Restoring Atmospheric Carbon Dioxide to Pre-Industrial Levels: Re-Establishing the Evolutionary Grassland-Grazer Relationship

Adam D. Sacks[1], Richard Teague[2], Fred Provenza[3], Seth Itzkan[4], Jim Laurie[1]

[1]Biodiversity for a Livable Climate, Lexington, Massachusetts
[2]Ecosystem Science and Management, Texas A&M AgriLife Research Texas A&M University System, Vernon, Texas
[3]Dept. Wildland Resources, Utah State University, Logan, Utah
[4]Planet-TECH Associates, Somerville, Massachusetts

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Abstract

The quantity of carbon contained in soils is directly related to the diversity and health of soil biota. Since virtually all organic carbon sequestered in soils is extracted from the atmosphere by photosynthetic organisms, and converted to complex molecules by bacteria and fungi in synergy with insects and animals, we propose an effective and sustainable method for increasing soil organic carbon by restoring degraded and desertified grasslands worldwide. This approach to grassland management uses livestock according to the principles of Holistic Planned Grazing, the effectiveness of which has been demonstrated on over millions of hectares on four continents, primarily in semi-arid and arid areas, since the 1970s. We maintain that it has the potential to remove excess atmospheric carbon resulting from anthropogenic soil loss over the past 10,000 years and as well as all industrial-era greenhouse gas emissions. This sequestration potential, when applied to up to 5 billion hectares of degraded range and agricultural soils (former wild grasslands), could, in theory, return 10 or more gigatons of excess atmospheric carbon to the terrestrial sink annually and lower greenhouse gas concentrations to pre-industrial levels in a matter of decades. It is a low-tech

approach that bears minimal risk of the unplanned or unintended consequences that are the norm with technological "fixes" to large-scale environmental problems. Other benefits include restoring grassland and water catchment health, and providing jobs and high quality protein for millions of people, especially in rural communities.

Introduction

Harmful Changes in Earth's Climate and Carbon Fluxes

It has become increasingly clear that harmful changes in the earth's climate have been accelerating considerably faster than the scientific community had anticipated. While there are good reasons that scientific assessments tend to be conservative (Brysse 2013), surprise about the extent and rapidity of change are becoming the norm in global warming circles (Carey 2013; National Wildlife Federation 2013; National Climate Assessment and Development Advisory Committee 2013; Lyall 2013).

Over the past one billion years, the natural flux of carbon from geological stores (i.e., the earth's mantle/volcanoes, fossil fuels) has been in the range of roughly 0.03 Gt/year (DePaolo 2012:25). Since the human use of fossil fuels, the flux has grown by a factor of 300 to the range of greater than 9.0 Gt/year (DePaolo 2012:50). This can *only* be the result of human activity. The disruption of global biogeochemical processes is directly linked to our excessive use of fossil-fuel energy resulting in large increases in greenhouse gases (GHGs), including CO_2. This threatens not only climate but ocean and terrestrial chemistry as well, and reduces water and air quality (Kerr, 2010; Galloway et al., 2008).

In theory, a major part of human-induced climate change can be controlled by balancing the sources and sinks of atmospheric carbon dioxide (CO_2). While 20-35% of carbon dioxide may remain in the atmosphere for up to 20,000 years that time may be reduced by neutralizing calcium carbonate through slow weathering of rock (Archer 2009). But that long timeframe does not address current anthroprogenic climate change.

There is another factor in the increase in average global temperature, one which is insufficiently considered: the "air conditioning" effect of water. A healthy biosphere is essential in water cycles, as evapo-transpiration by plants absorbs heat and condensation releases it. Temperature extremes are thereby moderated. This effect is widely observed in changes of land use, such as deforestation and the plowing of grasslands for agriculture, which dramatically alter rainfall patterns and transform formerly healthy biodiverse soils into deserts. Unfortunately, global climate institutions almost always speak only about the effect of climate change on the water cycle and not about the reverse process, the profound effects of the water cycle on climate change [Kravcik 2009].

Re-establishing both carbon and water cycles are essential in addressing climate change; in fact, the two cycles work in tandem. While in-depth discussion of the water cycle is outside the scope of this paper, the reader is strongly encouraged to explore water-cycle restoration as a collateral path to reversing global warming (Kravcik, 2007; Schwartz 2013:74-94).

Table 1. Accelerating Rate of Atmospheric Carbon Dioxide Increase

Decade	Total Increase	Rate Annual of Increase
2003 – 2012	20.74 ppm	2.07 ppm per year
1993 – 2002	16.73 ppm	1.67 ppm per year
1983 – 1992	15.24 ppm	1.52 ppm per year
1973 – 1982	13.68 ppm	1.37 ppm per year
1963 – 1972	9.00 ppm	0.90 ppm per year

Atmospheric CO_2 is accelerating upward from decade to decade. For the past ten years, the average annual rate of increase is 2.07 parts per million (ppm). This rate of increase is more than double the increase in the 1960s, and 100x that of natural glaciation cycles.
http://co2now.org/Current-CO2/CO2-Trend/

Failure of Emission Reduction Strategies

For reasons both logically and culturally defensible, 25 years ago it seemed straightforward that reducing emissions would lower the amount of carbon in the atmosphere. Furthermore, we collectively believed that substituting non-carbon energy sources would be both technologically feasible and culturally acceptable as resulting in the least possible economic and social disruption. Accordingly, most efforts to combat global warming since 1988 have been directed only at controlling sources, and primarily only fossil fuel sources at that, ignoring the extensive quantities of carbon emitted from degraded soils. Efforts to address sinks, such as restoring forests, have been well-intended but with marginal effect (see, for example, Xu 2011).

The result is that the emissions-reduction strategy has, to date, been a decisive failure. It is beyond the scope of this paper to investigate the causes of said failure, which are primarily social, political and economic. For present purposes suffice it to say that generally the obstacles to emissions reduction have been a function of political inertia and economic vested interests, as well as difficulties in changing carbon-emitting cultural habits based on the unsustainable use of fossil fuel energy, for example, use of motorized ground and air travel in all aspects of life, and intensive synthetics-based agricultural productivity in all developed parts of the globe. The advancement of energy-conserving practices and suitable technologies would likely have made far more significant progress in the presence of strong political and popular will. Consequently, despite almost three decades of attempts on the part of governments, non-governmental organizations, the scientific community and citizens worldwide, the total atmospheric carbon burden has increased by approximately 42 parts per million (ppm) to our current level of 393 ppm (NOAA 2013), and the rate of increase is accelerating (IEA 2012).

Alternative Focus on Ecosystem Carbon Sinks

Since it has become increasingly apparent that emissions reductions will not take place in a reasonable timeframe, there have been alternative proposals for reducing the concentration of atmospheric greenhouse gases (GHGs) by actively removing them from the atmosphere. The advantages of such undertakings include the opportunity to bypass the impossibly slow international emissions-reduction agreement process, and the possibility of succeeding in reversing global warming *in spite of* persistent ongoing emissions. Unfortunately, most of these proposals rely on high-tech geo-engineering schemes, which are largely untested for effectiveness, fraught with unintended consequences, and potentially very expensive in both direct (economic) and indirect (environmental and social) costs (World Economic Forum 2013; American Meteorological Society 2013; Humphreys 2011).

Unfortunately, natural carbon sinks are currently decreasing because agricultural land, grazing lands (Follett 2001:404; Conant 2010:5-6) coral reefs and rain forests are being degraded at an increasing rate. To balance atmospheric carbon flux we believe that it is important both to restore and protect these ecosystems in addition to making drastic cuts in fossil-fuel use (Goreau 1992). Efforts to limit emissions from fossil-fuel combustion alone are incapable of stabilizing levels of carbon dioxide in the atmosphere, especially with increasing permafrost and seabed methane emissions along with destructive positive feedback loops such as dramatic melting of Arctic ice. Therefore it is imperative that we consider and implement optimal strategies for removing carbon from the atmosphere.

The Grassland Potential and Restorative Grazing

We believe that the most feasible and cost-effective approach to carbon sequestration is in restoring the massive sink in degraded grassland soils. Numerous instances from around the world attest to the fact that degraded grasslands can be restored to benefit biodiversity and ecosystem health using non-toxic low-technology methods while sequestering carbon (Savory 1999; Tainton 1999; Teague 2011), and this information is making its way into popular media (Savory 2013; Schwartz 2013). Although many attempts have been made to adopt technical solutions to reverse this degradation, most involve large amounts of capital and expensive technology, require energy inputs from unsustainable sources, have often been culturally inappropriate, and have not been successful in creating large-scale, sustained improvements to the landscape.

That terrestrial ecosystems are an important global carbon (C) sink is well known (Prentice 2001; Schimel 2001) and the size of this sink is related to the rangelands and grasslands of the world (Pacala 2001). See Figure 1.

Table 17

Estimated Range of Total Carbon Storage by Ecosystem

Ecosystem Type [a]	Total Land Area (10^6 km^2)	Global Carbon Stocks (GtC): Vegetation [b] (Low-High)	Soils [c] (Mean)	Total (Low-High)	Carbon Stored/Area (t C /ha) (Low-High)
Forests					
High-latitude	10.3	46-115	266	312-380	303-370
Mid-latitude [d]	5.9	37-77	84	122-161	206-273
Low-latitude	12.8	48-265	131	180-396	140-310
Sub-total	**29.0**	**132-457**	**481**	**613-938**	**211-324**
Grasslands [e]					
High-latitude	10.9	14-48	281	295-329	271-303
Mid-latitude [d]	20.1	17-56	140	158-197	79-98
Low-latitude	21.7	40-126	158	197-284	91-131
Sub-total	**52.6**	**71-231**	**579**	**650-810**	**123-154**
Agroecosystems [f]					
High-latitude	3.4	8-18	45	52-62	156-187
Mid-latitude [d]	12.7	21-52	134	155-186	122-147
Low-latitude	9.5	20-72	85	105-157	110-164
Sub-total	**25.6**	**49-142**	**264**	**313-405**	**122-159**
Other [g]					
High-latitude	18.6	3-31	65	69-96	37-52
Mid-latitude [d]	11.1	9-25	61	70-86	64-78
Low-latitude	8.8	4-16	34	38-50	43-56
Sub-total	**38.5**	**16-72**	**160**	**177-232**	**46-60**
Grand Total	**145.7** [h]	**268-901**	**1,484** [i]	**1,752-2,385**	**120-164**

Sources: PAGE calculations based on Batjes 1996; FAO 1995 and 1991; GLCCD 1998; and Olson 1994a and b.

Figure 1. Note that grasslands store more carbon in soils than any other ecosystem, although forests store more tons per hectare (White 2000:51). Soils are a significantly more stable long-term carbon sink than above-ground biomass.

Globally, grasslands comprise approximately 40% of the global land surface area, excluding Greenland and Antarctica (White 2000:12; see Figure 2), and are typically areas of low and seasonal rainfall (see Figure 3).

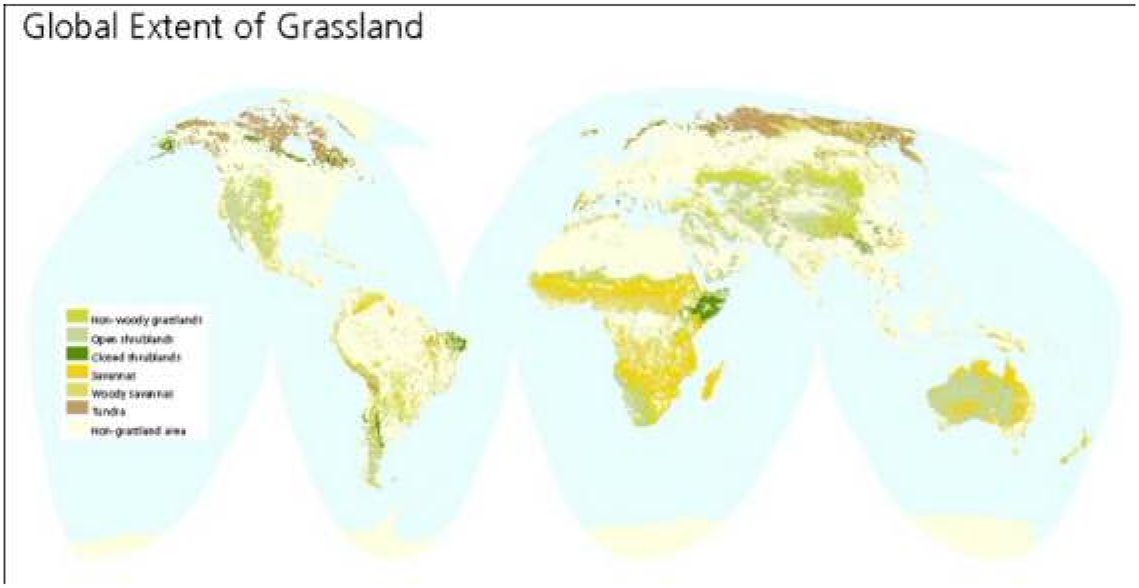


Figure 2: Global Extent of Grassland (White 2000:12).

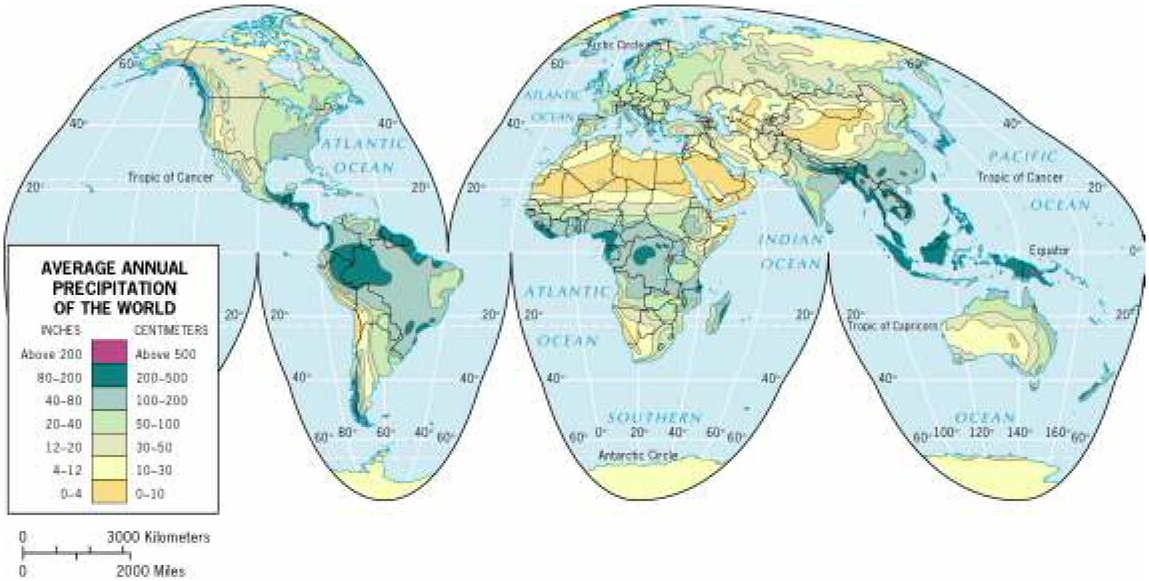


Figure 3: Average Annual Precipitation of the World (Planetolog n.d.)

For many centuries grasslands have been degrading primarily through destructive grazing practices and poorly managed agricultural encroachment of permanent grasslands (Millennium Ecosystem Assessment 2005). At least one billion rural and urban people depend on grasslands for their livelihoods, often through livestock production, or for ecosystem services that affect human well-being (Ragab 2002, Neely 2009). Therefore, there are huge economic and social costs associated with this degradation apart from the diminished role they are able to play in sequestering carbon.

To achieve restoration and sustainable use of billions of hectares of grasslands worldwide requires low-input technology, as well as management procedures that are adaptive and use a suitable flexible framework to restore ecosystem function (Neely 2009). Therefore, one of our objectives in this paper is to outline how such restoration is being accomplished in many locations around the world by changing the way livestock managers make decisions to achieve ecological restoration, and to enhance their livelihoods and quality of life. A direct consequence of restoring ecological function to these ecosystems is that net carbon sequestration and other essential ecosystem services is significantly enhanced, using an approach that has developed in the natural world over millions of years and has minimal likelihood of unintended consequences.

The Need for Sustainable Solutions

The future challenges to humankind are considerable, with climate change at the top of the list. It is projected that food production, which is entirely dependent on a benign climate, will have to increase by 50% by 2050 to keep pace with global population needs (Millennium Ecosystem Assessment 2005). Our ability to produce food increased dramatically in the latter half of the last century through technological and biological innovations driven by cheap fossil fuels, but that has not and will not free us from the fact that global resources are finite (Janzen 2011). Ironically, overuse of agrochemicals is gradually decreasing our ability to produce food. While their application dramatically increased yields during the Green Revolution, not only is their continued overuse making farms less productive by exhausting the soils, but the over-reliance on chemical inputs has put the global agriculture industry at major risk as these inputs are running out. Nor does this take into account that increasing productivity has resulted in substantial and increasing damage to the ecosystems upon which we and all forms of life depend.

Large urban populations and the intensive agriculture they depend on are severely impacting the supply of fresh water (Carpenter 2010). We use water extravagantly - from personal uses within our homes to irrigating lawns and crops. In the future we will have to use water resources much more carefully and efficiently while managing the major portions of our water catchments more effectively.

A considerable part of our ability to produce food now and in the future depends on having affordable forms of energy from sustainable sources. Cheap energy is a thing of the past because alternative sources of energy - solar, wind, water, biofuels and nuclear - are not abundant enough, and are more expensive or more difficult to use (Pimentel 2008). Nonetheless, to become more sustainable we will have to transition to renewable, non-fossil fuel based systems as quickly as possible (MacKenzie 1996, MEA 2005). In addition, global industrial production and development will have to restructure significantly to reduce emissions and pollution as well as use material inputs more efficiently (Hawken 1999). Whether humanity can proceed with resource consumption at anywhere near the rate of the exuberant past several hundred years is open to serious question.

The Role of Rangelands in Ecosystem Health

It is in the interests of humankind that we do not merely increase food production but link ecology with economics to produce foods as nature does, i.e., with minimal inputs (Ikerd 2005, Provenza 2008). As energy becomes more expensive we will have to manage for healthier ecosystems with fewer purchased and synthetic supplements. We will also have to change our philosophy of land use from a maximum production to a regenerative and minimum-cost approach. We will have to learn to work harmoniously with the landscapes we inhabit, and breed plants and livestock that are able to thrive locally and sustainably (Provenza 2008). Greater management expertise will enable us to manage land more effectively with less labor, less capital and fewer inputs.

The shrinking amount of habitat available for us to conserve numerous wild species is largely contained within rangelands. These ecosystems are too dry or have topographic limitations that dictate they remain dominated by native vegetation, not food crops. As semi-natural communities, they have high floral and faunal diversity which, if managed in harmony with nature, will avoid dependence on mechanical interventions, synthetic fertilizers, pesticides and other expensive inputs that threaten farmer and rancher income and exacerbate problems such as soil erosion and depletion, pollution, and loss of biodiversity (MEA 2005). In addition, since they cover such large areas, rangelands are extremely important in managing water catchments and sequestering soil carbon.

The unsustainable technologies that developed to support large-scale industrialized farming have become common on rangelands, increasing inputs and costs. These are the source of many concerns regarding health, pollution and ecological degradation, all consistent with the high production philosophy of the industrial agriculture paradigm (Provenza 2008, Teague et al. 2010). These include:

- replacing locally adapted livestock with genetic lines that are productive but dependent on high inputs of feed and medication;
- avoid stocking with excessive numbers and single species of livestock;
- ending use of performance enhancing drugs and hormones;
- feeding purchased supplements to maintain animal numbers in times of low productivity;
- eliminating high mechanization and transport costs;
- relying on heavy machinery and equipment for land management; and
- replacing diverse plant communities with few or single species forage sources that often require high inputs of water, fertilizer, and herbicides.

Fortunately some rangeland managers have rejected such expensive and ecologically unsound practices, and in rangeland ecosystems around the world examples exist of low input managers practicing more sustainable and economically viable management (Savory 1999; Gerrish 2004; Provenza 2008; Teague et al. 2011). These examples provide an excellent knowledge base on which to build more sustainable management in all rangeland ecosystems. This existing knowledge must be developed to facilitate the restoration of damaged ecosystems and to provide guidance for the future so we use the tools at our disposal more wisely and proceed with development sustainably.

Soil Health and Ecosystem Function

Although many rangelands have been badly degraded (Figures 4 & 5) it is possible to manage them to reverse degradation. Well-managed rangelands have a very important role to play globally as providers of livelihoods, water catchments, and bio-diverse habitat for a multitude of plants and animals, and many are managed to provide good wildlife habitat as well (Milchunas and Lauenroth 1993; Savory 1999). In addition, they hold a large reserve of soil C which, released when rangelands degrade, adds to CO_2 emissions. However, under restorative management such rangelands can significantly enhance soil C sequestration (Derner 2006; Allard 2007; Soussana 2010; Teague et al. 2011).

Photo: USDA

Figure 4. Soil Erosion, New Mexico. Shows almost five feet of soil loss. The mound that remains is held together by an isolated stand of native bluestem grass roots; the rest of the soil was dispersed by the winds (*National Geographic 2008:150)*.

Table 12

Decline in Prairies of Central North America

Prairie Type/Location	Past area (km^2)[a]	Current area (km^2)[a]	Decline (percent)
Tall-grass Prairie	**677,300**	**21,548**	**96.8**
Manitoba	6,000	3	99.9
Illinois	85,000	9	99.9
Indiana	28,000	4	99.9
Iowa	120,000	121	99.9
Kansas	69,000	12,000	82.6
Minnesota	73,000	450[b]	99.3[b]
Missouri	60,000	320	99.5
Nebraska	61,000	1,230	98.0
North Dakota	1,300	1	99.9
Oklahoma	52,000	N/a	N/a
South Dakota	26,000	200	99.2
Texas	72,000	7,200	90.0
Wisconsin	24,000	10	99.9
Mixed-grass Prairie	**628,000**	**225,803**	**64.0**
Alberta	87,000	34,000	60.9
Manitoba	6,000	3	99.9
Saskatchewan	134,000	25,000	81.3
Nebraska	77,000	19,000	75.3
North Dakota	142,000	45,000	68.3
Oklahoma	25,000	N/a	N/a
South Dakota	16,000	4,800	70.0
Texas	141,000	98,000	30.5
Colorado	N/a	N/a	N/a
Kansas	N/a	N/a	N/a
Montana	N/a	N/a	N/a
Wyoming	N/a	N/a	N/a
Short-grass Prairie	**181,790**	**62,115**	**65.8**
Saskatchewan	59,000	8,400	85.8
Oklahoma	13,000	N/a	N/a
New Mexico	N/a	12,552	N/a
South Dakota	1,790	1,163	35.0
Texas	78,000	16,000	79.5
Wyoming	30,000	24,000	20.0
Colorado	N/a	N/a	N/a
Kansas	N/a	N/a	N/a
Montana	N/a	N/a	N/a
Nebraska	N/a	N/a	N/a
TOTAL	**1,487,090**	**309,467**	**79.2**

Figure 5. Dramatic decline in central North American Prairies since 1830 (White 2000:21-22).

Successful conservation-minded rangeland managers enhance the health of the ecosystems upon which they depend by using soil, water and plant resources efficiently and sustainably (Walters 1986; Holling and Meffe 1996; Walker 2002). To do so, they combine scientific principles and local knowledge to manage animals adaptively to influence four ecosystem processes (Stinner 1997; Reed 1999; Savory 1999; Gerrish 2004; Barnes 2008; Provenza 2008; Diaz-Solis 2009; Teague et al. 2009a):

- efficient sequestration of solar energy by plants;
- interception and retention of precipitation in the soil;
- optimal cycling of nutrients; and
- and promotion of high ecosystem biodiversity with more complex mixtures and combinations of desirable plant species.

Scientific evidence of grazing management to improve ecosystem health

Rangelands with healthy soil and diverse mixes of plants and animals are more productive, stable and resilient than those in poorer condition and they provide greater earnings and more abundant ecosystem services. Indeed, they may represent the most benign use of natural resources. *Contrary to common belief, they regenerate with disturbance and they deteriorate in the absence of periodic disturbance in the form of proper grazing or appropriate and limited use of fire* (Savory 1999:430). They retain diverse ecological forms and function under infrequent and light to moderate defoliation and the impact of grazing herds (Oesterheld 1992; Milchunas and Lauenroth, 1993; Knapp 1985; Hulbert 1988; Seastedt 1995).

Large herbivores play a key role in the function of ecosystems by increasing forage concentration, grazing efficiency, forage nutrient concentration and aboveground plant production (Frank and Groffman 1998; Frank et al., 1998). Their digestive systems are designed to provide humidity and microorganisms to produce biological decomposition of huge volumes of plant material.

Nutrients return to the soil in the form of urine and dung, which represent an accelerated cycling of nutrients otherwise locked in aboveground vegetation biomass. They also improve mineral availability by enhancing soil microbial nutrient enrichment and soil microbiological processes that ultimately augment plant nutrition and photosynthesis (Hamilton and Frank 2001) in addition to increasing nutrient cycling within patches of their urine and excrement (Holland et al., 1992). *Consequently, grazing is an optimization function*: excessively low or high levels of herbivory (eating plants without killing them) yield low levels of primary production, while intermediate levels of herbivory yield maximum productivity (McNaughton 1979; Dyer et al., 1993; Turner et al., 1993).

The grasslands of the world evolved under large herds of migratory herbivores that supported more herbivore biomass and sustained considerably higher levels of herbivory than any other terrestrial habitats (Frank and McNaughton 2002). However, the relatively recent replacement of free-ranging herbivores and herding pastoralists with sedentary livestock has resulted in widespread overgrazing (Oesterheld 1992; Milchunas 1993; Weber 2011), which often has degraded vegetation and soils, reduced biodiversity, and led to the loss of the capacity of soils to sequester carbon.

Domesticated livestock, without pressure from predators, do not graze uniformly over a landscape but instead apply constant grazing pressure and repeatedly consume preferred plants and patches of vegetation. Such excessive herbivory removes biomass and litter which causes soil exposure and degradation in heavily used areas.

Soil, plants, and animals benefit when herbivores roam. These are natural behaviors in response to changes in forage quality and availability and in response to predators. Beyond that, satiety mechanisms ensure herbivores eat a variety of foods and forage in a variety of places (Provenza 1996; Bailey and Provenza 2008). Variety stimulates appetite and enhances nutrition; production; and the health of soil, plants, herbivores, and human beings (Provenza et al. 2007; Provenza 2008).

To manage animals sustainably requires adopting long-term planning horizons, conserving primary resources, choosing appropriate management goals, and continually adapting to dynamic ecological, social, and economic conditions (Savory and Butterfield, 1999). Unless sufficiently sensitive indicators of change are continually monitored, landowners who focus on short-term profit maximization may not realize that the ecosystems upon which their production systems depend are being systematically degraded (Kothmann 1971; Whitson 1982; Knight 1990; Teague et al. 2009b). Consequently, narrowly focusing on *maximizing* livestock production from rangelands is inevitably an unsustainable goal both ecologically and economically (Workman 1986).

The Life of the Soil

In healthy soils, along with water and nutrients, carbon is stored in complex biomolecules, which can remove carbon from global cycles for hundreds or even thousands of years. Australian soil scientist Christine Jones notes (Jones 2009b:16-17):

> [i]f soil is of high ecological integrity, soil microbes, especially fungi, resynthesise and polymerise labile carbon (mostly exuded from plant roots) into high molecular weight stable complexes, referred to collectively as humic substances. Humus, a gel-like substance that forms an integral component of the soil matrix, is the best known of the long-lived stable organic fractions.
>
> Humified carbon differs physically, chemically and biologically from the labile pool of organic carbon that typically forms in agricultural soils. Labile organic carbon arises principally from biomass inputs (such as crop

> residues) which are readily decomposed. Conversely, most humified carbon derives from direct exudation or transfer of soluble carbon from plant roots to mycorrhizal fungi and other symbiotic or associative microflora.
>
> Humus is composed of large, complex molecules made up of carbon, nitrogen, soil minerals and soil aggregates. It is an inseparable part of the soil matrix that can remain intact for hundreds, sometimes thousands, of years.
>
> Once carbon is sequestered as humus it has high resistance to microbial and oxidative decomposition.

Plants in a healthy biodiverse soil will release much of their photosynthetic sugar (perhaps 40%) to symbiotic mycorrhizal fungi. In return the fungal mycelia distribute energy in the form of sugars to microbial communities deep in the soil, which find and extract minerals for the plant. The mycelia are also active in finding water in pores inaccessible to plant roots. This mycorrhizal system also produces a carbon-rich glycoprotein called glomalin, which comprises a large percentage of organic matter in healthy soils. They are sticky substances that can bind soil particles together, providing air spaces and structure for the movement of water and soil organisms and holding many times their own weight in water (USDA 2008; Comis 2002).

Christine Jones has studied this “Liquid Carbon Pathway” and proposes the following:

> In addition to reducing levels of atmospheric carbon dioxide, the activation of the soil sequestration pathway results in the release of plant nutrients from the theoretically insoluble mineral fraction, which comprises by far the largest proportion (96-98%) of the soil mass. This increased mineral availability improves the health of pastures, crops, livestock and the people consuming agricultural produce. Everyone benefits when food is more nourishing.
> Mineral availabilities are determined more by the rate of carbon flow from plants than by the stock of carbon in the soil. The "key" to mineral management is appropriate groundcover management.

Jones has been studying pasture cropping on the Seis Ranch in New South Wales, Australia for over 20 years. From 2008 to 2010, the sequestration rate was 33 tons of CO_2 per hectare per year, the equivalent of 9 tons of SOC. Stable, non-labile compounds comprise 78% of the carbon gain. Jones is finding that over time the biggest gains are made deeper in the soil. "That is, over time, fertile carbon-rich topsoil will continue to build downwards into the subsoil." (Jones 2011:3). Recent evidence, in this instance in boreal forests, further illustrates how critical healthy fungal networks are to soil carbon stores (Clemmensen 2013).

Conventionally managed soils on the other hand, using synthetic fertilizers and pesticides, destroy essential soil biota and lead to widespread soil degradation (Neely 2011). Mycorrhizal fungi and associated bacteria are strongly inhibited by excessive soil disturbance such as plowing, and by high levels of water soluble phosphorus and nitrogen commonly used as fertilizers in agriculture (Killham 1994; Leake 2004). Such soils become "addicted" to artificial inputs, requiring ever larger "fixes" over time while yielding diminishing outputs (Khan 2007). Farmers compensate by using even more fertilizer, creating a vicious cycle of over-farming and chemical abuse.

The energy supplied by green plants is necessary to keep fungi functioning effectively; the fungi reciprocate by providing plants with essential minerals. Mineral depletion and the structural degradation of grassland soils have largely been the result of human mismanagement, diminishing the effective function of fungi. It is almost trivial to state that when the supply of soil carbon is limited by the loss of primary plant production (that is, sugars and other carbon compounds created via photosynthesis and metabolic processes) the carbon sequestration by the physical, chemical and biological processes in healthy soils is markedly reduced (Jones 2008).

To maintain soil health in rangeland and more intensive pastures this means moderate defoliation during the growing season and adequate recovery before once again grazing them (Gerrish 2004; Teague et al. 2011). By doing so it is possible to keep the plants photosynthesizing for as long as soil moisture permits.

This increases the growing season, animal diet quality and the amount of energy for the plants themselves, and the fungi and other soil microbes that obtain energy from them.

Restoring Grasslands

Synergy is at the heart of effective eco-restoration. To restore grasslands as healthy ecosystems and effective carbon sinks, we must re-establish the evolutionary relationships between grazing animals and their habitats. Grassland habitats have suffered worldwide since the advent of agriculture and pastoralism by human use of wild lands for food and other products (Suttie 2005). But recently degradation has accelerated (Weber 2001:2):

Some pastoral cultures (e.g., the Herero of Namibia and the Samburu of Northern Kenya) have degraded their environments to the point where temporary abandonment is required (Hill 2006). Still, numerous pastoral cultures (e.g., Rashayada Bedouin of the Sudan, Mongolian and Chinese herdsman, and Pyrenean herders) have subsisted on rangelands for thousands of years despite various hardships and challenges. Indeed, the degraded landscapes observed today are considered a relatively recent phenomenon that has accelerated during the late 20th and early 21st centuries.

This has culminated in the modern industrial approach to animal husbandry that has so distorted our raising of goats, sheep, and cattle that we don't understand how essential they are to healthy landscapes.

The Role of Livestock in Grassland Ecosystem Destruction

Livestock have a large and growing impact on global ecosystems. In biomass they exceed humans and other mammals, and because of the growing demand for livestock products this impact is likely to increase markedly (Janzen 2011).

The increase in demand for livestock products is a major driver in changing land use to expand livestock production, as in the clearing of forests in Brazil. These and other expansions are causing serious loss of wildlife habitat, biodiversity and terrestrial carbon stocks (Steinfeld and Wassenaaar 2007). In addition, approximately a third of cultivated land is used to produce animal feed, decreasing the amount available for human consumption. The amount of water livestock require, either directly or in the production of animal feed, competes with human and agricultural uses. Improperly managed livestock may also be a threat to water quality through their impact on watersheds and directly through fecal contamination (de Vries and de Boer 2010; UN FAO 2006).

Where more intensive animal agriculture is conducted there are major problems with livestock excrement disposal and pollution (Galloway et al. 2008), the heavy dependence of such industrial activities on the use of non-renewable energy (Bartlett 1978), and the competition for human food with up to 40% of cereal production globally being used for livestock feed (Garnett 2010). In addition, from a climate change perspective intensively reared livestock are significant contributors to GHG emissions (Steinfeld et al., 2006). These issues have resulted in numerous calls to reduce livestock agriculture to control these many and widespread problems (Popp et al., 2010).

The Role of Livestock in Grassland Ecosystem Restoration

On the other hand there is an entirely different perspective, one honed by millions of years of evolution. It is one in which, with appropriate management, livestock are major determinants in maintaining and restoring ecosystem function and services while providing products that humans need without being in competition with them. In contrast to cereal grains that humans can digest, herbivores transform pasture and rangeland plants (grasses, forbs, and shrubs which are high in cellulose, which humans cannot digest) into animal products (meat, milk, and fiber) that humans can use.

Rangelands occupy approximately one third of the earth's land area not covered by ice (White 2000). At least a billion rural and urban people depend on them for their livelihoods, through livestock products and ecosystem services that affect human well-being (Ragab and Prudhomme, 2002; Millennium Ecosystem Assessment, 2005; Neely 2009). Rangelands are not suitable for cultivation and they should not be cultivated, as this would virtually eliminate their value in maintaining human and biodiverse populations and supplying ecosystem services.

Research during the past fifty years has shown that grazing animals are *essential* for the rapid restoration of degraded rangelands (Savory 1999, Gerrish 2004). Properly managed grazing by herbivores can create diverse plant species with different chemical characteristics, enhance soil organic matter and nutrients, moderate soil temperature, and increase water infiltration rates (Figure 6). Proper grazing management also can increase the fungi to bacteria ratio by more than 4 times over land not grazed. Fungi access and transport nutrients, extend root volume and depth and increase drought resistance (Killham 1994; Leake 2004).

On the one hand, standard practice prescribes long-term, indefinite "rest" for overgrazed grasslands, that is, removal of animals for years or decades. On the other hand, such rest does not work to restore grasslands in "brittle" environments, that is, environments with highly seasonal or erratic precipitation patterns and often long dry periods (see for example West et al. 1984). Brittle environments comprise 75% of all grasslands on the planet (grasslands with year-round rainfall are far more resilient). Despite clear evidence that over-rest is destructive, not restorative, the application of over-rest remains firmly entrenched in the dominant paradigm (Beschta 2012). It is important to note that there is a vast difference between land partially rested with plants either grazed or overgrazed, and land where rest has been replaced by periodic high impact of grazing animals and plant recovery.

Therefore an appropriate undisturbed recovery period punctuated by well-planned grazing is essential for maintaining plants and ecosystem processes in brittle environments. The purpose of such a recovery period is, after proper grazing pressure, to allow bitten plants to regrow. The recovery period may be anywhere from 30 days to 2 years depending on factors such as the climate, time of year, animal density, precipitation and many other factors (Savory 1999:501 ff.) This mimics the way nature cycles animal impact in wild herds. An appropriate recovery period is never measured over a span as long as several years or decades, over which time the deleterious effects of over-rest become increasingly apparent.

Figure 6. Land in the semi-arid Karoo region in South Africa. Healthy land on the left was managed with Holistic Planned Grazing, degraded land on the right is over-rested, with no animal impact for decades. Average annual rainfall here is 250-450 mm/yr (Palmer n.d.). For comparison, average annual rainfall for humid Massachusetts, USA is ~1,200 mm/yr.

Introducing Holistic Management

Rangeland ecosystems are complex and variable and to achieve desirable sustainable goals a flexible management framework is essential. As each ranch or management area is unique, such a framework must be able to incorporate a great deal of complexity and monitoring to achieve multiple goals while maintaining a flexible format.

The Holistic Planning protocols developed by Allan Savory (Savory 1999) are unique in providing such a comprehensive management framework based on maintaining or improving the ecological function and biological resources upon which productivity is based while simultaneously addressing both social and economic complexity. Traditional teachings on management of rangeland, exemplified by Briske et al. (2008), have concentrated more on achieving the highest productivity without examining long-term consequences on ecosystem function or ranch profitability. As discussed below, this management approach has been a major cause of rangeland deterioration.

The use of the holistic framework ensures that all objectives are consistent with the holistic context and that all actions are socially, environmentally and economically sound, both short- and long-term. Success using Holistic Planned Grazing (Savory 1999) is achieved by monitoring and making adjustments as conditions change to continually improve the four ecosystem processes:

- efficient sequestration of solar energy by plants;
- interception and retention of precipitation in the soil;
- optimal cycling of nutrients; and
- promotion of high ecosystem biodiversity with more complex mixtures and combinations of desirable plant species.

The complexity that ranchers and pastoralists have to contend with are too great for any prescribed rotational or other management system, and are thus addressed through a planning process involving the use of a planning tool (referred to as an "aide memoire" by Savory) that breaks the many factors into small easy-to-manage segments. Such segments build upon one another until the plan is complete for any period. Because different dimensions such as areas of land, time over many months, numbers of animals, and seasonal variations are involved, the actual plan is done on a chart with symbols and figures where planned moves of the animals are plotted.

Key principles invoked are:

- Partial or total rest of the land is detrimental and thus the herd effect of the animals is used to ensure repeated and periodic high disturbance to ensure annual rapid biological decay of dead plant material and soil cover. This is put into practice through moving livestock in a tight packs (Figure 7) and in regular movements of the corrals (every seven to ten days) to maximize the cover of dung and plant litter (Figure 8).
- Only plants (not land) can be overgrazed or overbrowsed. Over-use is a function of time in a paddock, not animal numbers. Through planned grazing, plants are assured adequate recovery between grazings for full root re-establishment -planning is based on plant recovery periods, not grazing periods.
- Drier than average years are a regular feature in low rainfall environments, accordingly every year is planned as a drought year but in terms of months of reserve of forage and not forage reserve areas. This is done to keep production of both animals and plants high in all years including those not drier than average.
- Planning always includes dovetailing livestock moves with all other land uses, including considerations of how to prevent conflict with wildlife.

Photo: Africa Center for Holistic Management

Figure 7. Dense Packs. Livestock, of mixed species, are moved in tight and mobile packs, replicating the co-evolutionary and beneficial behavior of wild herds.

Photo: Seth J. Itzkan

Figure 8. Mobile Corrals. Corrals are moved every seven to ten days to maximize the area covered in dung and plant litter, providing cover for bare or highly degraded ground and helping to ensure better water retention the during rains.

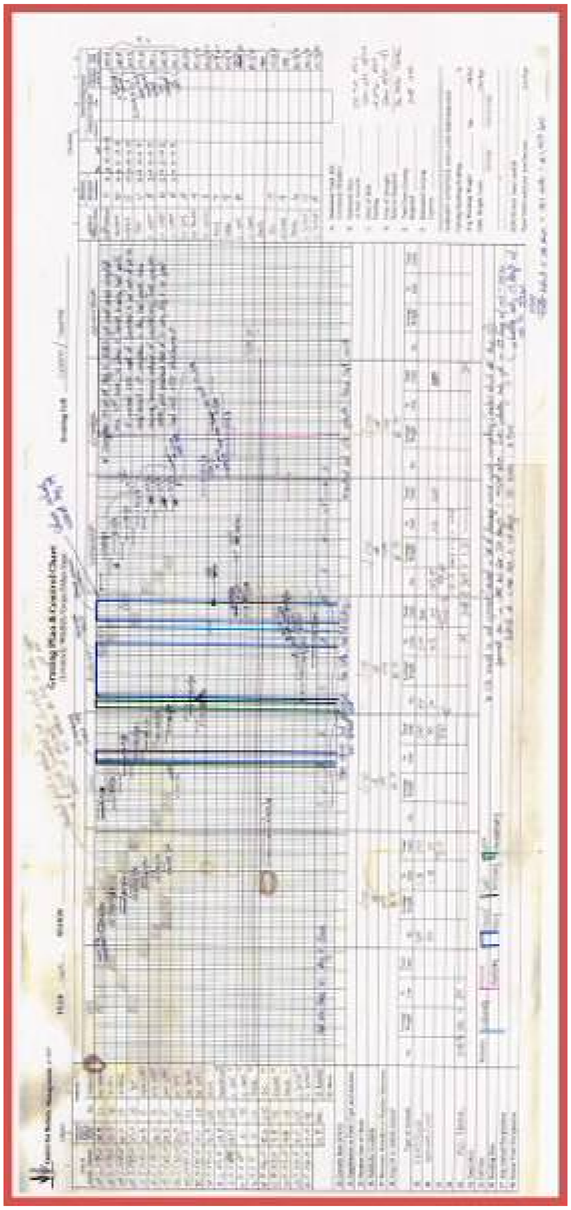


Figure 9. Holistic Grazing Plan and Control Chart

The Holistic Management process provides the manager with the protocols and forward planning to implement timely adjustments to counter overgrazing and over-rest as well as plan ahead to achieve biodiversity and wildlife goals. The process allows for such goals to be tailor-made to specific situations in different portions of a management area and coordinate disparate requirements of different areas (Savory 1999).

Long-term ranch-based research and theoretical analyses indicate that reducing livestock numbers when forage availability declines is insufficient to maintain rangeland health and productivity and may in fact prevent maintaining health (Müller et al., 2007; Teague et al., 2004; 2011).

Adequate post-grazing recovery during the growing season is also necessary. Subdividing grazing units into smaller pastures ("paddocks") effectively increases the area and biomass of plants animals graze. In the process, animals can learn to eat mixtures of plant species, including so-called unpalatable plants, in ways that can increase forage intake and improve animal health (Provenza 2003a,b; Provenza et al. 2003; Villalba et al., 2004; Shaw et al., 2006; Provenza and Villalba 2010). This increases available forage, a significant advantage over continuous grazing (Teague et al., 2011). Under such management, biodiversity and ecosystem function are considerably enhanced. When combined with a decision-making process that responds to frequent changes in conditions, it can also pro-actively mitigate the damage caused by the recurring periods of drought.

Much evidence supports Holistic Planned Grazing as a highly effective means of restoring soil health. This includes articles from the mainstream literature (Savory Institute 2013), empirical data from ranchers and various agricultural services, reasonable inference from conventional soil carbon measurements, and historical data on loss (and therefore restoration potential) of soil organic matter (SOM) and soil organic carbon (SOC). The same is true for Management-Intensive Grazing

(MIG) (Gerrish 2004). While the former (HPG) has focused more on rangelands than pastures and the latter (MIG) more on pastures than rangelands, the principles and practices with regard to grazing are the same. Collectively, these approaches have led to planned and managed grazing by many people on land throughout the world.

Rangeland and pasture restoration can play a central role in addressing climate change, since restoring soil health *always* results in storing significant quantities of carbon: we know that soil health, biodiversity and soil organic carbon go hand in hand. As we will discuss, the potential for carbon sequestration in soils is massive, likely equal to the task of storing over 250 years of industrial carbon emissions should we choose to implement it in earnest.

How Pasture and Rangeland Soils Come Back to Life

Holistic Management is successful because it mimics nature's approach to a sustainable ecosystem. A typical illustration of the essential process of soil restoration, beginning with mostly bare, dry ground and using any of a wide variety of animals as grazers, from cattle to goats to sheep to bison to antelope is as follows:

First and foremost, a grazing plan is created in order to manage livestock properly in their particular and unique habitat. Even on severely degraded lands there is usually some forage available - the more diverse the better (Provenza et al. 2007) - to get the process started. Infrequently, it may be necessary to provide hay or other feed, for example, in an area where the soil has been degraded by materials such as mine tailings (Dagget 2005:9-23). The animals are run in tight groups, confined to relatively small paddocks, or herded in sequences that optimize use of all plants on landscapes (Meuret 2010, Meuret and Provenza 2013), having intense but brief impact (several hours to a few days) on the land.

All planning is done on the basis of ensuring adequate recovery of grazed plants. Accordingly, during grazing constant monitoring is used to ensure that plants are not being overgrazed. When a new situation is experienced, the manager assumes the decisions are wrong and monitoring focuses on the earliest detectable changes to ensure that management is moving the system toward the desired state. If not, further changes are made to ensure the desired state is reached in what is proactive management. These are essential elements of Holistic Management-- Plan (and assume that original plan may have been wrong) - Monitor - Control - Replan (Savory 1999:501 ff.; Figure 10).

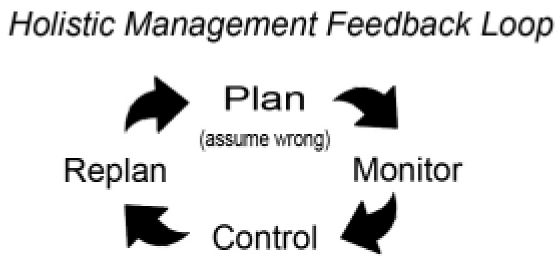
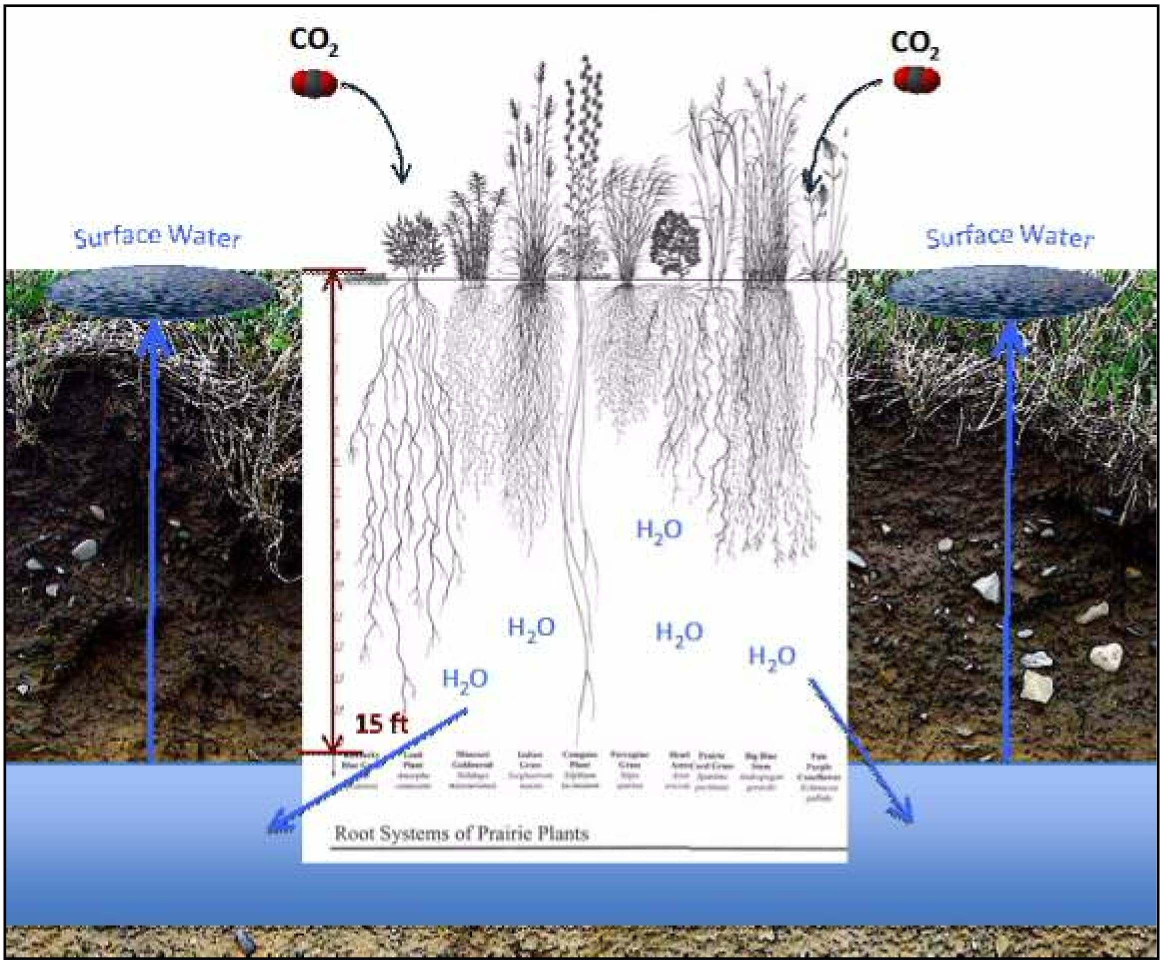


Figure 10.

During their first impact on degraded soils the animals break the soil cap with their hooves, fertilize it with urine and dung rich in gut bacteria, and trample plant matter into the soil surface, including fresh seeds and dead biomass that interferes with new growth. This disturbance stimulates biotic activity by facilitating circulation of oxygen, carbon dioxide and other gases, by providing nutrients, allowing penetration of water (Weber 2011) and providing land cover to minimize or eliminate bare ground (Naeth 1991). Covering the ground with dung and trampled grass increases the effectiveness of rainfall, as the increase in organic matter helps to hold water in the soil (McGinty 1995). Biodiversity flourishes as the area of bare soil diminishes. Reclamation begins with covered ground to make the available rainfall more effective through reducing both soil surface water evaporation and runoff during high rainfall events.



Graphic: Seth J. Itzkan

Figure 10: Restoration of water table and surface water in grasslands. Animal impact stimulates deep-rooted prairie plant growth creating porous, absorbent soils. Water sinks into the ground rather than getting lost to evaporation and runoff. The increased water recharges and raises the water table, which feeds aboveground streams and ponds. Holistic Management practitioners routinely

report new surface water, often within a few years, where it hadn't appeared for as long as anyone could remember.

Over a period of as few as three years, many long-disabled processes come back to life. Insects such as dung beetles retrieve excreta and store it more than 18 inches beneath the surface (Richardson and Richardson, 2000). Worms and small mammals such as moles and prairie dogs churn the soil, while deep-rooted perennial grasses regrow and create channels for water and gases. Mycorrhizal fungi, with literally thousands of miles of hyphae in a small patch, transport nutrients which they have the unique ability to obtain from soil minerals, and exchange them for carbohydrates from photosynthetic plants. The fungi synthesize a stable glycoprotein, glomalin, which holds 4 to 20 times its weight in water (Reicosky 2005). Micro-organisms join the elaborate fray, accessing minerals that they supply to fungi which in turn supply them to the green plants, and in the process create complex carbon molecules that store carbon deep in the soils for a long period of time (Jones 2009a:4-5). This is the embodiment of carbon sequestration.

When grazing animals eat perennial plants, their root systems die back proportional to the amount of the plant that is eaten, and become food for communities of bacteria (Baskin 2005), leaving porous passages and complex carbon molecules which are aggregated into humus (Pucheta 2004). This is why healthy soils are dark in color (like elemental carbon), relatively low in density, and clump, not crumble, when handled.

Following defoliation, perennial plants, after first sacrificing root and root hairs to mobilize energy for leaf growth, then regrow new roots that season. The process repeats itself, increasing soil porosity, water and carbon content annually. Through each cycle every component of this complex system nourishes all the others, resulting in rich soils which, storing vast quantities of water and carbon, remain moist even during periods of drought, raise the water table to restore and maintain perennial streams and ponds, and create habitats for richly diverse microbial, plant, insect and animal life.

These are the healthy soils we strive to recreate, capturing carbon, providing food, re-establishing balanced hydrological and nutrient cycles, and imparting beauty to the land. Herbivores are organs as essential to the form and function of these processes as stomachs and hearts are to the form and function of mammals.

Eco-Restoration Case Studies: Lessons, Finances, Topsoil, Pasture and Rangeland Creatures

The following is an overview of ecological restoration case studies in which livestock have been a central factor.

Holistic Planned Grazing and Management-Intensive Grazing

A key place to examine eco-restoration is in the work of Allan Savory. In 1999, along with his wife Jody Butterfield, he published the second edition of his ground-breaking work, *Holistic Management: A New Framework for Decision Making* (Savory 1999). In it he examines the nature of the decision-making process that leads to destruction and desertification of terrestrial ecosystems and an alternative decision-making process that makes possible re-establishing healthy, whole, functioning ecosystems while also meeting human needs. Savory gives examples from arid regions worldwide - Zimbabwe, South Africa, Namibia, and the Southwest United States - where the reversal of desertification was achieved through a changed decision-making framework and modifications of livestock management (see Figures 11 & 12).

An equally productive place to examine eco-restoration is with the work of Jim Gerrish. His work, too, has broadly impacted the management of grazing lands, especially pasture lands. His book titled Management-Intensive Grazing is grounded in 30 years of research and filled with examples of how to use understanding of ecological principles and processes to implement grazing practices (Gerrish 2004).

Scientists in academic institutions have less readily embraced HPG than MIG (e.g., Briske et al. 2008), but managers have readily embraced both HPG and MIG (Teague et al. 2011). The discrepancy has to do mainly with how academics study grazing (analysis of parts, control of variables) and how practitioners use grazing to accomplish ecological, economic, and social goals (synthesis of wholes, flexibility) (Van Der Ploeg 2006).

Both practices have been adapted by practitioners at modest rates (Stinner 1997), but there is increasing interest in managing grazing as an integral component of meeting ecological, economic and social goals. This interest is being driven by ever increasing costs of fossil fuels, combined with growing awareness of the high costs - ecologically, economically, and socially - of management that relies on inputs such as fertilizers and pesticides that damage ecological and social systems. It is being accelerated by increasing consumer awareness of the relationship between diet and health and the desire to eat whole foods raised under healthful conditions that link soil and plants with animals and humans, including pasture-reared animals treated humanely.

Photo Credits: Africa Center for Holistic Management

Figure 11. Reversal of desertification in Zimbabwe. Average rainfall 600-700 millimeters. In the left picture (2006), wooden paddock fences can be seen in the background. Animals were corralled in the paddocks overnight for several consecutive nights to maximize the cover of dung and plant litter, then were moved to new sites in need of intense impact. After the rains new plant growth (2009) is incorporated into the holistic grazing plan. Blue arrow points to the same tree in both pictures.

Photos: Guillermo Osuna

Figure 12. Reversal of desertification in Mexico: Las Pilas Ranch in Coahuila, Mexico. Average rainfall 350-450 mm. The arrows mark the same point on the horizon. Over a twenty-five year period, from 1978 to 2003, the barren landscape was completely revived (although the first picture is from 1963, the restoration with Holistic Management didn't start until 1978). During the restoration period the livestock population was doubled and grazing was done according to a plan that paid close attention to grass health. Although there appears to be more water in the left photo, the man-made pond shown is merely runoff captured by a constructed dirt dam. The dry, sandy land surrounding it retains no water. The restored terrain in the photo on the right is estimated to hold six-times as much water as the depleted terrain on the left, but now the water is held in the soil and vegetative matter in a state referred to as "green water". Previously, a one-inch rainfall would fill the trough. Today, even a six-inch rainfall is all absorbed (as it should be). The trough has been overgrown and is no longer needed to water the animals, as formerly dried-up springs in the vicinity have begun flowing year-round once again.

Dan Dagget and Examples from North America

Ecologist and rangelands activist Dan Dagget (2005) has collected several illustrated examples of eco-restoration across the Southwestern United States and Northern Mexico using livestock and HPG. He emphasizes that degraded and desertified rangelands, most of which exist in a drought-prone environment with irregular rainfall, require animals for systemic health. Restoration examples with livestock include barren gold-mining land in Nevada that had been treated with cyanide, riparian embankment recovery along the Gila River in New Mexico, and native grassland recovery on the Audubon National Wildlife Refuge in North Dakota.

Jim Howell and the Role of Grazers

Rangeland expert Jim Howell has been practicing HPG for over twenty years, and has working experience with ranchers throughout the American West, Mexico, Argentina, Australia, New Zealand and Africa to improve the health and productivity of their lands in a wide variety of climates and conditions. He summarizes the importance of grazing animals to grasslands as follows (Howell 2008:2-4; emphases in the original manuscript):

> Perennial grass plants and large grazing mammals (in association with their pack hunting predators) have been living together for millions of years. Grasses are adapted to periodic defoliation. Most grasses grow from growth points that lie at the base of the plant, beyond the reach of the grazing animal's muzzle . . .
>
> Given sufficient **time**, the plant can completely recover from the severe grazing. . . . and many grass species in fact rely on properly timed grazing. . . . Overgrazing takes place when a plant is severely regrazed before it has had the chance to completely recover both its carbohydrate reserves and above ground leaf area.
>
> . . . [T]he bulk of the world's grazing animals live in areas with either highly seasonal or highly erratic precipitation patterns. The soil surface condition

is therefore dry and arid for much of the year, which means that microbes and insects in charge of decomposing plant material into the soil die off or become dormant during the dry, non-growing season. ***The only place that these decomposers survive during these long dry spells is in the gut of the grazing animal.*** In these seasonal environments, the grazing animals are therefore critical in maintaining the flow of carbon from the atmosphere to the plants and into the soil.

The Maddox Family: Saving the Farm While Improving the Land

In 1986, Joe and Peggy Maddox were managing a 8,800 hectare ranch near Colorado City, Texas, and like many ranchers at the time they were financially desperate. They had been following the recommendations of the local extension service regarding livestock stocking rates. That year they had a $200,000 bill for synthetic chemicals, mostly to fight mesquite, but the mesquite persisted in abundance.

They then took a course with Allan Savory and began Holistic Planned Grazing and Financial Planning. They eliminated a major share of their expenses and most of the chemicals. They ran three to four times as many animals on the land but concentrated them in one herd and moved them weekly. It was six months before the herd came back to any paddock after it had been grazed. Within three years, the land was much better able to capture rainfall and the perennial grasses were coming back. Their income greatly improved and wildlife began to show up to take advantage of the ponds and streams emerging from the land. The Maddox family often had open houses and shared what they were learning (Laurie, 1997).

Joel Salatin & Restoring Topsoil

Joel Salatin's family has been grazing in Virginia's Shenandoah Valley since 1960. Estimates of soil lost after plowing began range from 3 to 8 feet. When

Salatin's father began grazing, there were areas of bare shale rock as extensive as 100 feet in diameter. In 2000, after 40 years of grazing, the largest of these rocky galls had been reduced to a few feet in diameter. By 2010, he can't find any of these areas with less than 8 inches of new soil. He is making a case for 8 inches of soil created within a decade using a grazing plan with high-density herd impact followed by ample recovery time. (Salatin 2010:2-5)

Walt Davis & Dung Beetles

Walt Davis is a rancher in southern Oklahoma. When he stopped using insecticides in 1975, he noticed within a year that dung beetles were burying his cow pads. Over the years his dung beetle populations have increased, and by 2000 there were 5 species of dung beetles on the ranch.

Patricia and Dick Richardson visited the Davis Ranch in the 1990s and discovered that dung beetle activity increased the soil's water infiltration by over 120%. They also estimated that dung beetles were capable of burying 2.5 tons of wet manure per hectare per day. Over 1000 dung beetles were seen on single dung piles. The potential to transport tons of organic matter into the soil is significant.

In 1975, Walt could find no earthworms in his pasture soils. Over the next decade, in areas where he observed concentrated dung beetle activity, he also began to see earthworm castings. At a 1996 field day at the ranch, he dug large core soil samples from a number of these pastures and counted 12 to 30 earthworms per cubic foot. Today, at several sites on the ranch, harvester ants have built their mounds out of earthworm castings. We like to think of this type of reuse as a most elegant sign of rangeland health (Richardson and Richardson, 2000).

It may be that dung beetle activity was necessary to bring organic matter into the soil before earthworms were viable on the Davis Ranch. Water is also affected:

> We have compared water infiltration rates where a cow pad has been buried by dung beetles vs. no cow pad on a variety of pasture and soil conditions. We find on average a 129% increase in infiltration rate over control (Table 1). An extra inch (25 mm) of rainfall absorbed per acre means the addition of 27,225 gallons/acre (254,530 l/ha) of water in the soil, reducing the detrimental effects of either drought or flood years (Richardson and Richardson, 2000).

The many benefits that dung beetles bring to an ecosystem (and to human enterprise) are substantial: improved soil health and reduced runoff, increased pasture productivity, reduced infection of livestock by parasitic worms, reduced fly pests and human disease, reduced greenhouse gas emissions, and economic benefits (extensive references at http://dungbeetle.org.nz/benefits/).

Table 2. Greg Judy's Example of Soil Creation: Calculating Soil Organic Carbon (SOC)

If we assume a soil bulk density of $1.0 g/cm^3$:

$$1\ g/cm^3 \times 10^8\ cm^2/ha \times 7.5cm = 7.5 \times 10^8\ gm\ soil/ha = 750\ t\ soil/ha$$

$$\times 0.045\ SOC = 33.75\ t\ SOC/ha$$

Dividing by 4 years yields a SOC annual increase of 8.4 t/ha. For further explanation of these calculations, see "Calculating Soil Carbon Sequestration Potential," below.

Greg Judy and Earthworms

Greg Judy owns and leases several farms in central Missouri. He has written extensively about his work grazing cattle, sheep, goats, and pigs. Yet he considers his most important "livestock" resource to be earthworms. Judy's goal is 25 earthworms per square foot, which he estimates would yield annually 250 tons/hectare of worm castings at no expense. Many of Judy's fields now have worm densities of 17 per square foot.

Earthworms are of key importance to healthy soils. Their burrows, which may be mainly horizontal or vertical depending on species, can be extensive. As they work their way through the soil they disperse litter from the surface and may move biomass up to several meters deep, spreading nutrients and providing easy passage for root growth (Brady 2002:459-462).

Judy's grazing strategy, built on HPG, is very high density animal herds grazing in a paddock for one day and then moved to the next paddock. The goal is for animals to consume a third to half the grass in the paddock and to trample the rest into the soil. This feeds his earthworms and soil microbes (Judy 2008:231-237).

A critical point is that he does not use de-worming agents and other chemicals that will poison soil biota such as dung beetles, whose beneficial impact is significant. Dung beetle holes help create paths for earthworm activity and other soil creatures, and the dung dried out by beetle activity and taken below ground reduces the fly populations.

Based on soil depth measurements, Judy estimates that his grazing practice has built 7.5 cm of soil in many fields in 4 years. The trampled grass, animal manure, and worm casting mix becomes a very rich layer of topsoil. The dry matter of worm castings are typically 70% organic matter and 30% minerals. Estimating the SOM of this new soil at a very conservative 8%, the SOC would be at least 4.5% or over 8.4 t/ha (Table 2).

In addition to earthworms, the activities of dung beetles carrying animal dung balls down as much as 1 meter and the increased flow of sugars from healthy plants to support microbial communities will also increase soil organic matter and therefore carbon. Conventional soil science, which does not generally assess capacity of new biologically created soils, considers 2.5 tons of carbon sequestered per hectare each year to be significant, but the true soil carbon sequestering potential may be much larger (Judy 2011:45"-60").

Abe Collins, The Keyline Plow and Prairie Dogs

Abe Collins is a grazier in Vermont who runs dense herds and moves them once or more daily using electric fencing. He observes directly how this builds healthy soils. He says:

> As the cattle graze, they cream - eat the top third of the plants - and trample. The large amounts of plant material left behind form a mulch layer, which encourages fast regrowth, preserves soil moisture and helps build soil organic matter. (Behling, 2009).

Collins has seen several inches of organic matter develop in his soils within a few years, and he has been communicating with several universities to study this soil building process. There is interest, but he has been asked to provide several million dollars to fund the research, a sum not readily available to an innovative small farmer. That agribusiness interests are now doing the preponderance of soil research is a serious barrier to soil improvement, but beneficial to the corporate bottom line: poor soils will require ever more chemical inputs to produce crops.

Collins has also used the Keyline system, an approach to sub-soil contour plowing that can rapidly increase the depths at which soil biota are active (Yeomans Plow, n.d.; Keyline Vermont, n.d.). From a whole-system perspective, however, this technology is only a proxy for the essential impact of burrowing mammals, many of which have been eliminated as a result of modern agricultural and rangeland practice. Burrowing mammals and their predators must be considered within the context of holistic planning.

The digging and churning activities of these animals enable the capture of far more rainwater on capped soils, and begin eco-restoration in areas where it is difficult to bring livestock on a regular basis. Prairie dogs and moles were once numerous in North America when our soils were much deeper. Similarly in Australia, there were once many more small marsupials such as potoroos and bettongs, which broke up the waxy surface caps of soils in their search for truffles. They may well be critical to the hydrology of Australian land and to the reduction of wildfires in a warming climate (Maser et al., 2008:45-49).

At Janos Preserve in the Mexican Chihuahuan Desert, there are thousands of prairie dogs and very few mesquite or juniper trees. Healthy stands of grass predominate and some grazing of livestock and buffalo occurs.

> The black-tailed prairie dogs are vital to this grassland system as ecosystem engineers that create habitats for other plants and animals through their

burrowing activities. They are herbivores and also serve as prey for other animals creating an important link in the food chain. The threatened status of these prairie dogs causes a cascade of effects throughout the grassland ecosystem (Nature Conservancy 2010).

In Texas, many millions of dollars are spent to control mesquite and to eradicate prairie dogs as enemies of the grass. Prairie dogs at Janos, however, will chew at the mesquite roots, constantly impeding their growth. They want a better view of the landscape looking for predators like hawks and coyotes. It may be that prairie dogs are critical to the return of grasslands in relatively dry and brittle landscapes. A single prairie dog town in Texas was the size of Maine and contained an estimated 400 million animals. This was at a time when the grasslands were much healthier than now. One hundred forty species of wildlife benefit directly from prairie dog towns including large grazing animals, predators, small birds, mammals, reptiles, and insects (Williams 2008:33-37). Prairie dog dens are dug as deep as 3 to 4 meters, making pathways easier for all the other soil biota from worms and beetles to fungal mycelia seeking minerals (Outwater 1996:67-83).

Pasture Cropping: A Regenerative Solution from Down Under

Since the late 1990s, Australian farmer Colin Seis has been successfully planting a cereal crop into perennial pasture on his sheep farm during the dormant season using no-till drilling, a method that uses a drill to sow seeds instead of the traditional plow. He calls it pasture cropping and he gains two crops this way from the land—a cereal crop for food or forage and wool or lamb meat from his pastures. Its potential for feeding the world in a sustainable manner is significant.

Today, over 2,000 farms practice pasture cropping across Australia and many more worldwide. The practice is spreading for several reasons: high crop yields; sustained high pasture and animal production from cropped land; increased fodder for livestock; high rates of carbon sequestration; marked improvement in the water-holding capacity of the soils; improved nutrient cycling; increased biodiversity and resilience, even in drought; greatly reduced input costs and risks; improved economic return from the vertical stacking of enterprises; and improved happiness quotient on the farm.

Capture and Storage of Atmospheric Carbon in Grassland Soils

Factors in soil carbon storage

Soil organic carbon (SOC) compounds, which constitute approximately 60% of soil organic matter (SOM), have beneficial effects on the chemical, physical and biological functions of soil quality (Bardgett 2005). SOC increases water-holding capacity, and contributes to soil structural stability. Organic matter increases adsorption of nutrients, cations and trace elements that are of importance to plant growth, prevents nutrient leaching and is integral to the organic acids that make minerals available to plants. It also buffers soil from strong changes in pH. Consequently, it is widely accepted that the C content of soil is a major factor in overall soil health, plant production, the health of water catchments and, central to this discussion, a sink for atmospheric C to offset climate change (Charman 2000; Lal 2008).

The manner in which land is used and managed affects the soil's ability to sequester and retain organic C. Practices that increase plant productivity and C inputs to the soil and those that decrease soil exposure to erosion and exposure to sunlight allow higher levels of C to accumulate in the soil (Parton 1987).

Soil carbon storage, whether as root biomass, associated microbes, or soil organic matter, is sensitive to climatic conditions such as rainfall and temperature. Temperate grasslands will store more carbon, although all grasslands will show improvement with managed grazing. Organic carbon content of cool temperate grasslands is higher than that of tropical savannas, largely because of high night-time respiration in hot climates. There will be benefits for all such habitats, but some areas will be more effective than others at storing carbon. For example when tropical savanna soils are compared to temperate grassland soils, the cooler soils are found to have much higher soil organic matter, higher soil carbon to plant biomass carbon ratios, and storing carbon for longer than warmer grasslands (Baldock & Bruce, 2012). High nighttime respiration and decomposition is thought to be the cause of inefficient carbon storage in warmer soils.

In rangeland ecosystems, maintaining normal soil function and ecosystem health is only possible if adequate plant and litter cover is present to provide protection from soil loss and to allow soil microorganisms to perform optimally (Thurow 1991; Rietkerk 2000; Bardgett 2005). Plant and litter cover enhances infiltration, buffers soil temperatures and decreases evaporation so that soil moisture is retained for longer after each precipitation event. This enhances soil microbial activity, which promotes soil aggregate stability, sustains nutrient availability and plant nutrient status, improves plant growing conditions, and results in the incorporation of more organic matter into the soil.

The amount of bare ground is a good indicator of soil function and erosion risk (Thurow 1991). Bare ground is not protected from the sun and gets much hotter than covered soil, causing a decrease in microbial activity, accelerated loss of organic matter, and the erosion risk increases if there is insufficient cover to dissipate the energy of raindrops before they strike the soil (Blackburn 1975; Blackburn 1986). Elevated soil temperature and soil loss have a direct negative effect on infiltration rates, water evaporation from soil, nutrient retention and biological functions that contribute to ecosystem function (Neary et al. 1999; Wright and Bailey 1982).

Mycorrhizal fungi play an important part in facilitating sequestration of soil C. They access the mass of soil volume and increase availability of water and nutrients, thereby increasing plant productivity (Bardgett 2005). Consequently, management of the soil to achieve C sequestration goals requires carefully managing plants to reach their full potential.

Carbon measurements in soils.

A variety of estimates of organic carbon in soils, as well as the extent of loss of carbon through transformation of forests and grasslands into croplands, may be found in the mainstream soil science literature. Rattan Lal estimates that the total carbon in the soil measured to a depth of one meter is about 2300 gigatons (Gt), comprising approximately 1550 Gt of SOC and 750 Gt of SIC (soil inorganic carbon, i.e., carbon
primarily from weathered and eroded rock). Hiederer (2011:50) estimates global SOC at 2469 Gt (Figure 13).

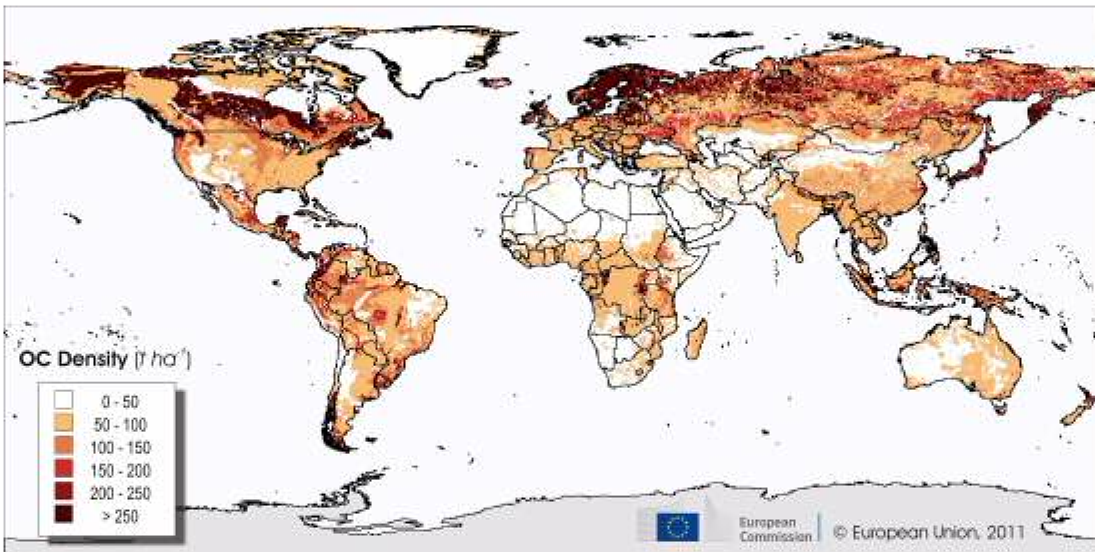


Figure 13: Soil Organic Carbon Density (Hiederer 2011:50)

In estimating the amounts of SOC, it is important to note the depth of the soil samples because reports of SOC measurements vary considerably, as do estimates of carbon-storing potential, based on depth. In many studies soils are only measured to depths of 30 cm., which underestimates SOC capacity by a large margin. For example, The magnitude of SOC is estimated at 684 to 724 Pg [1 Petagram = 1 Gt] in the 0- to 30-cm layer, 1468 to 1548 Pg in the 0- to 100-cm layer and 2376 to 2456 Pg in the 0- to 200-cm layer (Lal 2001:4, citing Batjes 1996).

And

The topsoil layer (0-10 or 0-30 cm) SOC stock comes to 967.3 *Gt* C and the subsoil layer to 1,502.2 *Gt* C. The subsoil layer thus contains about 1.5 times the amount of OC of the topsoil. (Hiederer 2011:50).

It is crucial to note that in our measurements we may not have explored soils nearly deep enough to have an adequate understanding of the extent of carbon soil sequestration possibilities. As much as three-quarters of the mass of plants is below ground. Roots grow to well over 2 meters in depth, with interesting and complex interrelationships among different life forms—grasses, forbs, and shrubs (e.g., Weaver 1950; Richards and Caldwell 1987). Thus, assumptions about the ability of soil to store carbon may vary by greater than threefold depending on soil depths sampled in a study, especially considering that deeper stores of carbon are more stable and removed from the cycling carbon pool for hundreds or thousands of years. These differences take on even greater significance in restoring degraded and desertified rangelands over a period of years, since deep-rooted grassland plants may store carbon to depths of greater than 2.5 meters (Nippert 2012:4; Brady 2002:215) to almost 5 meters in depth (USDA 2008:5).

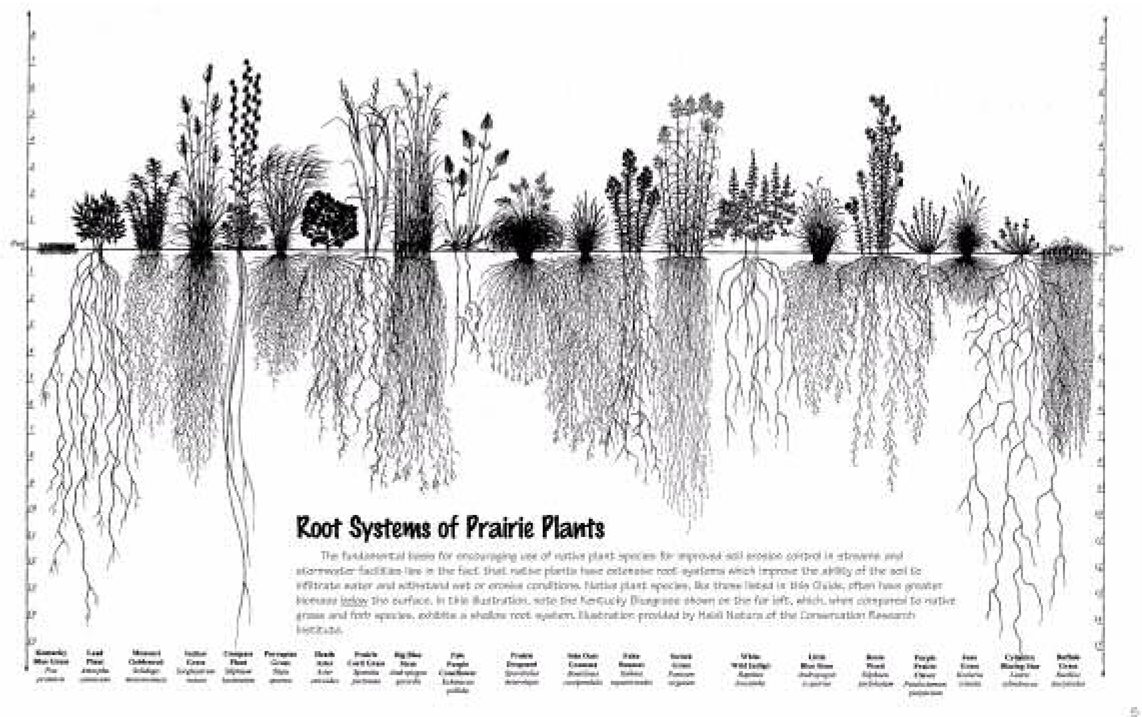


Figure 14. Illustrating the deep root systems of many prairie plants; they create porous soils and interact in complex ways with soil biota, including creating long-lived stores of carbon in complex biomolecules (USDA 2008:5).

The Case for Soil Neogenesis

Another conventional assumption that is open to question leads to a potentially dramatic underestimation of SOC storage capacity in assessing sequestration potential with respect to global warming. That is, that the only soils available for restoration are those that already exist; any additional soil will be of geological origin - which accumulates only slowly, over thousands of years.

Some investigators assume that soils have a limited carbon sequestration capacity. Follett et al. (2001) assert that "turnover time of 25 years is necessary for achieving a practical upper limit for C sequestration in soil" (Follett:404). Jones and Donnelly (2004) estimate that ". . . time to saturation range from 10 yr (Janzen et al. 1998) to 100 yr (Potter et al., 1999), but other models of SOC dynamics predict that soil C stocks can, in theory, be increased without limit (Six et al., 2002)" (Jones and Donnelly 2004:428). Both estimates, however, effectively remove new soil creation from the equation and thereby underestimate soil sequestration capacity by an unknown but potentially significant magnitude.

Thus soil creation of biological origin, which can be rapid, remains unaccounted for in these analyses. Christine Jones notes that

> the rates of soil formation provided in the scientific literature usually refer to the weathering of parent material and the differentiation of soil profiles. These are extremely slow processes, sometimes taking thousands of years.
>
> Topsoil formation is a separate process to rock weathering and can occur quite rapidly under appropriate conditions. In fact, soil building occurs naturally in most terrestrial habitats unless reversed by inappropriate human activities . . . (Jones 2002:3)

Jones cites examples of rapid soil accumulation:

> The late P.A. Yeomans, developer of the Keyline system of land management, . . . was able to produce 10 cm of friable black soil within three years, on what was previously bare weathered red shale on his North Richmond farm (Hill 2002).
>
> Bennett (1939) calculated a rate of topsoil formation of just over 11 t/ha/yr for soils in which organic material was intermixed into surface layers. In situations where plant root mass is high, rates of topsoil formation of 15-20 t/ha have been indicated (Brady 1984). Healthy groundcover, high root biomass and high levels of associated microbial activity, are fundamental to the success of any technique for building new topsoil.

. . . If the land management is appropriate, evidence of new topsoil formation can be seen within 12 months, with quite dramatic effects often observed within three years (Jones 2002:3).

Historical data on loss of soil organic matter (SOM).

The extent of historic loss of SOC since the advent of agriculture ranges from 40 Gt to 537 Gt, the wide variations being "attributed to differences in methods used, variability in the available data, and the baseline used as a reference point" (Lal 2007:945). On the high end, Buringh et al. (1984) estimate that the amount of organic carbon in soils, -- carbon in complex molecules formed by living things -- is approximately 1477 Gt. This is roughly 537 Gt less than total organic carbon in soils in prehistoric times, "or 27 per cent of the amount present prior to the spread of civilization in the last two millennia" (Buringh 1984:91).

Rattan Lal's estimates are lower. He states that the "maximum sink capacity of the world soils, equal to the historic carbon loss (78 +/- 12 Pg C), is substantial and must be included among the possible strategies of stabilizing atmospheric CO_2 at a desired level" (Lal 2008:113A). Note that Lal's assertion of limited carbon sequestration capacity seems to assume that there is no biological accumulation of soils. Elsewhere Lal estimates that there is considerably more soil carbon lost (456 +/- 5 Gt), but does not seem to consider the major part of it replaceable (Lal 2004: 1625):

Table 1. Estimates of pre- and postindustrial losses of carbon from soil and emission from fossil-fuel combustion. Data were compiled from diverse sources (*1*–*3*). Ruddiman (*1*) estimated the emission from land-use conversion during the postindustrial era at 0.8 Gt C/year for 200 years at 160 Gt C.

Source	Historic carbon emission (Gt)	
	Preindustrial era	
Fossil-fuel combustion		0
Land-use conversion at 0.04 Gt C/year for 7800 years		320
	Postindustrial era	
Fossil-fuel combustion (since 1850)		270 ± 30
Land-use conversion		136 ± 5
Soil cultivation	78 ±12	
Erosion	26 ± 9	
Mineralization	52 ± 8	

If, for the sake of argument, we accept Buringh's 537 Gt number for the historic loss of carbon from soils, it is the equivalent of 218 ppm that was once safely stored in the ground instead of in the atmosphere, and is roughly twice the excess carbon that we've injected into the atmosphere since 1750 (half of which was absorbed by the ocean and other carbon sinks). We need only put 224 Gt (112 ppm) back into the ground, even though a percentage of the excess didn't come from soil, it's from our burning of fossil fuels. **To emphasize, *replacing just half of the soil carbon we have lost in the past ten thousand years has***

the realistic potential for reducing atmospheric carbon to a pre-industrial 280 ppm, presumably restoring a relatively stable climate. Note that in so doing we would also sequester *all* past and current emissions from fossil fuels.

Such discrepancies in estimates of lost SOC are of concern when proposing a strategy for sequestering over 200 Gt of carbon in soils, as we are doing here, and we will address this issue in the "Calculating Soil Carbon Sequestration Potential," below. For the moment, suffice it to say that it is reasonable to propose that carbon, which was once stored in the soil in what was but a moment ago in geological terms, could be stored there once again by employing effective animal and soil management approaches.

That changes in land use have induced soil carbon loss is well known:

> Soil carbon stocks decline after land use changes from pasture to plantation (−10%), native forest to plantation (−13%), native forest to crop (−42%), and pasture to crop (−59%) (Guo and Gifford 2002:345).

Practices such as HPG, MIG, and pasture cropping reverse the most significant of these land-use changes: they can return degraded croplands to pasture, and even more significantly, desert to pasture, thereby storing significant quantities of carbon in the ground, all the while restoring communities, economies and production.

Calculating Soil Carbon Sequestration Potential

Soils are created through geological and biological processes. Geological soil generation is primarily the weathering of rock that removes carbon dioxide from the atmosphere by wearing down rocks and limestones over millennia. Biological soil generation is the combining of plant litter and animal dung and the action of myriad soil life forms to create soil. Under proper management, biological processes can add an inch or more of soil per year, and turn 2.5 tons or more of atmospheric carbon into stable complex biological compounds per hectare, compounds that stay in the ground for centuries or millennia.

There is mainstream scientific research that supports restoring soils for carbon sequestration, even without restoring nature's grazer/grassland co-evolutionary relationship. For example, a five-year study of grasslands planted with switchgrass for use as biofuels demonstrated that soil carbon could increase by more than 1.7 tons per acre (4.25 tons per hectare). This was on conventional farmlands *without* the added benefit of grazers and the diverse assortment of animals, insects and fungi that capture significant additional quantities of carbon dioxide (Liebig 2008).

The Rodale Institute in Pennsylvania has conducted the longest running U.S. study comparing organic with conventional farming. Its results: "organic systems have shown an increase of almost 30 percent in soil carbon over 27 years." Furthermore, "During the 1990s, results from the Compost Utilization Trial (CUT) at Rodale Institute—a 10-year study comparing the use of composts, manures and synthetic chemical fertilizer—show that the use of composted manure with crop rotations in organic systems can result in carbon sequestration of up to 2,000 lbs/ac/year. By contrast, fields under standard tillage relying on chemical fertilizers lost almost 750 pounds of carbon per hectare per year. Storing—or sequestering—up to 2,000 lbs/ac/year of carbon means that more than 7,000 pounds of carbon dioxide are taken from the air and trapped in that field soil." (LaSalle 2008) The Rodale study shows sequestration of up to 1 ton of carbon per acre, again even without employing the essential evolutionary relationship between grazing animals and grasslands.

A third example shows that perennial pasture on sandy soils in Western Australia can sequester 5 to 10 T CO2e per hectare per year, or approximately 0.5 to 1 T C / acre (Wiley et al. 2013). The authors write that there is mixed grazing with non-grazing and that there was below average rain during the trial period.

With respect to soil characteristics (Jones 2002:5), Mineral soil has a higher bulk density (is more compact) than living soil, and is far more easily eroded. Soil loss figures usually assume an average bulk density (weight per unit volume) of around 1.4 g/cm^3 (Edwards and Zierholz 2000). If one millimetre of soil is eroded (about the thickness of a 5-cent coin) that represents about 14 t/ha soil loss.

When new topsoil is forming, it will have better structure and will contain more air and more pore spaces than degraded soil, so the bulk density will be less. That is, a given volume of new topsoil will weigh less than an equal volume of non-living mineral soil.

The bulk density of healthy topsoil may be as low as 0.5 g/cm^3. In practical terms, a one millimetre increase in the height of new soil would equate to the formation of around 5 to 10 t/ha of organically enriched topsoil.

For calculation purposes, using a mid-point of soil densities we can make a reasonable assumption of bulk soil density in healthy, newly created biological soils of 1g/cm^3.

Since there are 1×10^8 cm^2/ha, to a depth of 1 cm we have 1×10^8 g of soil per hectare, or 100 t/ha. SOM will vary according the characteristics of the soil. SOC is generally estimated at 58% of SOM (Lal 2001:4), which we will use in our examples; Jones says that the range is from 50%-62% (Jones 2013). If we reasonably calculate that 1% of total topsoil weight is composed of SOM (Troeh 2005), then the weight of SOC will be:

Total Weight of Soil	x	% Soil Organic Matter (SOM)	x	% Soil Organic Carbon (SOC)	=	Weight of SOC per cm of soil depth
100 t/ha	x	.01 (1%)	x	0.58 (58%)	=	0.58 tC/ha/cm

Table 3. Calculating weight of soil organic carbon per centimeter of soil depth.

To calculate the quantity of carbon captured from the atmosphere and stored in organic molecules in the soil in terms equivalent to those used by climate advocates, the equivalent formula is expressed as follows:

Total Weight of Soil	SOM as a percent of total soil weight	x	SOC 58% of SOM in this example	x	Soil Density in g/cm^3	x	Depth in cm.	x	Billions of Hectares	=	Total Weight of Carbon in Soil in Billions of Tons (Gigatons, Gt) per Billion Hectares
100 t/ha	.01 (1%)	x	0.58 (58%)	x	1	x	30	x	1	=	17.4 Gt C

Table 4. Calculating carbon captured in soils from atmospheric carbon dioxide, in gigatons per billion hectares, for the first 30 cm of soil depth.

That is, at a conventional soil measurement depth of 30 cm, we would have a total soil carbon weight of 17.4 Gt C captured per billion hectares, or in terms of atmospheric carbon dioxide, a value of 8.7 ppm. How long it would take to store 8.7 ppm depends on how quickly we are able to restore degraded soils and create new soils, and that will vary across climate and soil types. Keep in mind that there are an estimated 5.25 billion hectares of grasslands worldwide (Suttie et al. 2005: Ch. 1) that would, in theory, be candidates for significant improvement and restoration.

These calculations may well underestimate soil carbon storage potentials because it does not account for the greater and more stable carbon accumulation in the soils, up to 5 meters deep, which is created by the interactions of plant roots, mychorrhizal fungi, bacteria, small mammals and insects as the health of the land returns.

Here is an example of applying the formula above to a different set of numbers, a soil which, at 100 t/ha, with 2% increase SOM of which 58% is SOC, at a density of 1.2 g/cm^3, 60 cm deep over 3 billion hectares of grasslands would yield storage of approximately 250 GtC:

Total Weight of Soil	SOM as a percent of total soil weight	x	SOC 58% of SOM in this example	x	Soil Density in g/cm^3	x	Depth in cm.	x	Billions of Hectares	=	Total Weight of Carbon in Soil in Billions of Tons (Gigatons, Gt) per Billion Hectares
100 t/ha	.02 (2%)	x	0.58 (58%)	x	1.2	x	60	x	3	=	~250 Gt C

Table 5. Example of calculating atmospheric carbon sequestered in soils with 2% soil organic matter to a depth of 60 cm over 3 billion hectares.

Note that sequestration of 250 Gt C is equivalent to 125 ppm, or approximately 62.5 times the carbon currently added to the atmosphere annually.

The 5-Billion-Hectare Potential

If we were to capture 2.5 tons of carbon per hectare per year on the roughly 5 billion hectares of target grasslands worldwide, we would remove 12 Gt of C from the atmosphere per year, that is, 6 ppm annually. If gross soil sequestration is approximately 6 ppm/year, after subtracting current net annual carbon emissions of 2.5 ppm/year net sequestration would be 3.5 ppm per year.

In principle this returns us to pre-industrial atmospheric CO_2 levels in less than 40 years. How realistic these numbers are is unknown, since the bases for them have yet to be tested. Nor does it yet take into account how to address potential pulses of carbon from melting permafrost and seabed sinks. However, it is apparent that beyond the current limited conventional perspective on soil sequestration of carbon, the potential may indeed be promising.

Ruminant Methane

The issue of ruminant methane emissions is frequently raised in discussions about grazing. Methane from livestock has been estimated to be approximately 22% of anthropogenic methane emissions in 2005, or 67.6 million tonnes out of a total 313 Mt (Hoglund-Isaksson 2012). Hristov (2012:2) estimates that historical emissions from wild herds before European settlement in the United States was 86% of current emissions. It is reasonable to infer that this estimate applies more generally across the world. If such is even close to the case, given that pre-industrial atmospheric methane did not exceed 788 parts per billion by volume (ppbv) for 650,000 years, and were at 600 ppbv or less for most of that period (Spahni:55), we may justifiably conclude that ruminant methane emissions were balanced by natural methane decomposition processes.

Livestock's Long Shadow (UN FAO 2006:86) points out that:

The respiration of livestock makes up only a very small part of the net release of carbon that can be attributed to the livestock sector. Much more is released indirectly by other channels including:

- burning fossil fuel to produce mineral fertilizers used in feed production;
- methane release from the breakdown of fertilizers and from animal manure;
- land-use changes for feed production and for grazing;
- land degradation;
- fossil fuel use during feed and animal production; and

- fossil fuel use in production and transport of processed and refrigerated animal products.

Except for the use of fossil fuels in final product processing and transport, HPG and MIG incur none of those burdens, and in fact reverse most of them. Furthermore, there is evidence that better animal management will reduce methane production (DeRamus et al. 2003:269):

> Projected CH_4 annual emissions in cows reflect a 22% reduction [resulting] from BMP [Best Management Practices] when compared with continuous grazing in this study. With the BMP application of MIG [Management-Intensive Grazing], less methane was produced per kilogram of beef gain."

Green plants also emit methane, most likely from methane gas dissolved in water and released during transpiration (estimates from 4 to 38 Mt/year), up to more than half that emitted by ruminants. As there is no known active methanogenesis under aerobic conditions, "the emission of methane by plants is therefore a passive consequence of other physiological processes" (Nisbet 2009:6).

Microorganisms that break down methane (methanotrophs) live in healthy soils but they are destroyed by artificial nitrogen fertilizers and pesticides. Other mechanisms of methane decomposition as yet undiscovered likely exist. The steady planetary methane levels over the past 650,000 years attest to that, and it is highly unlikely that any significant fraction of the post-industrial methane spike is attributable to livestock. The important understanding here is that intact ecosystems work in ways that we still understand only poorly, and the best we can do to reverse the damage that civilizations have wrought is to regard ecosystems as wholes far greater than the sums of their parts, and proceed accordingly.

Carbon Calculation Summary

In closing, we note that our soil carbon sequestration calculations are based on the following assumptions, which are admittedly speculative at the current time:

- Biological restoration of crop, pasture, and rangeland soils will sequester carbon deep in the ground every year worldwide;
- The average carbon sequestration over a wide variety of soils and climate worldwide may approximate 2.5 t/ha.

Furthermore, we are sidestepping global and social and political issues for the moment, assuming that it will be strategically possible to mount a massive effort to restore billions of hectares of grasslands in a relatively short period of time. Whether global political will can overcome longstanding preconceptions about land management, even when conventional approaches carry great risk, remains to be seen. We reiterate, however, that current emissions reduction efforts have proved fruitless to date and to hold limited promise, and that grassland restoration has the potential to bypass much of the resistance faced by traditional climate efforts.

Finally, it is important to note that we have not calculated the impact of positive feedbacks such as melting Artic summer ice, seabed methane emissions and destruction of forests by accelerated reproductive cycles of predatory insects such as pine beetles (to name but a few). This has been common practice in climate science, and has been a widespread source of underestimation of climate change impacts. This source of error in mainstream studies is likewise a source of error in the calculations here (Torn & Harte 2006; Steinacher 2013). Consequently, the progress of climate degradation is quite possibly further along than many estimate. Nonetheless, we believe that our assertions about grassland management remain valid: there is no better way to store carbon, at so little expense and with so many potential benefits.

Reconciling the Perspectives of Advocates for Climate Action and Practitioners of Planned Grazing

Unfortunately at this point in time most climate advocates are resistant - often fiercely so - to the use of grazing animals, particularly livestock, to sequester carbon in soils. There are several reasons for this: misunderstanding of the capacity of soils to sequester carbon; lack of awareness of the extent of carbon emissions from soil loss through human activity over millennia (Ruddiman 2003); current dogma about the damage inflicted by livestock (United Nations Food and Agricultural Organization 2006); and the almost exclusive attention to emissions reductions.

Furthermore, exchange of information among climate advocates and rangeland managers is complicated because supporting evidence from the grazing community is in a form unfamiliar to climate activists and scientists, who are accustomed to direct measurement of atmospheric carbon, and who therefore may find it difficult to grasp how effective soil carbon sequestration can be. Climate advocates feel the need for "hard" numbers and a definitive answer to just how much carbon sequestration we can expect grazing herds to accomplish.

Given the diversity of climatic, edaphic (soil-related) and topographic features that structure plant communities on landscapes and the influence that has on fixing carbon, no one knows for sure how much carbon can be captured through managing cropping, pastures, and rangelands, but people are actively working to determine those amounts (Donovan n.d). Regardless of the exact amounts of carbon that can be fixed in soil through managed grazing, changing farming and grazing practices is valuable ecologically, economically, and socially. It is important to build the health of soil, the diversity of plants and animals, and the welfare of the ecological communities we inhabit and upon which we depend for life.

One reason that carbon soil measurements in holistically managed lands have been limited is that ranchers view soil very differently from climate advocates. What is important to Holistic managers is the visible and functional health of the soil that they restore and maintain. In other words, direct measurement of carbon in a handful of healthy dirt - brimming with microbial, fungal, green plant, insect and animal life - is, in practical terms, far less important to ranchers than it is to those immersed in issues of climate. Here are some of the questions ranchers ask (all of which are eventually answered in the affirmative with properly managed grazing land, and are directly related to the quantities of carbon captured in the soil):

- Is the plant life vigorous and diverse, and are perennial grasses reappearing with roots that penetrate up to 5 meters deep into the ground (USDA 2008)?
- Is there good soil moisture content, do streams and ponds have water even during a drought?
- Are the dung beetles, earthworms and other soil organisms present and functioning in a productive manner?
- Is the diversity of wildlife returning?
- Is the soil turning black (the color of carbon), soft and sweet from biotic activity?
- Is there less need for winter hay because healthy land in combination with planning provides more options for dormant season sustenance of the livestock?
- Are the animals healthy, less prone to disease and parasites?
- Are people more productive with less work, are our lives happier and more secure?

The bottom line for climate advocates, on the other hand, is that there's less carbon in the atmosphere. Unfortunately for communication purposes, SOC measurements are relatively new in HPG circles, since soil, animal and human health and productivity - not carbon sequestration - have been HPG's primary concerns.

Experienced ranchers know when soil is full of carbon just by holding it in their hands. Those observations do not qualify as "hard" data, but it is those kinds of observations that blaze trails into new areas of knowledge and application, and begin to turn paradigms on their head. In other words, to practitioners of HPG quantitative measurements of C are irrelevant to their task: growing healthy, high-functioning animals and optimal maintenance of the land that feeds them are of utmost importance. The difference in worldviews between climate and rangeland contingents is another example of the tension between quantitative and qualitative approaches to science, respectively.

In order to understand how this process applies to addressing global warming, climate advocates will have to adjust their preconceptions to include the following considerations:

Grazing animals, including goats, sheep, and cattle, are ***essential*** *to healthy lands and climate restoration*. They are part of the solution when raised in accordance with nature's rules, not part of the problem the way they are when raised on factory farms or grazed continuously on large tracts of land.

In nature, everything is connected to everything else. We have to begin to understand that global warming is not a carbon or other greenhouse gas problem, it is a problem of how humans are living on earth -- and that we can learn to live well differently. There are no simplistic, linear, reductionist solutions, only complex dynamic systems ever transforming. Only by understanding wholes and transformation with the systems we inhabit can we address the loss of ecological integrity in systems upon which we depend for life.

There are several conventional assumptions in different mainstream disciplines that are obstacles to re-establishing the evolutionary grassland-grazer relationship for long-term sequestration of carbon in soils and restoring atmospheric carbon dioxide to pre-industrial levels. Each of these disciplines - climate science and advocacy, rangeland science, and soil science – has contributed its own prevailing and questionable assumptions, such as that:

- Grazing animals chronically overgraze rangelands and destroy soils and plants which must be "rested" to be restored;
- Climate action should focus on reducing emissions; livestock are destructive and contribute to emissions;
- Soils are a limited carbon sink, and new biologically generated soils are not part of the equation;
- Soil sequestration of carbon is only significant in the first 60 cm; and
- "The turnover time of 25 years is the time for achieving a practical upper limit for C sequestration in soil" (Follett 2001:404).

Collectively these assumptions create a mechanistic view of how the world works. They can be addressed readily by dedicated measurements of carbon in soil roots, mycorrhizae, bacteria and as soil humin through time as a function of management. Unfortunately the needed data are still scarce. Yet there is good evidence that proper management can restore biomass at much faster rates than have been assumed.

The number of scientific publications and observations we provide in this paper suggest an alternate paradigm is credible. We maintain that the current paradigm is preventing the implementation of management that shows widespread evidence of being able to more effectively restore ecosystem function on grazing lands. Furthermore, such ecosystem restoration will positively affect such fundamental biogeodynamics as carbon and water cycles and mitigate, quite possibly significantly, the extremely destructive anthropogenically generated atmospheric carbon burden.

The ultimate consideration is that, to date, global restoration of grazing lands is the one thing, so far *the only thing,* that shows any promise of reversing climate damage *at a scale commensurate with the scale of the problem*. While there are other potential methods for restoring carbon in soils, as outlined in this book, none have so many associated benefits, not the least of which is that managed grazing, by producing marketable animal and other products, generates income and food for local communities worldwide, requires minimal short-term investment after which it is self-supporting, needs no new or complex technology (little beyond optional portable electric fencing), and is sustainable in the long-term. Moreover it is culturally relevant throughout virtually all grassland contexts.

Figure 15. Young woman teaching Holistic Planned Grazing in an African village.

Conclusions

The main points in this paper are:

- Planned grazing can restore soils, and HPG has been the most broadly successful and widely implemented planned grazing approach to date;
- Soils are a prodigious sink that are inadequately assessed, and soil neogenesis is an important mechanism for storing carbon in soils;
- Current prevailing paradigms are impeding us from taking quicker, more effective restorative action

The authors take the perspective that:

- Nature functions as complex, interactive wholes, and humans can adequately manage only the holistic contexts. We cannot micromanage the details.

- Nature is self-organizing, and when all the elements of biodiversity are in place ecosystem health is the norm, not the exception. There have been significant changes in geophysical and biological contexts over the ages; nonetheless relatively stable states of ecosystem health have been the prevalent condition under which living creatures have thrived.

- Healthy soils are complex collections of interdependent life forms, and as a synergistic system soil activity may become seriously impaired when any of its elements are compromised or destroyed, as currently occurs worldwide with chemical agriculture, mismanagement of grazing animals, and over-rest of grasslands.
- Effective eco-restoration, of which HPG, MIG, and pasture cropping are all essential components, can restore geophysical cycles in grasslands and savannas, and have the potential to stabilize carbon in the atmosphere at around 280 ppm in a time and as a result significantly mitigate the damaging effects of global warming.

Since the advent of agriculture, humanity has been moving carbon out of the soils and into the atmosphere. We plow and leave agricultural land bare for much of the year, exposing soil life and humus to sunlight, desiccation and oxidation. On bare ground solar energy, necessary for plants to enable humification, is not harvested. Today we make matters worse by using nitrogen fertilizers, seriously inhibiting the flow of energy to fungi that make stable, carbon-sequestering molecules, and by stimulating growth in bacterial populations destructive to soil fungi.

In some circumstances, unnecessary use of fire also exposes bare ground, destroys organic soil matter, and emits massive amounts of carbon into the atmosphere. And of course, we emit vast amounts of geological carbon from burning fossil fuels, amounts unprecedented since the beginning of life on earth (DePaolo 2012). While these practices seemed like good ideas at the time, now we know that they are leading us to soil and climate catastrophe.

Today we are in the early stages of understanding the extent to which soils can sequester atmospheric carbon, and it is evident that far more data is needed for a comprehensive understanding of the conditions that maximize storage of soil carbon. Unfortunately, given the exigencies of climate change, it is necessary to act on removing carbon from the atmosphere immediately.

Therefore, we must rely on qualitative empirical evidence, which is unequivocal with respect to eco-restoration of grazing lands, as the basis for moving forward. Furthermore, outcomes of improper management of livestock and inadequate soils models have led us to underestimate significantly the potential of soil capture and storage of carbon for reversing climate change. Restoring the evolutionary relationship between grazing animals and their grassland habitat is an essential - and hopeful - part of the equation.

Climate advocates can learn to appreciate the potential of practices embodied in Holistic Management and Management-Intensive Grazing to reverse global warming, *but not within the framework of conventional climate thinking*. To some extent changing frameworks involves bridging the gap between quantitative and qualitative science, between observing wholes and isolating parts, and tempering the assumption that parts elucidate wholes.

To some extent parts do, in fact, elucidate wholes. But we forget, in our fascination with parts, and especially with the numbers that we can generate with our sophisticated experimental technologies, that the wholes are not only greater than the sums of their parts, but they are *qualitatively different* (just as the pigment green is different from its components, yellow and blue; or as carbon, oxygen and hydrogen combine to create millions of molecules that share few if any superficial characteristics and certainly look nothing like their elements).

We must learn once again to embrace the non-cognitive, intuitive, systems understandings of which we are capable. We have used such faculties successfully over tens of thousands of years, just as we have embraced the cognitive, rational, analytical facets of our nature during the past 400 years. In order to respond appropriately to currently disintegrating global ecosystems, our current quantitative framework will have to yield, at least in part, to an empirical grasp of wholes. As Peter Donovan has stated (personal correspondence, 2013):

[Indent this paragraph]
[T]he dynamics of the carbon cycle (circle of life) are NONLINEAR, that is, not a simple input-output system but one with numerous and complex feedback loops, not all of them understood. The possibilities for increased production as well as soil health are EXPONENTIALLY GREATER than linear models would allow.

When we begin to think in wholes, we can see carbon when we look at living things, we can feel carbon when we grab a clump of soil. As strange as it may seem from an experimental perspective, we know when carbon is in the ground and when it's not *just by looking*. A green biodiverse landscape is brimming with carbon dioxide transformed into the molecules of life, that biochemical square one, in the substance of trees, grasses, flowers and many other life forms. When the ecosystem is intact much of this carbon is stored deep in the soils. A bare landscape is doing none of this, and when left alone in a brittle (seasonal rainfall) environment it only gets worse.

We also know, from our study of carbon cycles, that *to the extent the global store of carbon is in the ground it's not in the atmosphere*, and vice-versa. Furthermore, we know that grazing animals can be used to create healthy soil and plants as much as healthy soil and plants create grazing animals. They are part of a complex and miraculous system that includes microbes, insects, fungi, grasses and forbs, birds and mammals, large and small. They all feed each other. They created the deep soil that we humans continue to diminish and destroy. We can and need to restore them using the most effective management we are capable of.

For now we've lost the huge wild herds that used to roam the plains, steppes and savannahs of the world, but livestock are herbivores too, and their function in ecosystems is the same as their wild relatives, *when they are permitted and encouraged to graze the way nature designed it*.

We post-industrial humans can create those soils again - after nearly a half century of experience we know how to do this. And we know, for a fact, that restoring the hectares we've destroyed can sequester the carbon that we've lost, potentially all of it. We know that because that's the way intact ecosystems work, observed through time immemorial, confirmed by qualitative science - and, as outlined in this paper, there is even supportive evidence from some experimental circles.

The challenge for climate scientists and activists will be to think more like rangeland herders, and to understand why people who graze animals don't care about carbon numbers. They must also learn that when we aim for the health and productivity of our life support systems, as wholes, the numbers will take care of themselves.

Finally, it is clear that there are obstacles to the extraordinary effort that will be necessary for successful soil-carbon sequestration. Steps to success will include changing the cultural mindset about the role of herbivores and soils in reversing global warming, the learning curve that new practitioners will have to master, the current shortage of expert teachers, gaining access to land, adequate numbers of animals, and equitable distribution of benefits.

Yet, despite daunting challenges and the uncertainties regarding precise quantities of attainable soil carbon levels, there are so many ecological, social and economic benefits that accrue from proper grassland management that we are well advised to pursue such eco-restoration with all due dispatch.

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