Land as livestock's measure

Henry Janzen

Agriculture and Agri-Food Canada
Lethbridge, Alberta, Canada
henry.janzen@agr.gc.ca

Summary of paper presented at
the Bertebos Conference 2012
Hotell Falkenberg Strandbad
Falkenberg, Sweden
September 9-11, 2012

Introduction

The theme of this conference – "How can we ensure sustainable cattle production systems for future generations?" – is both vexing and tantalizing. I am only a student of soil, and claim little expertise in animals; but what astonishes me, looking at this question, is the enormity of livestock's overwhelming presence on the planet. The biomass of livestock, dominated by cattle, has multiplied over recent decades, to the point where it now dwarfs that of all wild mammals, easily superseding even our own substantial biological bulk (Barnosky 2008; Smil 2011). Given their mass and the vast area they occupy, then, we cannot ponder the fate of the biosphere without considering our animals. On this ever more crowded planet, with its manifold stresses impending, we therefore ask: how do we now manage our animals? In pondering that question, I hope to explore the following premise: that we start with land – each local patch of the biosphere – and then ask: how do animals fit here (or do they even)? In other words, let local land be the measure.

Why land as a measure? Firstly, because land enfolds the system. The land perspective allows us – indeed *forces* us – to look at the entire ecosystem: the soil below, the air above, the water within and running through, all creatures, all biota, within above and beyond it, all interwoven, intertwined, with each other and their physical place, through the endless flows of energy and matter. Secondly, land is the interface: it is the way we influence the biosphere, and the way it influences us. Consider the impending planetary stresses – the growing demand for food may be foremost, but also worrisome are the loss of species, the waning supplies of water and energy, and potential upheavals of climate and societies. Most or all of these impinge on land; land is often the first recipient of these stresses, and also the medium where adaptive reforms will be born. Thirdly, land is the limit. In 1961, for example, there was on average about 4 ha of land for each of us on the planet (FAOSTAT 2012). Now it is about 2 ha, and shrinking, as ever more of us

scrabble about the planet. Finally, land connects; it is a continuum across space, spanning the vast continents. But also, land is a continuum across time. While people come and go, the land stays; it is the medium on which we leave our footprints, the medium of sustainability. For all these reasons, maybe we let land be the measure – tuning livestock to land. In other words, rather than *imposing* livestock on the land, we are *asking* how and where they fit.

My approach in exploring this premise will be to posit four functions of land, and for each, by way of example, to ponder how animals might help or hinder. I will then contemplate briefly how this perspective might influence what we as researchers do in the coming decades. My overriding aim will be – *not* to dispense my own meager insights – but to elicit those of the reader.

Functions of land, and how they are influenced by livestock

To begin, then, let me proffer four general functions, neither discrete nor exhaustive (Figure 1). First, land is a receptor and re-distributor of solar energy – the ultimate fuel for all life on the planet. Second, land is a renewer, a restorer, a rejuvenator. Aside from infusion of solar energy, to use Bartlett's (1978) metaphor, we need to finish the trip with the supplies on board when earth was launched – ever recycled, ever re-used. Thirdly, land is a keeper, a repository, nature's memory; it is the carrier of sustainability, preserving vitality, resilience through time. And finally, land is our own habitat, land is home; we all live on the land, wherever we may reside.

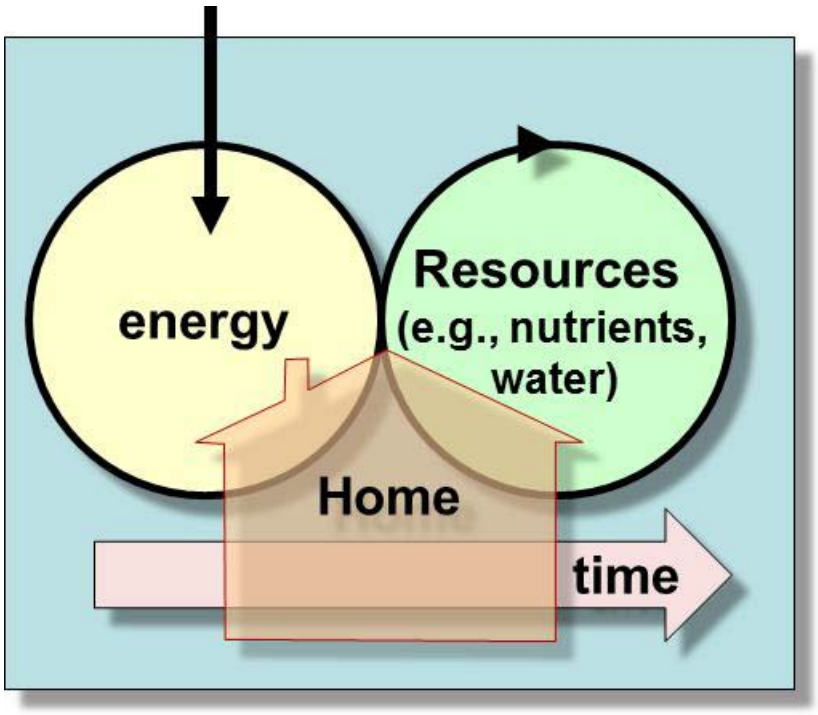

Figure 1. Four functions of land: 1. Receptor and re-distributor of solar energy; 2. Renewer, restorer of nutrients and resources; 3. Keeper and preserver of vitality (across time); and 4. Human habitat (home).

Land as receptor of solar energy

The sun fuels our existence, and that of all life. As Woodwell (1970) put it: "It is solar energy that moves the rabbit, the deer, the whale, the boy on the bicycle outside my window, my pencil as I write these words." Ludwig Boltzmann (1886), referring to photosynthesis, admitted that scientists at the time knew little about its mechanism, but, he said, "The products of this chemical kitchen constitute the object of struggle of the animal world." And we, as a species have been especially competitive; emerging as victors, at least for now. But we prospered in part by cheating; we burrowed down deep into the past and uncovered there great troves of ancient sunlight, "fossil sunlight" in oil and coal (Hardin 1993), which we are burning at ever higher rates, with emissions now exceeding 9 billion tonnes C (Boden and Blasing 2012), a spiralling trajectory that even a global economic crisis could not long forestall (Peters et al. 2012).

To illustrate this shift: consider that the Romans, in building their Coliseum, had to set aside vast areas of land to trap the solar energy to fuel the muscles of human and beast needed for construction (Homer-Dixon 2007). Now we would just dig up a little more “fossil sunlight”, borrowed from the distant past.

Our prosperity is fuelled by fossil sunlight, but it comes at a cost. Though vast stores of this fuel remain, we are having to dig deeper, go farther afield, and expend more energy to get it. And there are, of course, the ever-increasing CO_2 concentrations, now approaching 400 ppm, heading for reaches unknown, with potential consequences for climate and ocean pH. Consequently, many are saying we need to live again on current solar flows (Roston 2008; Smil 1991), not the “accumulated sunshine of paleolithic summers” (Daly and Cobb 1989). But that means that land’s role as energy receptor will once again be paramount, preeminent; it means the energy trapped in plant biomass will become even more precious, more and more in demand. We see that already in growing projections for biomass as future fuel (Richard 2010).

Current solar energy in biomass, however, is strictly limited: about 2000 EJ per year or so globally, much less in harvestable fractions (Moriarty and Honnery 2011, 2012; Haberl et al. 2012). And the laws of thermodynamics are quite unbending. You cannot remove matter or energy without disruptions somewhere (Daly 1996). If you remove an extra tonne of biomass and its energy, who loses? We might say: Well, it would only decay or respire anyway. But we forget, perhaps, that these are the processes whereby solar energy is delivered to the myriad other biota, including the mysterious microscopic biota performing functions we may not even be aware of.

The essence of farming, and of all land use, then, is managing the capture and flow of solar energy. And now we ask: how do our animals help or hinder that aim? We know that energy used as feed is much larger than that used directly as food, perhaps by a factor of 4 or 5 (Krausmann et

al. 2008), leading, then, to the familiar debate of feed *vs.* food. And there is no denying such competition, especially with grain-fed animals; but it's not always so straightforward. For one thing, much of the energy harvested by animals is not directly accessible to us: it exists in vast non-arable lands, or in forms unpalatable to us (Gill et al. 2010). Thus energy devoted to animals does not always subtract from energy for people; sometimes even it bolsters it.

But there may be another factor worth pondering. With solar energy it is not only how it is allocated, but how much is trapped in the first place – the size of the biomass yield. Global net primary productivity (NPP), it seems, is less now than it was, partly because of land degradation (Barnosky et al. 2012; Haberl 2012). How then do we reverse or restore such degradation? Soil conservationists have long had an answer – include livestock in the system. We need perennials – legumes and grasses – they say. And if you want such forages you will need animals to consume them. Thus livestock can divert solar energy; but also they can augment its capture.

A critical function of land, perhaps more so in the future even than now, is the trapping and re-directing of solar energy. It is a synthesizing, unifying question. And animal science may have much to offer here, drawing on accumulated wisdom from its long history of tracing energy flows.

Land as renewer

A second function of land is as renewer and restorer. It is land that takes our refuse, indeed the excreta of all biota, and cleanses them, restores them, refurbishes them into inputs fresh and new. And that leads to the metaphor of "ecological footprint": the area of land sufficient, without depletion or decline, endlessly to furnish the required resources and also to absorb the ensuing wastes (Rees 2003). So we ask: within a given tract of land, do livestock increase the collective footprint or do they reduce it?

To probe the question, consider, as an example, the nitrogen dilemma. The biosphere now is swimming in reactive nitrogen – nitrogen available to plants and animals (Townsend and Palm 2009). To feed ourselves, we've added more and more, now doubling global terrestrial inputs; indeed, about half of us now depend on industrially-produced reactive nitrogen for food (Davidson et al. 2012). But only a small fraction of that ends up on our tables; much of the rest leaks into air and water in various forms – some innocuous, others mischievous or even malevolent (Pelletier and Tyedmers 2010). Resolving this dilemma – the conundrum of too much and not enough – has thus become an ecological priority.

Livestock play a crucial role here, because much of the reactive nitrogen passes through our animals, so livestock often dominate the nitrogen flows (Bouwman et al. 2011). Sutton et al. (2011), for example, estimated that of N in crops harvested or imported in the EU some 85% was consumed by animals. The challenge, of course, is that animals excrete most of the nitrogen ingested (Tomich et al. 2011). This can be a problem or a promise: It is a problem if the animals are divorced from the land, so nitrogen piles up; it is a promising prospect if livestock and land are so entwined to favor endless re-use and restoration.

The same principle applies also, I think, to other nutrients and limiting elements. Livestock, it seems, can either expand the footprint or shrink it, they can be a source of pollution or a conduit of renewal, depending on how well they are tethered to local land. And so comes the question: can we re-align livestock to land, allowing it perpetually to turn wastes into inputs, favoring land's primal role of restorer and refurbisher?

Land as renewer

The third function of land is as keeper, as persistent repository of physical and biological resources. This function explicitly includes time; the notion of preserving vitality across seasons and human generations. In effect, land is the keeper of memories; it remembers the lengthening past, and one day it will remember also us – how we (and our animals) lived on the land.

We could cite here many examples of land as keeper, and how animals affect them. We could refer to stocks of carbon in soil organic matter. Although the effects of grazing on soil carbon storage remain ambiguous (de Boer et al. 2011), this much we know: grazing lands usually preserve much higher carbon stocks than do comparable cultivated lands (Franzluebbers et al. 2012), thereby withholding CO_2 from air and, more importantly, preserving a store of energy and nutrients, a reservoir of future fruitfulness.

A second example is preserving biodiversity. Our planet abounds with a dazzling array of species – some 9 million in all (Cardinale et al. 2012) – many of which remain unstudied and unknown. But as we sprawl across the landscape, we are squeezing them aside, jeopardizing the biosphere's resilience – the capacity to maintain ecosystem function in the face of coming disturbances (Holling 1973). The more diverse the system, the more it is buffered against disturbances we cannot yet foresee (Isbell et al. 2011; Chapin et al. 2011). And livestock, we know, are implicated in effects on biodiversity. First to mind are the incursions on once-forested lands by expansion of pastures, notably in the Amazon (Herrero et al. 2009). But also, it seems, animals might sometimes help preserve diversity, maybe enhance it even. For example, we know that grazing lands – well-managed – can be havens of diversity, rendering grazing an instrument of conservation (Steinfeld and Gerber 2010; Hampicke and Plachter 2010). And beyond the grazing lands, maybe the arable lands too can be re-diversified using animals. In the past, farming has

simplified such ecosystems, focusing on one or several products. Maybe we can again re-complicate these lands, thinking again of landscapes, not fields or paddocks, including the trees along the margins, the grasses on the water edges, the habitats along the fences – the many uncultivated places, where animals might roam and forage.

Biodiversity loss, some say is now "among the major drivers of ecosystem change" (Hooper et al. 2012), perhaps rivalling that of climate. And so the question comes: How can our animals help enhance diversity? Indeed, can we even envision landscapes, fully diverse, without including our animals there? As Howard (1950) mused, "mother earth never attempts to farm without live stock". The future place of livestock on land, I suspect, may rest to large degree on how well they are used to foster biodiversity – abetting the role of land as keeper and preserver.

Land as human habitat

One last function, maybe the one most daunting one and the most endearing, is land as human habitat. The landscape, says Odum (1997), "is not just a supply depot, it is also the oikos – the home – in which we live." There was a time when we were tangibly tied to land, immersed within it, eating and surviving directly from its providence. But in our flight from land, says Rachel Carson (1952), we've insulated ourselves "from the realities of earth and water and the growing seed", we've become estranged from it (Turner 1980). And yet, we need land as much as ever; we depend on it completely for physical and reflective nourishment, no less so than our technologically-primitive forebears. And so, say Folke et al. (2010, 2011) and many others: We need to look beyond ecosystems, to *social* ecological systems, to insert ourselves into land again – we need to re-connect people and land (Berkes et al. 2009).

And now the questions comes: How can livestock foster such re-connection? I don't know the answer to that question. But human communities have always involved animals (Midgley 1983), implying a deep-seated, lingering connection. What kind of creativity, courage, and ingenuity might such a question engender?

Our mistake, sometimes, has been to think of nature, of 'environment' as something 'out there', in lands pristine and pure, untarnished by human presence (Marris 2011). But maybe that's wrong: the animal watering pond is environment as much as some crystal mountain lake; the dairy pasture is environment as much as some flowered alpine meadow; the patch of weeds behind the barn is environment as much as the remotest tundra. If we are to live well in the biosphere, that will happen not only in some unsullied nature reserves – far from us – but mostly in the ground beneath our feet, the landscapes where we work and live. How can animals enhance this most critical function – restoring land as home?

So these, then are four functions of land; and a few reflections on how animals might help to foster and sustain them. I trust you've had your own thoughts (and likely corrected some of my errant ones). Next, then, let me ponder how these perspectives might guide our work in coming decades.

Implications

If land is to be the measure, that emphasizes a systems perspective; seeing the full picture not just the pieces, considering connections, not just the components (Hardin 1993). But this poses a dilemma. We now face a "burden of knowledge" (Jones 2009), a "data deluge" (Baraniuk 2011). As we learn more and more we risk becoming ever bigger experts in ever more and smaller pieces.

Assembling the whole picture, therefore, becomes more and more imperative, because with the complexities of land, "we can never do merely one thing" (Hardin 1963). We might suppress methane emissions, for example, but increase N_2O emissions. We might suppress N_2O but elsewhere have eruptions of NH_3 (Peterson and Sommer 2011). And it gets even more complicated when we include all these other functions. Consider the aesthetic benefits of land, for example. "Admiration of a field of hay, of a cow producing milk, of a shapely and fragrant head of cabbage, is a great force for good" said an agricultural philosopher a century ago (Bailey 1915). Indeed – but how exactly do you quantify such benefits? What is the value of a floral array on well-kept pasture, or of a songbird nest preserved on unplowed land; or of the thrill of seeing a new-born calf? The poets know about such things, and so do we, I think; but where do such things fit into our mathematical models and sophisticated economic analyses? And if we cannot quantify such things, are we justified in ignoring them?

We may aim for win-win ventures, but nature is not always so gracious; when she offers a gift, she usually demands some recompense. Sometimes, therefore, we may need to choose: Do we want lower methane emissions or more carbon stored? Higher productivity or greater biodiversity? Bigger economic return or stronger aesthetic appeal? Clearly, such questions cannot be answered by science alone; they are societal questions, they involve judgments of value.

Which leads to another implication: that we may need better ways of involving audiences outside our science, better ways of telling our stories. Although we try, we're really not always adept at that. Our scientific manuscripts, for example – mine among them – do not always make for gripping, riveting reading. Maybe we will need to lean more on society's master storytellers – novelists, poets, musicians, dramatists – to help us tell the stories of livestock and land more eloquently (Nisbet et al. 2010; Orr 2011).

Why is this so important? Because in learning to live on the land, in letting our animals re-connect us to land, fancy graphs and mountains of data alone will not suffice. All our gadgetry, our sophisticated predictive models will not be enough to make our lands sustainable; we will need also to influence human behaviour (Fischer et al. 2012), the way we and our livestock live on the land. And to influence behaviour, stories are sometime more powerful than statistics (O'Connor 1957).

But more than just telling, we may also need to do more listening: listening to voices of other science and social disciplines; and more than that, listening to the land. All that we know does not yet allow us to foresee how our lands will unfold over the decades. Indeed, sometimes as we learn more and more, our predictive certainty diminishes, because we become more and more aware of all we do not know (e.g., Maslin and Patrick 2012). So that means establishing places where we settle in for long and patient listening, we and our successors; because responses of land may be subtle and slow, occurring in time frames beyond the usual funding cycles, beyond a scientific career, beyond even the span of human life. We have such places for croplands – long-term experiments a century old or longer. But I wonder if we have enough such places for systems with animals. What places do we start now, places to outlive us, where we and those who follow us can listen to how the land responds to us and our animals? Undoubtedly, some practices that look good to us now, may in 50 years seem flawed and ill-advised. Without such long-term sites, how can we know if livestock are harming the land or helping it? How do we know what the land is saying if we have no places for such long and patient listening?

Closing thoughts

Our lands – the local patches of biosphere – are changing. Accordingly, we may need to make changes to the way we live on the land, perhaps fundamental changes in the way we manage our land and our livestock (Godfray et al. 2011; Gill et al. 2010). So we come back to the question that is the theme of this conference: How can we ensure sustainable cattle production systems for future generations? There is, I suspect, no single answer; for people and places are not the same everywhere (Thornton 2010). Indeed, there may be no answer at all; only countless questions for each of the countless local tracts of biosphere: What do we here ask of the land? And how can livestock best advance those functions?

In recent decades animal research has made astonishing progress, profoundly enhancing efficiency and yield of animal herds globally. That is a towering legacy, one that will need to continue. But there may yet be an additional dimension to this legacy, a longer legacy: melding our animals, and thus ourselves, back into land again.

Acknowledgements

I am grateful to the organizers of the Bertebos conference for support in developing this paper. Lurking within these paragraphs are the insights of many colleagues, current and past, including Karen Beauchemin, Shannan Little, and Ben Ellert. Linda Kremenik and Yvonne Bruinsma contributed invaluable editorial help.

References

Bailey, L. H. 1980 (originally published in 1915). The Holy Earth. New York State College of Agriculture and Life Sciences, Ithaca NY.

Baraniuk, R. G. 2011. More Is Less: Signal Processing and the Data Deluge. Science 331:717-719.

Barnosky, A. D. 2008. Megafauna biomass tradeoff as a driver of Quaternary and future extinctions. Proceedings of the National Academy of Sciences 105:11543-11548.

Barnosky, A. D., E. A. Hadly, J. Bascompte, E. L. Berlow, J. H. Brown, M. Fortelius, W. M. Getz, J. Harte, A. Hastings, P. A. Marquet, N. D. Martinez, A. Mooers, P. Roopnarine, G. Vermeij, J. W. Williams, R. Gillespie, J. Kitzes, C. Marshall, N. Matzke, D. P. Mindell, E. Revilla, and A. B. Smith. 2012. Approaching a state shift in Earth/'s biosphere. Nature 486:52-58.

Bartlett, A. A. 1978. Forgotten fundamentals of the energy crisis. Am. J. Phys. 46 876-888.

Berkes, F., G.P. Kofinas, and F.S. Chapin. 2009. Conservation, community and livelihoods: sustaining, renewing, and adapting cultural connections to land. In Chapin et al. (eds.) Principles of Ecosystem Stewardship, Springer, NY. Pp. 129-147.

Boden, T. and T.J. Blasing. 2012. Record high 2010 global carbon dioxide emissions from fossil-fuel combustion and cement manufacture posted on CDIAC site. *http://cdiac.ornl.gov/trends/emis/prelim_2009_2010_estimates.html*

Boltzmann, L. 1886. The second law of thermodynamics. In B.F. McGuinness (ed.) Theoretical physics and philosophical problems: selected writings. Kluwer/Springer.

Bouwman, L., K. K. Goldewijk, K. W. Van Der Hoek, A. H. W. Beusen, D. P. Van Vuuren, J. Willems, M. C. Rufino, and E. Stehfest. 2011. Exploring global changes in nitrogen and phosphorus cycles in agriculture induced by livestock production over the 1900–2050 period. Proceedings of the National Academy of Sciences (early edition)

Cardinale, B. J., J. E. Duffy, A. Gonzalez, D. U. Hooper, C. Perrings, P. Venail, A. Narwani, G. M. Mace, D. Tilman, D. A. Wardle, A. P. Kinzig, G. C. Daily, M. Loreau, J. B. Grace, A. Larigauderie, D. S. Srivastava, and S. Naeem. 2012. Biodiversity loss and its impact on humanity. Nature 486:59-67.

Carson, R. 1952 In Lost Woods: The Discovered Writing of Rachel Carson. Beacon Press.

Chapin, F. S., M. E. Power, S. T. A. Pickett, A. Freitag, J. A. Reynolds, R. B. Jackson, D. M. Lodge, C. Duke, S. L. Collins, A. G. Power, and A. Bartuska. 2011. Earth Stewardship: science for action to sustain the human-earth system. Ecosphere 2:art89.

Daly, H. E. 1996. Beyond growth - the economics of sustainable development. Beacon Press, Boston.

Daly, H. E. and J. B. Cobb, Jr. 1989. For the common good. Redirecting the economy toward community, the environment, and a sustainable future. Beacon Press, Boston.

Davidson, E. A., M. B. Davids, J. N. Galloway, C. L. Goodale, R. Haeuber, J. A. Harrison, R. W. Howarth, D. B. Jaynes, R. R. Lowrance, B. Nolan Thomas, J. L. Peel, R. W. Pinder, E. Porter, C. S. Snyder, A. R. Townsend, and M. H. Ward. 2012. Excess nitrogen in the U.S. environment: trends, risks, and solutions. Issues in Ecology Winter 2012:1-16.

de Boer, I. J. M., C. Cederberg, S. Eady, S. Gollnow, T. Kristensen, M. Macleod, M. Meul, T. Nemecek, L. T. Phong, G. Thoma, H. M. G. van der Werf, A. G. Williams, and M. A. Zonderland-Thomassen. 2011. Greenhouse gas mitigation in animal production: towards an integrated life cycle sustainability assessment. Current Opinion in Environmental Sustainability 3:423-431.

FAOSTAT (accessed 2012). http://faostat.fao.org/

Fischer, J., R. Dyball, I. Fazey, C. Gross, S. Dovers, P. R. Ehrlich, R. J. Brulle, C. Christensen, and R. J. Borden. 2012. Human behavior and sustainability. Frontiers in Ecology and the Environment 10:153-160.

Folke, C., S. R. Carpenter, B. Walker, M. Scheffer, T. Chapin, and J. Rockstrom. 2010. Resilience thinking: Integrating resilience, adaptability and transformability. Ecology and Society 15:20.

Folke, C., Å. Jansson, J. Rockström, P. Olsson, S. Carpenter, F.S. Chapin, A.-S. Crépin, G. Daily, K. Danell, J. Ebbesson, T. Elmqvist, V. Galaz, F. Moberg, M. Nilsson, H. Österblom, E. Ostrom, Å. Persson, G. Peterson, S. Polasky, W. Steffen, B. Walker, and F. Westley. 2011. Reconnecting to the Biosphere. AMBIO: A Journal of the Human Environment 40:719-738.

Franzluebbers, A.J., L.B. Owens, G.C. Sigua, C.A. Cambardella, and R.L. Haney. 2012. Soil organic carbon under pasture management. In Liebig et al. (eds.) Managing agricultural greenhouse gases. Elsevier, Amsterdam. pp. 93-110.

Gill, M., P. Smith, and J. M. Wilkinson. 2010. Mitigating climate change: the role of domestic livestock. Animal 4:323-333.

Godfray, H. C. J. 2011. Food and Biodiversity. Science 333:1231-1232.

Haberl, H., C. Körner, C. Lauk, U. Schmid-Staiger, V. Smetacek, E-D Schulze, R.K. Thauer, P. Weiland, and K. Wilson. 2012. The availability and sustainability of biomass as an energy source. In German National Academy of Sciences Leopoldina (2012): Bioenergy – Chances and limits. Halle (Saale).

Hampicke, U. and H. Plachter. 2010. Livestock grazing and nature. Conservation objectives in Europe. Pages 3-25 in H. Plachter and U. Hampicke, editors. Large-Scale Livestock Grazing. A Management Tool for Nature Conservation. Translated from German by Les Reay. Springer-Verlag, Berlin.

Hardin, G. 1963. Perspectives in Biology and Medicine, Autumn 1963: 58-84.

Hardin, G. 1993. Living within limits. Ecology, economics, and population taboos. Oxford University Press, Oxford.

Herrero, M., P. K. Thornton, P. Gerber, and R. S. Reid. 2009. Livestock, livelihoods and the environment: understanding the trade-offs. Current Opinion in Environmental Sustainability 1:111-120.

Holling, C. S. 1973. Resilience and stability of ecological systems. Annual Rev. Ecol. Syst. **4**:1-23.

Homer-Dixon, T. 2007. The Upside of Down: Catastrophe, Creativity and the Renewal of Civilization.

Hooper, D. U., E. C. Adair, B. J. Cardinale, J. E. K. Byrnes, B. A. Hungate, K. L. Matulich, A. Gonzalez, J. E. Duffy, L. Gamfeldt, and M. I. O'Connor. 2012. A global synthesis reveals biodiversity loss as a major driver of ecosystem change. Nature 486:105-108.

Howard, A. 1950. An Agricultural Testament. Oxford University Press, London.

Isbell, F., V. Calcagno, A. Hector, J. Connolly, W. S. Harpole, P. B. Reich, M. Scherer-Lorenzen, B. Schmid, D. Tilman, J. van Ruijven, A. Weigelt, B. J. Wilsey, E. S. Zavaleta, and M. Loreau. 2011. High plant diversity is needed to maintain ecosystem services. Nature **477**:199-202.

Jones, B. F. 2009. The burden of knowledge and the "Death of the Renaissance Man": Is innovation getting harder? The Review of Economic Studies 76:283-317.

Krausmann, F., K.-H. Erb, S. Gingrich, C. Lauk, and H. Haberl. 2008. Global patterns of socioeconomic biomass flows in the year 2000: A comprehensive assessment of supply, consumption and constraints. Ecological Economics 65:471-487.

Marris, E. 2011. Rambunctious Garden. Saving nature in a post-wild world. Bloomsbury, New York.

Maslin, M. and P. Austin. 2012. Uncertainty: Climate models at their limit? Nature 486:183–184.

Midgley, M. 1983. Animals and why they matter. University of Georgia Press, Athens, Georgia.

Moriarty, P. and D. Honnery. 2011. Rise and Fall of the Carbon Civilization - Resolving global environmental and resource problems. Springer, London.

Moriarty, P. and D. Honnery. 2012. What is the global potential for renewable energy? Renewable and Sustainable Energy Reviews 16:244-252.

Nisbet, M. C., M. A. Hixon, K. D. Moore, and M. Nelson. 2010. Four cultures: new synergies for engaging society on climate change. Frontiers in Ecology and the Environment 8:329-331.

O'Connor, F., R. Fitzgerald, and S. Fitzgerald. 1957. Mystery and Manners. farrar, Straus & Giroux, NY. [reprinted in 1969]

Odum, E. P. 1997. Ecology A bridge between science and society. Sinauer Associates, Inc., Sunderland Massachusetts.

Orr, D. W. 2011. Hope is an imperative. The essential David Orr. Island Press, Washington.

Pelletier, N. and P. Tyedmers. 2010. Forecasting potential global environmental costs of livestock production 2000–2050. Proceedings of the National Academy of Sciences 107:18371-18374.

Peters, G.P., G. Marland, C. Le Quéré, T. Boden, J.G. Canadell, and M.R. Raupach. 2012. Rapid growth in CO_2 emissions after the 2008-2009 global financial crisis. Nature Climate Change 2:2-4.

Peterson, S.O. and S.G. Sommer. 2011. Ammonia and nitrous oxide interactions: roles of manure organic matter management. Animal Feed Sci. tech. 166-167:503-513.

Rees, W. E. 2003. A blot on the land. Nature 421:898.

Richard, T. L. 2010. Challenges in Scaling Up Biofuels Infrastructure. Science 329:793-796.

Roston, E. 2008. The carbon age: how life’s core element has become civilization’s greatest threat. Walker & Company, NY.

Smil, V. 1991. General Energetics. Energy in the biosphere and civilization. John Wiley & Sons, NY.

Smil, V. 2011. Harvesting the biosphere. Population and Development Review 37:613-636.

Steinfeld, H. and P. Gerber. 2010. Livestock production and the global environment: Consume less or produce better? Proceedings of the National Academy of Sciences 107:18237-18238.

Sutton, M. A., O. Oenema, J. W. Erisman, A. Leip, H. van Grinsven, and W. Winiwarter. 2011. Too much of a good thing. Nature 472:159-161.

Thornton, P. K. 2010. Livestock production: recent trends, future prospects. Philosophical Transactions of the Royal Society B: Biological Sciences 365:2853-2867.

Tomich, T. P., S. Brodt, H. Ferris, R. Galt, W. R. Horwath, E. Kebreab, J. H. J. Leveau, D. Liptzin, M. Lubell, P. Merel, R. Michelmore, T. Rosenstock, K. Scow, J. Six, N. Williams, and L. Yang. 2011. Agroecology: A review from a global-change perspective. Annual Review of Environment and Resources **36**:193-222.

Townsend, A. R. and C. A. Palm. 2009. The Nitrogen Challenge. Bioscience 59:822-823.

Turner, F. 1980. Beyond geography: the western spirit against the wilderness. Viking Press, NY.

Woodwell, G. M. 1970. The energy cycle of the biosphere. Scientific American 1970:64-74.