, then, depends on the setting, on the land in question. In short, the question is ecological, not merely technical.

Much of the swirling debate on this question has focused introspectively on livestock; researchers have seen purported stresses and have sought to assuage them with new practices: a better diet, say, or a new way of handling manure. But if the problem is ecological, not technical, then it may help to re-cast the question from a wider vantage – from that of the land broadly defined. By starting with the land, and seeking first to understand its functions and services, we can then ask, how best do animals fit here (Tudge, 2008), or do they even fit at all? Thus we might tune the livestock to the land, not the land to the livestock. (Some modern livestock systems are sometimes referred to as 'landless' (Pitesky et al., 2009), but of course all livestock depend on land.)

Envisioning the place of livestock from the vantage of land, forces us to look through multiple lenses, including:

a. the 'systems' lens: seeing the whole, not merely the pieces. An ecosystem ('land') is an interwoven assemblage of biota in their habitat, so that no single constituent can be studied alone.
b. The 'place' lens: seeing the system within its local setting. Before you can know how best to manage livestock you need to first look to see where you are.
c. The 'time' lens: looking at a practice across long decades, not just the immediate future. Whether a system is harmful to, or beneficial for, land can be seen only over long time, because land responds only slowly and subtly to new disturbances.
d. The 'community' lens: seeing humans and their actions as integral to the ecosystems. Since 'land', broadly defined, includes humans – indeed, they are often its keystone species – we can no longer contemplate wise use of land without considering ourselves.

Looking through these four lenses a number of questions come into view, questions that may help direct our future research. A few of these follow, offered merely as examples to be considered, corrected and augmented.

4.1. Question 1: How do we better study whole systems?

Much of our research to date has focused on specific questions: What ration best reduces CH_4 emissions from beef cattle? How can manure be managed to reduce N_2O emissions? What grazing regime best preserves biodiversity? Such narrow studies yield impressive gains in knowledge and must continue. But ecosystems contain innumerable connections, and so tweaking them in one place invokes cascading consequences, not purely positive. A new diet that decreases CH_4 emissions might increase N_2O emissions from growing that feed in fields far away, or a practice that suppresses N_2O release might favor emission of NH_3. Only by looking at the whole can we decide whether a practice is, in the end, favorable or not (Janzen et al., 2006).

What is needed most urgently, therefore, is synthesis (Lundberg, 2006), a way to see the whole system – all its constituents and the flows of energy and nutrients between them. Re-greening of ecosystems will most likely come by studying – not the pieces such as cows, crops, soil, air, water – but their interactions. Inevitably, that means a concerted effort to think across scales, from microbes to landscapes, and across traditional boundaries of scientific inquiry (Brittain, 1928; Hanson, 1939). The soil scientist may have the most to learn from the rumen microbiologist, and the best collaborator for an animal nutritionist may be a micrometeorologist.

One way of enforcing such synthesis is through building of models – whether inscribed in simple illustrative diagram or complex mathematical code. Constructing a model forces researchers to look beyond their individual expertise, enfolding insights from across disciplines and across scales of space and time. And building models has a further advantage – it exposes our ignorance, pointing to those parts of the system where understanding is dimmest, and where new inquiry is most justified. Identifying what we do not know may be as important as describing what we do know (Carpenter, 2002). The highest benefit of models may be – not their predictive outputs – but in enforcing a discipline of synthesis and in revealing to us our ignorance.

Developing such systems will require creativity, sober reflection and patient ingenuity. But such contemplations are no less scientific, and no less urgent than, for example, sophisticated experiments seeking diets that suppress CH_4 emissions in dairy cows, or novel measurements of N_2O release from manure.

4.2. Question 2: How do we better tune the systems to the local land?

No single system is applicable and advisable everywhere (Carpenter et al., 2009). As Berry (2003) phrases it: "We are not asking what is the best way to farm everywhere in the world, . . . We are asking what is the best way to farm in each one of the world's numberless places. . ."

Global perspectives tempt us to seek and advocate ubiquitous 'best management practices' (BMP), but each hectare of land is unique, the sum of myriad interacting factors. Consequently, a practice favorable in one place may be detrimental elsewhere; livestock may be vital, indispensable constituents of a system in one place, but they may be redundant or harmful in another. What is needed is 'place-based research' (Carpenter et al., 2009), which recognizes the distinctness of each local ecosystem and seeks the most appropriate system for conditions there. It looks first at the land, and then tunes the livestock system to best fit the place.

Such study of place may be most urgent in developing nations. Ecosystems there are among the most vulnerable to impending global changes (UNDP, 2007) – it is where population growth will be most intense, where much of the growth in livestock numbers will happen and where lands are most fragile (Lal, 2007; Herrero et al., 2010; Thornton and Gerber, 2010). Many of the world's poor and undernourished live in rural landscapes of the developing world (Lindskog, 2005) and many depend on their livestock for many reasons (Herrero et al., 2009). To date, distribution of research intensity has not always reflected the urgency of place-based research (Kiers et al., 2008).

4.3. Question 3: How can we know the long-term consequences?

In any search for more enduring and resilient systems, the critical variable is time. Ecosystems often respond to changing conditions or management practices at rates which are initially imperceptible. Moreover, the temporal pattern of responses may vary; for example, the effects of a new grazing system on enteric CH_4 emission can be measured immediately, but those on soil C storage may be measurable only after years or decades. Further, effects on soil C accrual are of finite duration – the soil eventually approaches a new steady-state – but those on CH_4 emissions may persist indefinitely (IPCC, 2007b). Thus the final full effect of a management change or external stress can only be determined by long and patient watching.

One essential tool for following the effects of time are long term ecological sites, persisting for decades or longer. Such sites, if patiently maintained, not only yield essential insights to us, but also give our successors a legacy of history, samples and data from which *they* can measure the hardiness of proposed systems over successive decades (Janzen, 2009). While many such sites already exist for farmlands, most are devoted to agronomy; perhaps more should explicitly include livestock in arable or grazing systems.

Wise use of land depends on the perspective of the 'long now' (Carpenter, 2002), the knowledge, crucial in ecology, that choices made now are tied irrevocably to the distant past, and also to the far future. To meld livestock cohesively into our use of land, we will have to find ways of looking beyond our short term funding cycles to the decades ahead, seen through the wisdom of decades past.

4.4. Question 4: How do we measure progress?

When monitoring a system over time, how do we know whether it is improving or winding down? And if we are comparing two systems, how do we decide which of the two is 'better'? Clearly, we need a widely accepted measuring stick.

An important objective in livestock research, recently, has been to reduce GHG emissions. Progress toward that aim is typically measured by calculating overall emissions, expressed in units of CO_2-eqv, to account for different global warming potentials of the individual gases (Martin et al., 2010; Pelletier et al., 2010). But measuring CO_2-eqv alone may not suffice; the primary aim of farming systems, after all, is usually not to minimize GHG emissions, but to profitably furnish outputs, notably food. Consequently, emissions are increasingly expressed/unit product: CO_2-eqv/L milk, or /tonne wheat, or /kg meat (de Vries and de Boer, 2010; Gill et al., 2010; Nguyen et al., 2010). Such analyses allow comparison of different practices delivering the same product – milk, beef or grain, for example – but they do not allow easy comparison among systems – livestock based *versus* plant based, for example. For that purpose, we need a common denominator – an expression of output applicable to all production systems. One approach is to express emissions/unit protein (Stewart et al., 2009; Gill et al., 2010). Another might be to use 'food baskets', where a 'food basket' represents any combination of foods that supplies the minimum nutritional needs of a person for one year, provided by any combination of sources, animal or plant based.

Whatever the unit used to express output (protein, 'food basket', or some other unit), expressing GHG emissions as an efficiency ratio – unit output/tonne of CO_2-eqv – might re-cast GHG emissions as an investment. Now, a tonne of CO_2-eqv is viewed as a necessary cost (Garnett, 2009), and the intent is to maximize returns (*e.g.,* food) from the investment. This approach might be extended to include outputs beyond food such as bioenergy, biodiversity conservation and enhanced soil fertility as examples. And it could also include other investments (costs) besides GHG emissions, such as water use or reactive N inputs. Such examples are incomplete, but they illustrate the need for a consistent measuring stick to gauge progress toward systems – with or without live stock – that best preserve land and sustain the multiple services we and our successors derive from it (de Vries and de Boer, 2010; Nguyen et al., 2010).

4.5. Question 5: How do we choose among trade-offs?

Managing ecosystems almost invariably involves trade-offs (MEA, 2005a; Becker, 2009; Rodriguez et al., 2006). Although we look intuitively for win–win opportunities, nature is not always so accommodating: a gain in one attribute often exacts a cost in another (DeFries et al., 2004; Janzen, 2007; Pilgrim et al., 2010). Including livestock in an ecosystem, for example, may enhance soil quality but also increase GHG emissions; it may enhance aesthetic and economic appeal, but increase water use. Given potential conflicts and trade-offs, decisions in the end depend on values assigned to various indices, some of which may defy numerical quantification. For example, what is the value of diversified plant populations from judicious grazing, or of watching sheep graze on a hillside at sunset? What is the value of a songbird's nesting ground, saved by avoided plowing, or of eating a succulent steak? Should a tonne of CO_2-eqv emitted by a luxury car driven to a golf course count the same as a tonne CO_2-eqv produced as CH_4 from a milk producing cow?

Clearly, choices of ecosystem management are not strictly scientific – they are societal choices, based on values applied by society, ideally instructed by scientific understanding. If that is so, decisions about the place of livestock in a re-greening earth best involve researchers as participants, not as arbiters. And for scientific findings to be applied most constructively and influentially, researchers will need to interact humbly and directly with other disciplines – sociology, history, philosophy, among others (Jasanoff, 2007; Anon., 2010b) – as well as with the practitioners and beneficiaries of land use: farmers, ranchers, consumers (Zimdahl, 2006). At one time scientific data may have enjoyed pre-eminence in making societal decisions; in the future its influence in choosing how best to manage the land will likely depend on how well scientists engage other disciplines and participants in two way exchanges of insights and wisdom.

4.6. Question 6: How do we engage society?

A sixth question follows directly upon the fifth: how do we more directly include societal perspective in seeking best ways to manage livestock on land? Humans are not merely managers of 'land', they are also participants therein, intimately ensconced and intertwined in its fate along with that of other biota in a common habitat.

Many of the troubles facing humanity arise from our own disconnectedness with the land (Pretty, 2007; Friedman, 2009) – the delusion that we have by our cleverness broken free from the limits of nature (Hillel, 2009). We forget that what happens on 'land' affects powerfully the fate of those who may seem removed from it and, conversely, that the choices we all make – what we eat, how we behave – eventually affects the land. Animal husbandry, even on modern farms, can be a reminder of our mutual dependence on the land. "Anyone who has been involved in the husbandry of fulfilled animals on farms. . .", says Rawles (2008) "knows how truly and powerfully farming can reconnect us with meaningful, sustainable and ethical ways [of] making our living on this, one, earth."

Such connections are not always obvious to those who may mistakenly see themselves separated from land. A starting point in bridging this gap, perhaps, is for researchers to find more lucid and persuasive ways to dispense their understanding. For example, there is now a blizzard of manuscripts describing earnestly and rigorously the processes of GHG emissions and ways of reducing their emissions from farms. Yet these findings do not always find their way in alluring form into the minds of the practitioners, public and policymakers. Our scientific manuscripts, while fulfilling an essential role, seldom make riveting reading. To better inform and influence, we might need to solicit also those most proficient in telling stories – writers, poets, artists among them – in tying together and dispensing our insights.

4.7. Question 7: What will our successors' livestock systems look like?

In times of change, like now, the most important question for researchers to ask may be: how will livestock systems in the coming decades look or, better, how *should* they look? What features should our successors' systems have, and what can we do already now to furnish understanding toward those aims? Such questions demand creative foresight, always risky in the face of uncertainty, but still essential. Research aimed merely at fine tuning and retuning existing systems may soon be obsolete, because such systems may no longer fit a world soon changed. Without farsighted vision, approaches developed might be pertinent to conditions that existed when the research was begun, but not to those when research reaches fruition.

What those bold and innovative new systems might look like is beyond my limited purview. But one facet may be a 'regenerative' approach (Pearson, 2007), wherein nutrients, energy, and organic materials are more efficiently re-circulated (Francis and Doran, 2010). Some industrial livestock systems today, while offering numerous advantages, face a fundamental ecological challenge – a disconnect between plant and animal production, the decoupling of cows and crops (Odum and Barrett, 2005; MEA, 2005b; Wilkins, 2008). "The industrial livestock sector," say Naylor et al. (2005), "has become footloose – no longer tied to a local land base." Thus, for example, feed is transported long distances to centralized feeding sites but, because of transport costs, the nutrients in manure are not returned to their origin, creating a costly deficiency in one place, and a polluting surplus in another (Rees, 1997; Oenema and Tamminga, 2005; Sims et al., 2005). What is needed is a re-linking of livestock and land; in short, a system based on loops, not lines. One partial solution, perhaps self-evident, is to restore proximity between livestock and the land it depends on (Gerber et al., 2010).

The preceding is merely one example. While simplistic, it may illustrate that if livestock systems are to enhance the re-greening of land, they may require some fundamental re-structuring (Naylor, 2010), perhaps in ways that seem economically dubious today. Freed from the strictures of short-term economics, the patient innovator can envision new systems that might flourish in a time when costs and returns will not be the same as they are now. A reluctance to envision bold new systems not viable now relegates us merely to retuning the status quo.

5. Conclusions

What place for livestock in a re-greening earth? This brief paper can offer no definitive answer, for the question is complex, especially in the face of imminent changes. But given the rootedness of the 'ancient contract', and the way the fate of people and livestock have long been intertwined on the land, livestock seem firmly entrenched in many ecosystems. "Mother earth never attempts to farm without livestock", said Howard (1940). Livestock offer many benefits to ecosystems; notably they provide a means for managing grasslands while furnishing human nourishment from them. And they provide also non-food benefits to society: aesthetic value, for example, and the rewards of human–animal connectedness. These, among others, will likely ensure the continued raising of domestic livestock for a long time to come.

But that raising livestock is justifiable ecologically does not mean that all ways of raising them are, or even that they are needed everywhere. So researchers, in concert with other disciplines, will need to look some decades ahead, and envision new ways of raising animals to amplify their benefits while minimizing attendant stresses. These new ways may demand bold and visionary inventiveness, even changes risky and initially painful. But by looking first at the local lands, and asking "How best do livestock fit here?", we may find ways of raising livestock that not only persist in a re-greening world, but deliberately advance the re-greening; thereby restoring animals and ourselves as instruments of stewardship.

Conflict of interest statement

None.

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