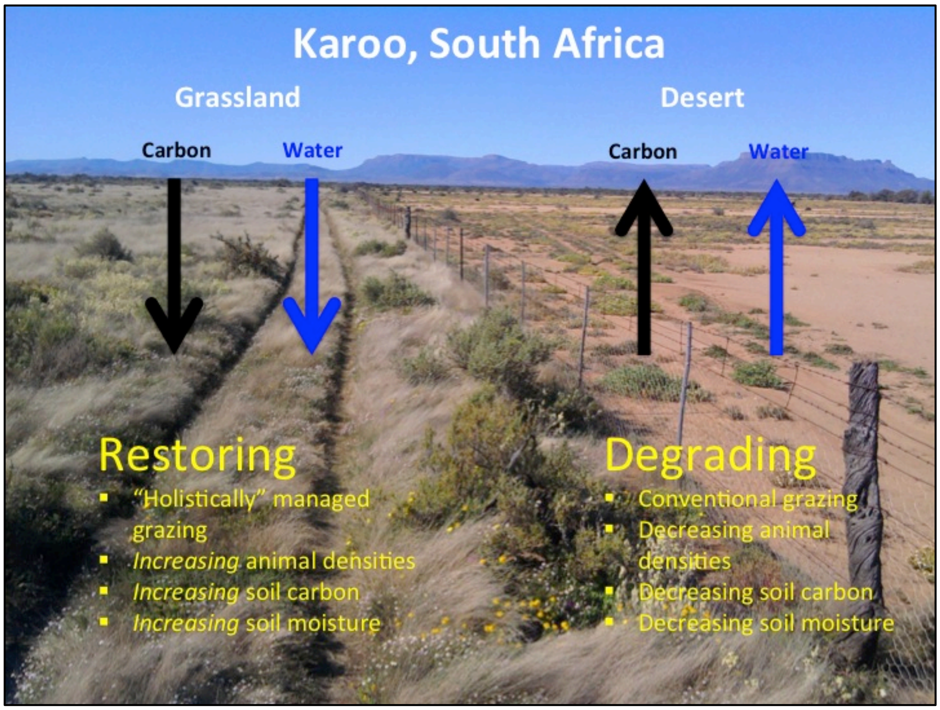
Upside (Drawdown)
The Potential of Restorative Grazing to Mitigate Global Warming by Increasing Carbon Capture on Grasslands

An Emerging Narrative



Seth Itzkan, © 2014
Planet-TECH Associates
240B Elm Street, Suite B1
Somerville, Massachusetts 02144, USA

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Trends, Innovations, Opportunites

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Beginnings

Statement of Need

The global warming crisis is forcing consideration of innovative and alternative approaches to climate mitigation and reversal. Simply going to a zero fossil fuel economy will not stop catastrophic consequences, even if such an about-face in energy use were achievable. At our current level of 400 ppm atmospheric CO_2, we are already well beyond what has been deemed the maximum safe level for human habitation, 350 ppm (Hansen, 2008). Indeed, recent anomalous weather and warming related events, including the unexpectedly rapid loss of arctic sea ice (Maslowski, 2012), may indicate that "amplifying feedbacks" are already underway (Glikson, 2013; Torn & Harte, 2006). This situation, unfortunately, is not likely to be remedied with a simple return to 350 ppm. Doing so may only slow warming to the rate it was at in 1988, when it was last at 350 ppm, and evidence of impact was already alarming (Hansen, 1988; Shabecoff, 1988). In fact, warming will likely be worse in a future 350 ppm scenario, because the cumulative impacts will have weakened the planet's potential to absorb excess heat. There is probably no actual reversal of warming until CO_2 concentrations are brought back to preindustrial levels, well under 300 ppm.

Simply going to a zero fossil fuel economy will not stop catastrophic consequences.

We must also draw down 200 Gt carbon. Ecological restoration is the only feasible and practical approach.

To accomplish this essential and herculean task requires not only cessation of fossil fuel emissions, but also a drawdown of approximately 200 gigatons carbon (200 Gt C) from the atmosphere. It is clear that the only conceivable safe and long-term solution for this is through global ecosystem restoration. This will include forests and wetlands, but particularly, also, grasslands, including prairies and savannas, where carbon is sequestered through the roots of perennial plants and bound in organic soil compounds for decades to millennia (Rabbi, 2013). In total, grasslands comprise the largest ecosystem on Earth and are major stores of terrestrial carbon. By various estimates, they cover between 26% and 40% of the world's land while containing 20% to 35% of soil carbon (FAO, 2010; Ramankutty, Evan, Monfreda, & Foley, 2008; R. White, Murray, & Rohweder, 2000). Even small percentage increases in soil carbon worldwide can dramatically reduce atmospheric CO_2 concentrations.

Entering this conversation is the practice of Holistic Planned Grazing (HPG), in which livestock are herded in a fashion that replicates the beneficial grazing, trampling, dunging, and nutrient recycling dynamics with which wild herding ruminants coevolved with perennial grassland plants and carbon-rich soils (Savory & Butterfield, 1999). Decades of anecdotal evidence and recent studies suggest this practice has great promise, both for ecological functioning, including plant growth and hydrology, and for increasing soil organic carbon (SOC) (Dagget, 2005; Earl & Jones, 1996; Gill, 2009; Howell, 2009; Norton, 1998; Stinner, Stinner, & Martsolf, 1997; Teague et al.,

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2011; K. T. Weber & Gokhale, 2011). For example, Teague (2011) showed that land managed under a restorative grazing regimen (multi-paddock with ecological goals) had a far higher SOC value than land on a similar site managed with traditional (heavy continuous) grazing. When factoring across all soil profile depths measured, this added carbon equated to a 30 t C/ha. Additionally, Weber (2011) showed that land under a restorative grazing regimen (simulated Holistic Planned Grazing, SHGP), had significantly improved water holding capacity, measured as percent volumetric-water content, %VWC, when compared with traditionally grazed lands. Hydrological functioning is correlated with soil carbon (Feger & Hawtree, 2013; Franzluebbers, 2002).

In the absence to date, however, of robust HPG carbon data, this paper infers soil-carbon sequestration potential, based on known SOC values for representative biomes (DOE, 1999; FAO, 2009; Hiederer & Kochy, 2011; Lal, 2004b; UNEP, 2009; R. White et al., 2000; W. White, Wills, & Loecke, 2013), and, in light of this innovative approach to grasslands restoration, reevaluates current estimates on soil C losses and sinks (Lal, 1999, 2004b, 2011). The investigation shows that grassland carbon capture may be far greater, and more rapid, than what has previously been considered possible, where restoration via enhanced ruminant impact had not been factored. Managing livestock in this entirely new way, not just as consumers of grass, but also as essential elements in ecosystem balance, and with restorative goals as an intention, enables significant upward estimation of soil-carbon sequestration potential. Although there are many uncertainties, and future research is needed, these considerations broaden the narrative on climate change mitigation.

Objectives

1. Infer soil organic carbon (SOC) sequestration potentials of rangelands under Holistic Planned Grazing (HPG) by using known SOC values on comparable lands as reference, considering both yearly and total carbon capture opportunities.

2. Reevaluate the oft-cited estimates from noted Ohio State University soil scientist Rattan Lal regarding historic SOC loss and sequestration potentials in light of new considerations for both rangeland degradation and repair – where degradation can occur from sedentarization ("over rest"), and repair can occur through proper ruminant management, replicating the beneficial co-evolutionary impacts of herding grazers.

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Units

Common

- Pg = petagrams
- Tg = teragram
- Mg = megagrams
- t = tons
- Gt = gigatons
- ha = hectares
- a = acres
- Mha = million hectares
- Bha = billion hectares
- cm = centimeter
- m = meter
- ppm = parts per million
- CO2 = carbon dioxide
- C = carbon
- SOC = soil organic carbon

Conversions

- 1 hectare (ha) = 2.47 acres (a) = 10,000 square meters (m)
- 100 centimeters (cm) = 1 meter (m)
- 1000 Mha = 1 Bha; One thousand million hectares = one billion hectares
- 1 km(2) = 100 ha; One square kilometer = 100 hectares
- 10 Mkm(2) = 1 Bha; Ten million square kilometers = 1 billion hectares
- 1 ton carbon = (converts to) 3.66 tons CO2 in the atmosphere
- 1 ppm CO2 = (contains) 2.12 Gt Carbon; 1 Gt carbon = 0.47ppm CO2; Thus, removing 100 Gt C from the atmosphere, draws down CO2 by 47 ppm.

Interchangeable Usage

- Mg (megagrams) = t (tons)
- Tg (teragram) = Trillion grams = 0.001 Gigatons
- Pg (petagram) = 1000 trillion grams = Gt (gigaton) = 1 billion tons

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Part 1: Infer Soil Organic Carbon (SOC) Sequestration Potentials of Rangeland with Holistic Planned Grazing (HPG)

Findings

- **HPG May Sequester 25 to 60 t C/ha in Semi-arid Grasslands -** Semi-arid grasslands under HPG may sequester between 25 to 60 t C/ha, demonstrating a shift from semi-desert, shrub land to healthy tropical savanna and perennial grassland. This range is inferred through comparisons with visual assessments of land improved through HPG with SOC density values for similar land in corresponding regions, using a wide range of sources (DOE, 1999; FAO, 2009; Hiederer & Kochy, 2011; Lal, 2004b; UNEP, 2009; R. White et al., 2000; W. White et al., 2013). This transformation represents an *inferred* increase in SOC of approximately 60 t C/ha, or from a 40 t C/ha to a 100 t C/ha profile. This transformation may be obtained in 25 years, giving an average carbon capture rate of 1 to 2.4 t C/ha/yr. The maximum carbon capture rate may be reached in about the tenth year (Akala & Lal, 2000).

Semi-arid grasslands introducing HPG may sequester between 25 to 60 t C/ha, demonstrating a shift from semi-desert, shrub land to healthy tropical savanna and perennial grassland.

- **Total Soil Sink Potential for Grasslands may be 88 to 210 Gt with a CO2 Equivalence of Approximately 41 to 99 ppm -** Assuming that the sequestration potential in semi-arid grasslands will be less than that on temperate prairie, we can infer the former potential to be a minimum, and thus the basis for a conservative estimate. Where there are 3.5 Bha of grasslands (FAO, 2010), all of which is postulated herein to be severely depleted from their antecedent SOC pools (Buringh, 1984), either through cultivation (Lal, 1999) or through sedentarization resulting from the loss of native ruminant impact (Savory & Butterfield, 1999; K. Weber & Horst, 2011) this paper calculates that the potential for SOC sequestration on grasslands is 88 to 210 Gt. This is the atmospheric CO_2 reduction equivalency of 41 to 99 ppm, enough to dramatically mitigate global warming.

Discussion

25 to 60 t C/ha for HM on Semi-arid Grassland

Using data from numerous sources for SOC density by biome (DOE, 1999; FAO, 2009; Hiederer & Kochy, 2011; UNEP, 2009; R. White et al., 2000; W. White et al., 2013), and for SOC loss from cultivation (Lal, 1999), this paper finds that a variation in SOC density of approximately 25 to 60 t C/ha represents a dramatic and visible transition in ecosystem health and classification (see Tables 1 through 2 and Figures 4 through 7). For example, visual mapping of SOC densities from Hiederer and Kochy (2011) show extreme desert regions of the world with SOC in the range of 0 to 25 t C/ha; dry, semi-desert, shrub-land and savanna regions of the world, such as much of the US southwest, Australia and sub-Suhara and southern Africa in the range of 25 to 50 t C/ha; agriculturally healthy and productive regions of the world, such as large swaths of eastern and central United States, southern and central Africa, the majority of India, and coastal Australia in the range of 50 to 75 t C/ha; and prime prairie and forest land such as large parts of Brazil, central US and southwestern Canada, in the range of 75 to 100 t C/ha. Highly forested and jungle regions are in the range of 100 to 200 t C/ha, and wetlands and peat-lands are at the upper extremes with SOC densities in excess of 200 t C/ha. W. White et al. (2013) shows that the arid US Southwest and Great Basin regions are in the range of 52 to 64 t C/ha, whereas most of

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Texas, Oklahoma and the Dakotas are in the range of 111 to 132 t C/ha. Statistical data from DOE (1999) state the SOC density for extreme deserts is 26 t C/ha; for desert and semi-desert, shrub land: 83 t C/ha; and for tropical savanna: 146 t C/ha. The DOE data also shows that cultivated and permanent cropland is 81 t C/ha, practically identical with tropical savanna. Lal (2004b) provides values for SOC on “desert and semi-desert”, and “tropical grasslands and savannas” as 42 and 117 t C/ha respectively. Lal (1999) also shows that the value for cropland, 103 t C/ha, is almost identical to that of tropical grasslands and savanna.

25 t C/ha: an SOC Density Delta Sufficient to Merit Delineation

Hiederer and Kochy (2011) choose 25 t C/ha as the range for delineation on most of the world’s surface. Given general knowledge of world geography, when viewing their maps, this seems appropriate. On a global scale, a finer presentation would appear unwarranted and a wider one, too coarse. W. White et al. (2013) have a similar delineation between many of the visually designated SOC regions in the lower 48 states in the United States. Certainly there is a continuum, where land changes are notable as they transform from one biome classification to another, either naturally through changes of geography and precipitation, or artificially through human intervention.

60 t C/ha: An SOC Density Delta Sufficient to Transform and Reclassify a Biome

The land transformation that seems most germane in this assessment is that from semi-desert and shrub land to healthy savanna, tropical grassland and cropland. Inferring from the visual data provided from Hiederer and Kochy (2011), this would clearly be visible given a land change of 50 t C/ha. Using classification from DOE (1999), the transition from semi-desert to tropical savanna is 63 t C/ha and from Lal (2004b), the transition from semi-desert to cropland is 61 t C/ha. Thus, the many fence-line and before-and-after pictures demonstrating land restoration through HPG (photos included) indicate an increase of SOC in this range (25 to 60 t C/ha). This delta in SOC density is also consistent with Lal’s thesis that a “new equilibrium” for land types will be obtained after a loss of 20 to 50 t C/ha (Lal, 1999). This paper assumes the opposite is also true. That is, a new equilibrium will be obtained through an *increase* of 20 to 50 t C/ha, moving from a depleted state toward a restored one, gaining through restoration, instead of losing through cultivation.

Dramatic Change Over 25 to 30 Years

These inferred changes have been realized on land under long-term HPG (25 to 30 years) and thus represent yearly sequestration rates slightly greater than, but not outside the range of, other sequestration demonstrations on similar land (Table 5). The improvement is attributed to the proper management of the ruminants that are providing beneficial grazing services to the land, while avoiding the overgrazing and “over rest” of convention. In some cases, dramatic land restoration is realized in only a matter of years. In such examples, it is because the livestock were tightly corralled on the site for seven to ten days, and thus intensive manuring occurred.

Sequestration Potential of 88 to 210 Gt on Grasslands, or the Atmospheric CO2 Reduction Equivalency of 41 to 99 ppm

On this basis, this paper finds that the restoration potential on depleted grasslands and savannas, using proper management of livestock as a tool, may be quite larger than Lal (1999, 2004a) has previously estimated. If such restoration, on the order of 25 to 60 t C/ha, were achieved over the entire grasslands biome, estimated at approximately 3500 Mha (FAO, 2010), the carbon drawdown would be 88 to 210 Gt C. This represents the atmospheric CO2 reduction equivalency of 41 to 99 ppm, enough to dramatically mitigate global warming. See calculations below.

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Equation 1: Global Long-term Sequestration Potential - Lal (1999)

Global Long-term Sequestration Potential Based on Lal (1999)

Total sequestration potential =

(yearly sequestration potential) x (years of effective sequestration)

Thus,

(1.2 to 2.6 Pg C/yr) x (25 to 30 years) = **30 to 78 Pg C (Gt)**[a]

Atmospheric CO2 reduction equivalency = **14 to 37 ppm**[a]

a. Calculations by Itzkan, this paper.

Equation 2: Revised Global Sequestration Potential

Revised Global Sequestration Potential

Total sequestration potential on grasslands =

(potential per hectare) x (number of hectares effected)

Thus,

(25 to 60 t C/ha) x (3500 Mha) = **88 to 210 Gt C**

Atmospheric CO2 reduction equivalency **= 41 to 99 ppm**

Equation 1 is derived from Lal (1999), a seminal paper that has largely set the narrative for what is considered possible through grassland ecosystem carbon capture. The formulation is yearly sequestration potential times the number of effective years. The yearly range, 1.2 to 2.6 Pg C/yr, is derived from studies on best practices in agriculture and grasslands management – such as non-till, cover crops, species selection, erosion control, reduction in overgrazing, and conversion of land to biofuels. The number of effective years, 25 to 30, is based on Akala and Lal (1998). That study found that after 25 to 30 years, soil C restoration was negligible and that the peak capture rate would be in years 10 to 15. Lal (1999) never actually performs the calculation of yearly potential multiplied by effective years. The readers are left to do that on their own, which this paper has done. The result, based on Lal (1999), is 30 to 78 Gt C with an atmospheric CO2 reduction equivalency of 14 to 37 ppm. Although certainly a highly desirable potential to be realized, this paper suggests the range is low, as the methodologies are principally limited to agriculture and traditional livestock management.

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The modified approach, Equation 2, factors restoration with proper ruminant impact. It takes the potential delta in SOC per hectare and multiplies by the number of available hectares. The SOC delta is based on the inferred changes discussed herein, taking into consideration that grasslands have lost considerable SOC from antecedent pools, not only from land use changes due to agriculture.

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Part 2: Reevaluate Rattan Lal's Estimates for SOC Loss and Sequestration Potential

Findings

> *Lal's oft-cited calculations for historic SOC loss (66 to 90 Pg) are based on depletion of croplands only. They are not total carbon losses from all antecedent pools, a number closer to 500 Pg.*

- **SOC Loss Calculations Limited to "Cropland" or Land Under Agricultural Regime Utilization** - Lal's oft-cited 1999 calculations for historic SOC loss (66 to 90 Pg) are based on depletion due to agriculture and on cropland only. They are not total terrestrial carbon losses from all antecedent pools. His tables and statements indicate this, and yet, when he is cited, this nuance is often overlooked. For example, Table 3 from (Lal, 1999) that gives the SOC loss range of 66 to 90 Pg, clearly states "Decline in SOC from cropland" (Figure 9, this paper). In the same table are columns for prehistoric and present SOC pool estimates of 2014 and 1555 Pg respectively, where the difference, 459 Pg, is the loss of SOC across all land types and utilization. Table 2 from the same paper, Lal (1999), uses a different calculation to derive SOC loss, but again, limits the scope to the agricultural utilization (Figure 8, this paper). Of the 3.4 billion hectares attributed to grassland, only 660 million hectares, or 19%, are considered impacted by agriculture and factored in the loss calculation. Given a loss rate 30 to 60 t C/ha, Lal calculates grassland SOC depletion of 20 to 40 Pg.

- **Factoring Non-Agricultural Land Greatly Increases Loss Estimate and Corresponding Sequestration Reservoir –** When SOC depletion for grasslands is considered beyond the restriction of agricultural utilization, larger measures for depletion and restoration potential are revealed. For example, if the loss rate of 30 to 60 t C/ha (Lal 1999) is applied to all 3.4 Bha (Lal 1999), as this paper speculates is reasonable, the SOC loss range from grasslands is 102 to 204 Pg. This larger range, which factors for all grasslands, is 1.5 to 3 times the estimate provided by Lal (1999) that was limited to soil C losses from *agriculture alone*. This larger value, however, may still be conservative. In a World Resources Institute report, *Pilot Analysis of Grassland Ecosystems (PAGE),* White (2000) estimates that the area for grasslands, including savanna, shrubland, and non-woody grasslands, is 4.5 Bha. Using that value with our estimated loss-per-hectare rate above, would yield a total soil C loss of 135 to 270 Pg, These larger values are also more inline with other estimate for total terrestrial C loss (Table 4). Bohn (1978) estimated 150 Pg soil C loss in the previous 150 years, Ruddiman (2003), Wallace (1994) and Buringh (1984) estimate historic C loss across all biomes at 480 Pg, 500 Pg and 537 Pg respectively. Lal (2004a) estimates all soil C loss since prehistoric times at 456 Pg.

- **Yearly Sequestration Potential Limited Principally to Farming, Erosion Control, and Biofuels Production on Agricultural Land – No Factoring of Soil C Capture Through Restorative Livestock Management – Doing So May Greatly Increase Yearly Sink** Lal's estimates for yearly soil C sink potential, given originally as 1.2 to 2.6 Pg C/yr (Lal 1999), and then subsequently as 1.2 to 3.1 Pg C/y (Lal 2011), are all principally based on best practices for agriculture, erosion control and biofuels production on the limited areas of land currently or once in cultivation (Tables 6,7,8). There is no discussion of restorative herd management to revive perennial grassland plants and their corresponding carbon-capturing potential. Where such ruminant impact is employed, the total yearly soil C sink potential may be quite higher. Using Lal's 2011 estimate for rangelands, 2.9 Bha, this paper estimates a revised yearly potential of 2.9 to 6.9 Gt C/yr, with a mean of 4.9 Gt

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C/yr, where the estimated per-hectare capture on semi-arid grassland is 1 to 2.4 t C/ha/yr for 25 years, or a cumulative total of 25 to 60 t C/ha. Although more than twice Lal's 2011 estimate, it is not without a theoretical or strong visually based evidential basis. Nor is it without precedent. The DOE (1999) estimated a yearly biome C sink potential of 5.6 to 10.1 Gt C.

Discussion

Cropland Only

Lal's oft-cited 1999 calculations for historic SOC (66 to 90 Pg from one calculation, and 47 to 104 Pg from another) are based only on loss on cropland and only in the post-industrial era. They are not his estimate for soil carbon losses from all periods, nor all depletion factors, such as erosion. His tables and statements indicate this, and yet, when he is cited, this nuance is often overlooked.

This paper estimates a peak soil C capture potential of 1 to 2.4 t C/ha/yr for semi-arid grassland with Holistic Planned Grazing. Although high for arid areas, it postulates that well managed livestock are the distinguishing factor.

The first case in point of Lal's estimates for total SOC loss being far greater than commonly noted is Table 3 from Lal (1999). Here the column clearly reads, "Decline in SOC from cropland" (Figure 10, this documented). A footnote states that the numbers are modified from Eswaran et al (1995) and the range, now popular in literature, is 66 to 90 Pg. Yet, directly to the left of the cropland columns are two others that show the prehistoric and present SOC pools. The totals from these, modified by Lal from Buringh (1984), are 2014 and 1555 Pg respectively. The difference, and hence the actual SOC loss across all land types and regimes, is 459 Pg. This is *5 to 7 times* the estimated SOC loss due to cropland alone provided in the same table. In a latter paper, Lal (2004a) calculates that pre-industrial era losses of carbon from soil is 320 Gt, and that post-industrial losses, including erosion and mineralization, equal 136 Gt, thus yielding a total historic carbon loss from soils of 456 Gt. Note this value is almost identical to the 459 Gt figured implied five years prior in Lal (1999), yet derived differently. Statements, therefore, that Lal's estimate of SOC loss is only 66 to 90 Gt are miscast. That range only stipulates loss specifically as a direct result of agricultural utilization in the last 150 years, particularly tilling and clearing of native vegetation. It does not include his estimates of pre-industrial loss, nor losses outside of croplands, nor even losses that may be indirect consequences of agriculture and cultivation, such as erosion. The erosion value alone is estimated varyingly at 17 to 35 Gt C (Lal, 2004a) and 19 to 29 Gt C (Lal, Hassan, & Dumanski, 1999).

The second case in point is Table 2 from Lal (1999). Here Lal estimates loss based on the impact of agriculture on specific ecosystems. He multiplies the rate of SOC loss per hectare for agriculture on that ecosystem by the number of hectares impacted (Figure 8, this document). Note that according to this table only 660 Mha, or 19% of the stated area for grasslands, 3.4 Bha, is used in the calculation. A footnote states that the value for grassland area impacted by agriculture is taken from Williams (1994). Multiplying 660 Mha by a depletion rate of 30 – 60 Mg C/ha gives a total grasslands SOC depletion estimate of 20 – 40 Pg. Using similar methodology, the total for all SOC loss from all ecosystems *due to agriculture* is 47 – 104 Pg (Lal 1999).

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Expanding Beyond Agriculture

The limitation to land within agricultural cultivation for calculations of SOC loss is consistent in Lal's writing. If, however, we postulate that historic and present SOC losses on grasslands may not be limited to agriculture, but may also be the result of gradual decay due to the disruption of essential ruminant and predator populations (and other burrowing and foraging species) (Savory & Butterfield, 1999; K. Weber & Horst, 2011), we arrive at a much larger number for SOC loss, and thus, also, a larger potential reservoir for sequestration.

Potential yearly global C capture in soil may be 2.9 to 6.9 Gt, with a mean of 4.9 Gt. This is twice Lal's estimate. DOE estimated potential biotic capture of 5.6 to 10 Gt C/yr.

For example, if we assign a depletion rate of 10 to 20 t C/ha, one third that for grasslands under cropland cultivation (Lal 1999), and apply that rate to the 2.7 billion hectares of grasslands that are not factored into his calculations (Lal 1999), we obtain an additional SOC loss range of 54 to 108 Gt. When added to Lal's 1999-estimated loss due to cropland cultivation of grasslands, 20 to 40 Gt, the combined total is 74 to 148 Gt. However, this paper postulates that even this enhanced estimate is conservative. Given visual observation of current grassland and savanna ecosystems, it seems reasonable to assume that the losses on non-agricultural grassland are as severe as on cropland. In both cases, there is profound degradation, to the extent, in many cases, of almost complete loss of topsoil.

Following from above, if we assign the depletion rate attributed to grasslands under cultivation (30 to 60 t C/ha) to the full 3.4 billion hectares of grasslands (Lal 1999), we get an SOC loss range of 102 to 204 Gt. To go one step further, if we use the larger grassland area of 4.5 billion hectares from White (2000), we derive a historic SOC loss range on grasslands of 135 to 270 Pg Gt. This paper postulates that these larger values are more accurate measures of both the loss and sequestration potential for grasslands.

Revised Sink Potentials

The yearly estimate for soil C sink potential is another salient parameter for reevaluation. Lal's estimates for yearly soil C sink potential, given originally as 1.2 to 2.6 Pg C/yr (Lal 1999), and then subsequently as 1.2 to 3.1 Pg C/y (Lal 2011), are all principally based on best practices for agriculture, erosion control and biofuels production on the limited areas of land currently or once in cultivation (Tables 6, 7, 8). The methods include no-till farming, cover crops, crop rotations, nutrient enhancements, water capture (Lal & Bruce, 1999), and growing short-rotation woody crops for biofuels on land that is extremely or strongly degraded (Lal 1999). Where Lal addresses rangeland and grazing land, the methodologies are similar to above, adding establishment of adaptable species and fire management (Lal 2011). There is no discussion of restorative grazing to revive perennial grasslands and their corresponding carbon-capturing potential. Where livestock are mentioned, it is in the context of cessation of overgrazing through stock reduction (Lal 1999).

Established carbon capture rates on grazing lands are given by Lal (2011) to be 0.2 to 0.5 t C/ha/yr and on arid lands, 0 to 0.15 t C/ha/yr (Lal, 2004a) and 0.08 to 0.125 t C/ha/yr (Lal et al., 1999). These are low given the resource restrictions, particularly of water and plant nutrients (Lal 2011), but also, this paper proposes, the restriction to methodologies that do not include ruminant action. Where strategic ruminant impact is employed, the total yearly soil C sink potential may be quite higher. Rates for carbon capture vary widely from approximately 1 to 10 Mg C/ha/yr (Table 5). Farming methodologies are in the range of 0.05 to 1.5 Mg/ha/yr (Lal, 1999) and reclamation

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efforts utilizing fertilizers, mulching and biosolids have sequestered 3 to 9 Mg C/ha/yr (Akala & Lal, 2000; EPA, 2011). Liebig, Schmer, Vogel, and Mitchell (2008) achieved capture rates as high 10 Mg/ha/yr using switch grass for biofuel.

Improving the "effectiveness" of rainfall may be the single most significant impact of HPG on degraded land. This is achieved by providing cover over previously bare surfaces.

This paper estimates a peak soil C capture potential of 1 to 2.4 t C/ha/yr for semi-arid grasslands under with HPG. Although high for arid and grazing lands, it is well within established range for temperate lands (Table 5), particularly where biosolids and manure are employed (EPA, 2011). It is theorized that the introduction of well-managed livestock is the salient distinguishing factor, where the animals provide the restorative services, including fertilization and irrigation, otherwise added artificially as amendments. Savory (1999) argues that perhaps the single most important contribution of properly managed livestock on degraded rangeland is to help increase the "effectiveness" of rainfall. This is achieved by providing cover over previously bare surfaces with dung and trampled grass, and by breaking capped surfaces though hoof impact.

Taking the estimated per hectare C sink range for land under HPG, 1 to 2.4 t C/ha/yr, and applying it to 2.9 Bha for grazing land (Lal 2011) gives us a revised yearly sequestration potential range of 2.9 to 6.9 Gt C/yr with a mean of 4.9 Gt C/yr. Although this mean is 50% greater than the high estimate from Lal (2011), it is not without a theoretical or strong visually based evidential basis. Nor is it without precedent. The DOE (1999) estimated a yearly terrestrial biome C sink potential of 5.6 to 10.1 Gt C. It was postulated that this could be sustained for 25 to 50 years.

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Conclusion

Using a wide range of statistical and visually representative assessments for soil carbon by biome, this paper infers that the many fence-line and before-and-after pictures documenting improvement to land under Holistic Planned Grazing, represents a soil carbon increase of approximately 25 to 60 t C/ha. Visibly, over a matter of decades, there is a transformation from near desert to healthy savanna and grassland. In small plots, where animals are corralled for seven to ten days in high densities, and on particularly degraded land, dramatic increases in grass cover can become apparent within only two years, as the corralling has significant manuring and positive disturbance impact. Over larger areas of rangeland, the beneficial transition will be slower, but sill in effect.

It is calculated that there is a total grassland soil sink capacity of 88 to 210 Gt C, enough to dramatically mitigate global warming.

Given the newly established potential increase of 25 to 60 t C/ha and applied over 3.5 billion hectares of grassland (FAO, 2010), this paper calculates that there is a total global grassland soil sink capacity of 88 to 210 Gt C, or the atmospheric CO2 reduction equivalency of approximately 40 to 100 ppm. This is an amount sufficient to significantly mitigate global warming, and greater than was previously considered possible without the added benefit of restorative grazing. Based on inferred increases in soil carbon stocks (25 to 60 t C/ha over 25 to 30 years), this paper calculates that there is a yearly sink capacity of 1 to 2.4 t C/ha/yr with a global mean of 4.9 Gt C/yr, or a CO2 drawdown of approximately 2 ppm/yr – nearly equivalent to the annual increase from fossil fuels. Enabling this soil sink could thus, on its own, halt further increases in atmospheric CO2 while providing additive ecological benefits. Although this mean yearly C drawdown, 4.9 Gt, is 58% greater than the high estimate of 3.1 Gt C/yr from Lal (2011), it is not without a theoretical or strong visually based evidential basis, as this paper has shown. Nor is it without precedent. The DOE (1999) estimated a yearly biotic C sink potential of 5.6 to 10.1 Gt C/yr.

This paper also finds that Lal's estimate for SOC loss and restoration potential is probably lowered by limiting calculations to agricultural land and by excluding properly managed livestock from the restoration paradigm. For example, Lal (1999) explicitly states that his oft-cited range for SOC loss of 66 to 90 Gt C, refers "cropland" only. On the other hand, in the same paper, figures for prehistoric and present soil carbon pools (2015 and 1555 Gt), reveal an actual soil carbon loss, across all soils (not just cropland) of 459 Gt. This represents *5 to 7 times* the SOC loss found on cropland, and is also more in line with the 480 Gt and 537 Gt figures provided respectively by Ruddiman (2003) and Buringh (1984). Unfortunately, the distinction between cropland and global soil capacities is often missed when citing Lal in climate change related papers and deliberations. Shifting the narrative from cropland loss to all soil C loss will be an important evolution in the discussion of climate change mitigation potentials and options. Similarly, introducing properly managed livestock into the mix of restoration and carbon capture remedies should result in significant upward estimation of soil-carbon sequestration potential. This will be particularly true in semi-arid areas, which are outside the reach of traditional agriculture.

Introducing restoratively managed livestock into the mix of carbon capture remedies will be an important evolution in mitigation discussions.

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Appendix: Supporting Figures and Tables

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Figure 1: Soil Restoration with HPG in The Karoo, South Africa

Photo credit: Kroon Family

Left side of fence shows a family ranch in the Karoo Region of South Africa that utilizes Holistic Planned Grazing. Average rainfall is 230 mm. The HPG regimen calls for higher stocking densities than convention, combined with tightly packed, frequent and well-planned movements – mimicking the behavior of natural herds in the presence of predation. No technology, irrigation, or fertilizer is needed. Right side of fence shows conventional, low-density "continuous" grazing that quickens desertification. Reversing desertification is a global warming mitigation strategy because atmospheric carbon is captured in stable and long lasting organic molecules in the soil. Improvement in soil and vegetative cover also restores water tables and contributes to evaporative cooling. This paper estimates that the conversion of semi-desert to healthy savanna, as shown here, represents a carbon capture opportunity of 25 to 60 t C/ha.

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Figure 2: Soil Restoration with HPG in Mexico

Photo credits: Guillermo Osuna

Las Pilas Ranch in Coahuila, Mexico. Average rainfall 500 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 Planned Grazing 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 earlier photo, the man-made pond shown is merely runoff captured by a constructed dirt dam. The restored terrain in the later photo is estimated to hold at least six-times as much water as the depleted terrain, but now the water is held in the soil and vegetative matter in a state referred to as “green water.” According to the owner, previously, a one-inch rainfall would fill the trough. After restoration, even a six-inch rainfall is all absorbed (as it should be), and there is no standing water in the depression. The trough has grown over and is no longer needed to water the animals as formerly dried-up springs in the vicinity have begun flowing year-round once again.

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Figure 3: Soil Restoration with HPG in Zimbabwe – Example 1 – "Two Tree" site

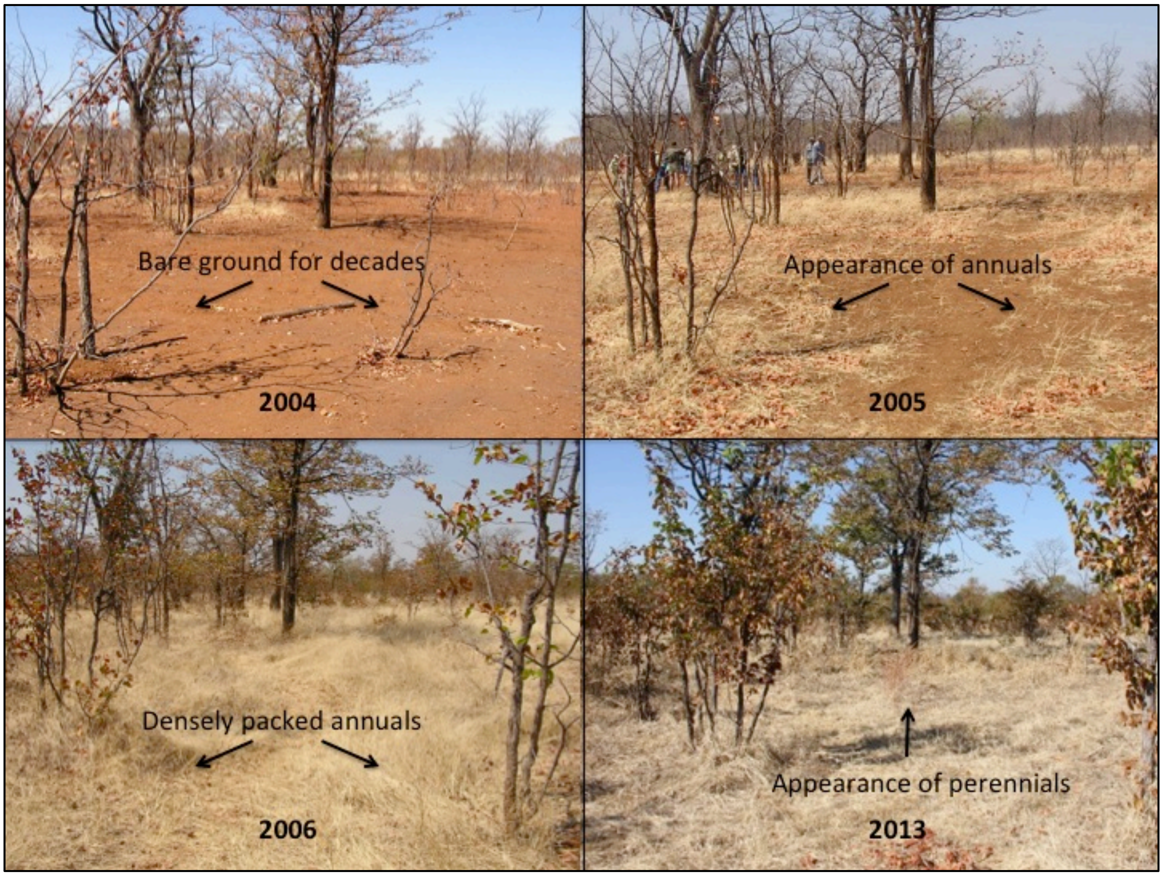

Photo credits: ACHM, Seth Itzkan

This time-series sequence shows the transformation from a barren landscape in Zimbabwe to a healthy grassland savanna from 2004 to 2013. Average annual rainfall is 600 mm. This is referred to as the "two tree" site because of the adjacent two trees in the center background. The land, which had been barren and eroding for decades, is "treated" with a heavy concentration of animals. About 500 cattle are corralled on the site for 7 to 10 evenings, leaving an excessive amount of dung and plant litter. Within one year after the animal treatment, short-rooted annuals start to grow (the white stringy plants – 2005 photo). With the emergence of these plants, the land is thus incorporated into a carefully monitored grazing plan. After only a few years, the annuals are densely packed and providing ground cover that helps retain moisture and builds biodiversity in the soil (2006 photo). These annuals are a first-phase in the restoration, but their carbon capture will be minimal. After about 8 years, however, perennials appear (the taller pinkish-beige colored plants – 2013 photo). These have deep roots and accelerate carbon capture in the soil (Post & Kwon, 2000). Note: The transformation is not over. Akala and Lal (1998) suggests that the improvement may continue for another two decades, and, eventually, this site will likely be covered in perennials. This is true as long as the grazing plan continues. If the grazing stops, however, the plants will oxidize, and the land will likely return to its prior desertified state (K. Weber & Horst, 2011). This paper contends that after full recovery, 25 to 30 years, SOC density on this spot will have increased by between 25 to 60 t C/ha.

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Figure 4: Soil Restoration With HPG in Zimbabwe - Example 2 - "Elbow" Site

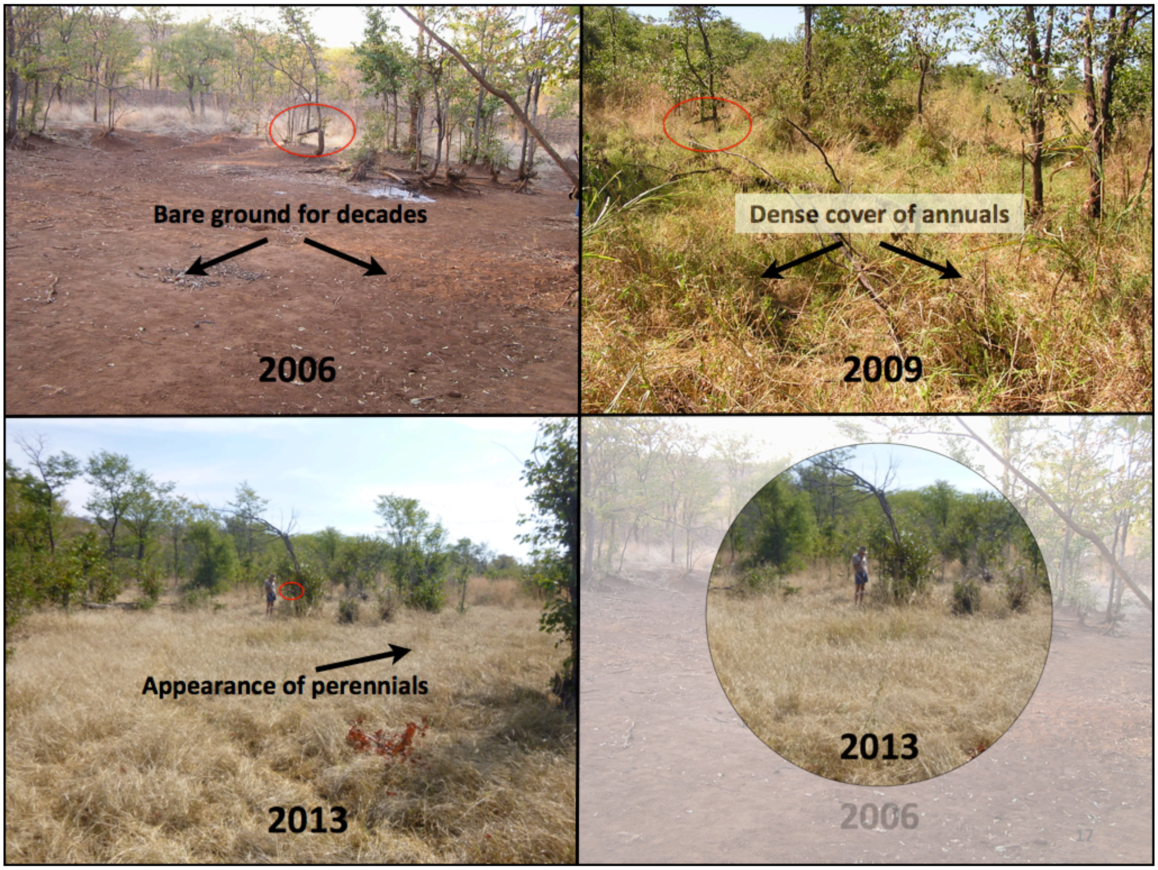

Photo credits: ACHM, Seth Itzkan

This time-series sequence shows the transformation from a barren landscape in Zimbabwe to a healthy grassland savanna from 2006 to 2013. Average annual rainfall is 600 mm. This is referred to as the "elbow" site because of the bend in the tree branch in center background. As in the figure above, the land, which had been barren and eroding for decades, is "treated" with a heavy concentration of animals. About 500 cattle are corralled on the site for 7 to 10 evenings, leaving an excessive amount of dung and plant litter. In this example, within only two growing seasons, fast growing annuals (2009 photo) have taken hold. With the emergence of these plants, the land is thus incorporated into a carefully monitored grazing plan. Four years later (2013 photo), the landscape is now densely packed with annuals, and the first perennials are starting to appear. The perennials have deep roots that accelerate carbon capture in the soil (Post & Kwon, 2000). The final frame (bottom right), superimposes a circular view from 2013 on top of the original view from 2006, helping to illustrate the rapid and dramatic change in landscape. The only treatment has been livestock management – first corralled to created the initial dung and litter cover, and then managed as a restorative herd, according to HPG guidelines.

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Table 1 Terrestrial Carbon by Biome - Lal 2004b

Ecosystem	Area (Bha)	SOC (Gt)	Density (tons C/ha)	Density (tons C/a)	% Total Area	% Total C
Forest tropical	1.76	216	123	50	12	10
Forest Temperate	1.04	153	147	60	7	7
Forests Boreal	1.37	471	344	139	9	22
Temperate grassland and scrub land	1.25	295	236	96	8	14
Grasslands and tropical savannas	2.25	264	117	48	15	13
Desert and semi-desert	4.55	191	42	17	30	9
Cropland	1.6	165	103	42	11	8
Tundra	0.95	121	127	52	6	6
Wetlands	0.35	225	643	260	2	11
Global Total	**15.12**	**2101**	139	56		

Source: Lal (2004b). Note SOC density values for highlighted rows. Delta from Desert-semi-desert to Grasslands-tropical-grasslands is 75 t C/ha. Delta from Desert-semi-desert is Cropland is 61 t C/ha.

Table 2: Terrestrial Carbon by Biome - DOE 1999

Biome	Area Bha	SOC (Gt)	Density (C t/ha)	Denisty (C t/a)	% of total area	% of total C
Forest, Tropical	1.48	367	248	100	11.10	14.4
Forest, temperate	0.75	182	243	98	5.63	7.2
Forest, boreal	0.9	157	174	71	6.75	6.2
Woodland, temperate	0.2	40	200	81	1.50	1.6
Chaparral	0.25	38	152	62	1.88	1.5
Grassland, temperate	1.25	304	243	98	9.38	12.0
Savanna, tropical	2.25	329	146	59	16.88	12.9
Desert and semi-desert, scrub	2.1	175	83	34	15.75	6.9
Desert, extreme	0.9	23	26	10	6.75	0.9
Cultivated and permanent crop	1.48	120	81	33	11.10	4.7
Wetland	0.28	214	764	309	2.10	8.4
Peatland, northern	0.34	455	1,338	542	2.55	17.9
Human area	0.2	11	55	22	1.50	0.4
Tundra, arctic and alpine	0.95	127	134	54	7.13	5.0
Total	13.33	2542	191	77	100.0	100.0

Source: DOE (1999). Note SOC density values for highlighted cells. Delta from Desert-extreme to Desert-semi-desert is 57 t C/ha. Delta from Desert-semi-desert to Savanna-tropical is 63 t C/ha.

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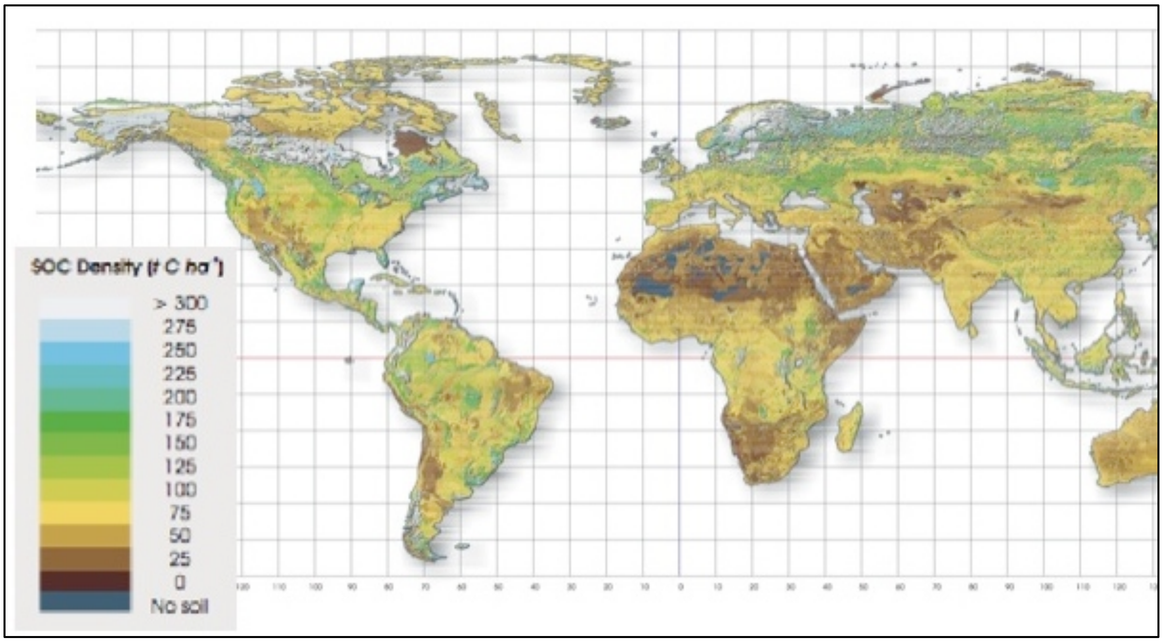
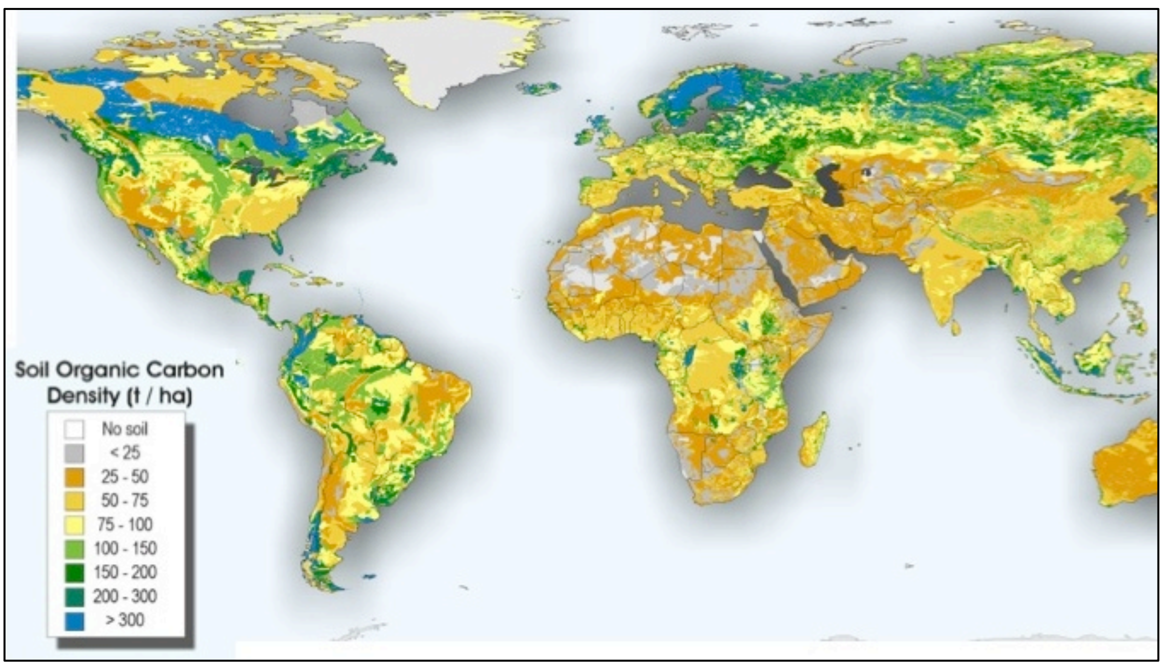
Figure 5: SOC Density World Map



Source: (Hiederer & Kochy, 2011)

Deltas of 25 t C/ha warrant visual separation. Semi-desert, arid regions of the US Southwest are in the 25 to 50 t C/ha range. Healthy grasslands are in the 75 to 125 t C/ha range.

Figure 6: SOC Density World Map – Alternate Colors



Source: Hiederer and Kochy (2011)

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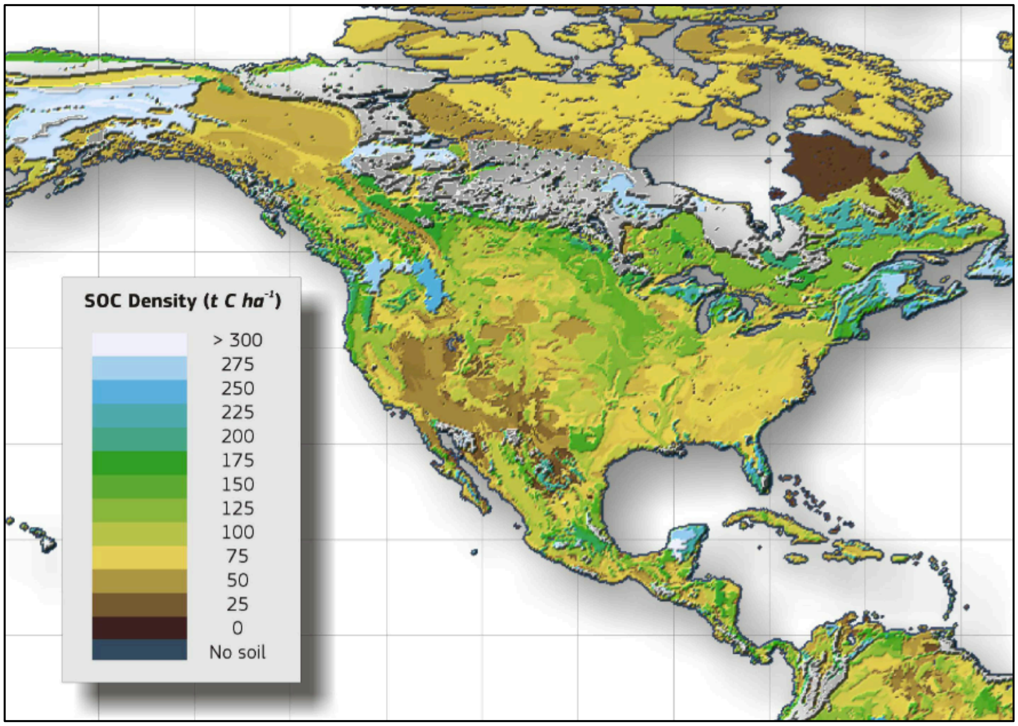
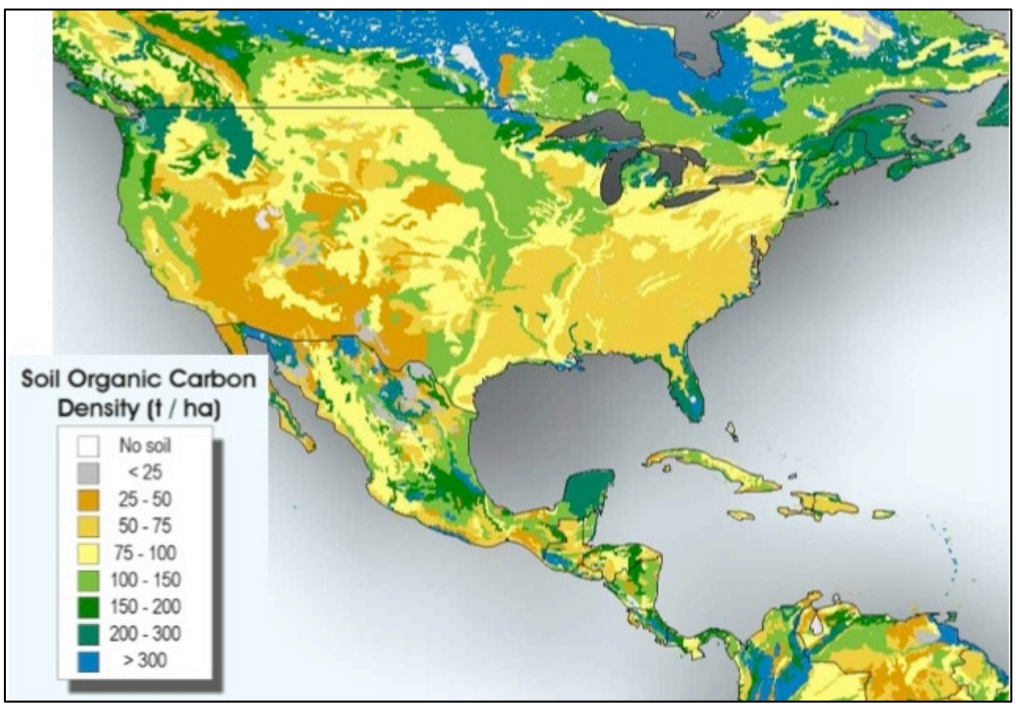
Figure 7: SOC Density Map – North America.



Source: (Hiederer & Kochy, 2011)

Figure 8: SOC Density Map – North America – Alternate Colors



Source: Hiederer and Kochy (2011)

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Figure 9: SOC Loss by Ecosystem - Lal 1999

Table 2 Estimates of the pre-agricultural and present land area in major ecosystems and of the SOC lost

Ecosystem	Pre-agriculture[1] (10^9 ha)	Present[1] (10^9 ha)	Change (10^6 ha)	SOC depletion (Mg C/ha)	Total SOC depletion (Pg)
Forests					
Tropical rainforest	1.28	1.20	600[2]	15–30	9–18
Other forest	3.40	2.7	700	20–50	14–35
Total	4.68	3.93	380	–	–
Woodland	0.97	0.79	180	15–40	3–7
Shrubland	1.62	1.48	140	10–30	1–4
Grassland	3.40	2.74	660	30–60	20–40
Tundra	0.74	0.74	0	0	0
Desert[1]	1.59	1.56	30	4–8	0.1–0.2
Cultivation	0.0	1.76	1760	–	–
Total SOC loss					47–104

Notes:
Desert lands may have lost an additional 10 Pg of inorganic C.
1) Estimates obtained from Williams (1994).
2) NRC (1993).

Source: Lal (1999), p 317. Highlighting added. The table clearly indicates that the calculation for SOC loss to grasslands is calculated only form the area of grasslands in agriculture (660 Mha). The remaining 2700 Mha hectares (2.7 Gha) are not considered. This paper postulates that all former grasslands have been subject to significant SOC loss since prehistoric times, not just areas converted to agriculture. The actual loss from antecedent pools when continental interiors were host to prodigious of herds of ruminants is likely far greater.

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Figure 10: SOC Loss By Soil Type – Lal 1999

Table 3 Estimates of the land area under different soil orders

Order	Total historic area[1] (Mha)	Cropland area[2] (Mha)	Pre-historic SOC pool[1] (Pg)	Present C pool[1] (Pg)	Decline in SOC[2] from cropland	
					(%)	(Pg)
Alfisols	1330.3	290	388.9	136	50–60	15–18
Andisols	106.0	50	–	69	15–20	5–7
Aridisols	1555.5	40	33.8	110	5–10	0.2–0.3
Entisols	2167.8	80	198.7	106	20–30	0.8–1.3
Histosols	161.0	0	41.5	390	2–5	0
Inceptisols	946.1	150	279.4	267	20–30	8–13
Mollisols	924.6	290	165.6	72	30–50	7–11
Oxisols	1011.7	300	255.5	150	50–60	22–27
Spodosols	347.9	50	62.9	98	10–20	1–3
Ultisols	1174.6	130	165.2	101	50–60	6–7
Vertisols	320.0	60	40.6	38	20–30	1–2
Gellisols	1119.9	0			0	0
Others	1870.0	110	382.0	18	20–30	0.2–0.3
Total	13035.4	1550	2014.1	1555		66–90

Notes:
1) Estimates obtained and modified from Buringh (1984).
2) Estimates obtained and modified from Eswaran *et al.* (1995).

Source: Lal (1999). p 317. Highlighting added.

The figure above clearly indicates that Lal's oft-cited estimate for the decline in SOC, 66 – 90 Pg, is calculated from "cropland" looses only. The actual total historic SOC is the difference between the Pre-historic SOC pool (2014 Pg) and the Present SOC pool (1555 Pg), were the delta is 459 Pg, approximately six times the loss from croplands only. This is consistent with other estimates for total SOC loose since prehistoric times, such as 480 Pg (Ruddiman 2003), and 537 Pg Buringh (1984).

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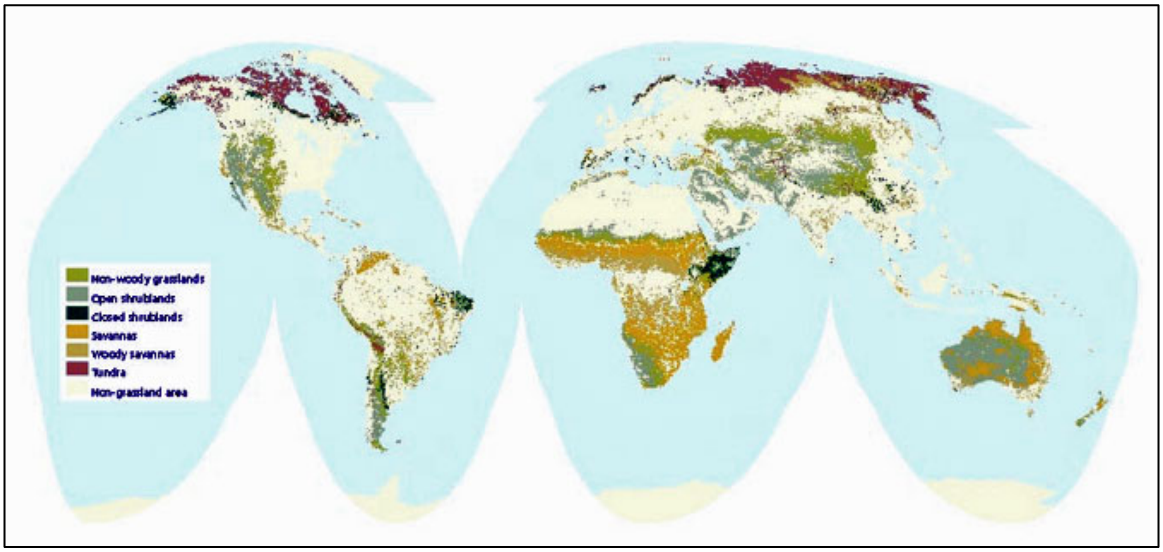
Figure 11: Global Extent of Grasslands



Source: R. White et al. (2000)

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Table 3: Grasslands and Carbon

Area (Bha)	% of Total Area[a]	SOC (Gt C)	SOC % of Total[b]	SOC Density (T C/ha)	Source adapted from	Notes
9.65	64	915	44	95	Lal (2004b)	1
8.05	53	750	36	93	Lal (2004b)	2
3.5	23	559	27	169	Lal (2004b)	3
5.2	35	730	35.3	140	R. White et al. (2000)	4
4.2	29	418	20	100	R. White et al. (2000)	5
5.9	40	864	33.3	143	DOE (1999)	6
3.8	26	671	26.4	179	DOE (1999)	7
		647	31.5		UNEP (2009)	8
		469	22.9		UNEP (2009)	9
8.05		833		103	FAO (2009)	10
3.5		634		181	FAO (2009)	11
3.5	26		20		FAO (2010)	12

Row Notes:

1. Including temperate grassland, tropical savanna, desert and semi-desert, and cropland. World total area 150 Mkm2.; Total terrestrial C 2101 Gt.
2. Excluding croplands
3. Temperate grassland & tropical savanna only. Excluding croplands and “desert and semi-desert.”
4. Includes tundra (0.7 Bha). Gives total Soil C ranges as 1753 to 2385 GtC with 2069 GtC as avg. Original source gave % of total area as 40.5, which excluded Greenland and Antarctica. Recalculated here, using total land area at 148 Mkm2, yields 35% of total area.
5. Excludes high altitude grasslands (mostly tundra).
6. Includes "Desert & semi-desert shrub". Does not include "Extreme desert" or "cultivated and permanent crop". Total terrestrial carbon at 1-meter given as 2542 Gt. Total original “non-perpetual ice” land area, given as 133 Mkm2. Recalculated here using total land area of 148 Mkm2.
7. Includes chaparral, tropical savanna and temperate grasslands. Excludes desert-semi-desert, desert-extreme, and cultivated-and-permanent-crop.
8. No areas given. Includes tropic savanna, temperate grasslands and “deserts and dry shrubland”. Total terrestrial C given as 2049 Gt.
9. Excludes “deserts and dry shrubland”
10. Includes temperate grasslands, tropic savanna, and “desert-semi-desert”
11. Excludes and “desert-semi-desert”
12. No total carbon stocks given.

Column Notes:

a. Various areas for world total area land depending on source. Range is 145 to 150 Mkm2.
b. Various totals for terrestrial C depending on source. Range is 2049 to 2542 Gt C.

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Table 4: Historic Terrestrial Carbon Loss

C Loss (Pg = Gt)	Explanation	Source
47 – 104 Pg	Estimated from ecosystem disturbance through agriculture.	Lal (1999)
55 Pg	Estimated from change in land cover and use.	Lal (1999) citing IPCC (1995)
66 – 90 Pg	Estimated from disturbance of soil types in cropland during the modern era, and only, via numbers from Buringh (1984), to a depth of 100 cm.	Lal (1999)
80 – 100 Pg	Stated in abstract.	Lal (1999)
100 – 150 Pg	Estimated loss from “world biota”, of which SOC would account for 80 – 100 Pg. Stated in Abstract.	Lal (1999)
136 Pg	Postindustrial land-use conversion	Lal (2004a)
150 Pg	Estimate based on 100 years of cultivation, releasing carbon at approximately 1 to 2 Pg per year.	Bohn (1978)
320 Pg	Based on preindustrial land-use conversion at 0.04 Gt C/y for 7800 years	Lal (2004a)
456 Pg	Based on summation of Lal (2004a) estimates for pre- and post-industrial soil carbon emissions. Summation calculation (136 + 320 = 456) by Itzkan (this paper).	Lal (2004a)
459 Pg	Calculation based on Lal (1999) estimates for prehistoric and present soil C pools. Actual calculation (2014 – 1555 = 459) by Itzkan (this paper).	Lal (1999)
480 Pg	Preindustrial = 320 GtC. Postindustrial = 160 GtC.	Ruddiman (2003)
500 Pg		Lal (1999) citing Wallace (1994)
537 Pg	Based on changes in carbon densities by soil type (“order”), considering all forests and grasslands (not just land that is cultivated), and going back to “prehistoric” times. Estimates vegetation that once was present, based on indicators in the soil. Original pool estimate (at one meter deep) is 2014 Gt. New pool estimate is 1477 Gt. Difference is 537 Pg.	Buringh (1984)

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Table 5: SOC Enhancements

Location	Practice	Rate (t C/ha/yr)	Source Adapted From & Notes
North America	Best Management Practices (BMP). Includes no-till, cover crops, crop rotation, etc.	1.5	Lal (1999). Citing previous work.
Ohio, USA	Mineland reclamation on pasture. Fertilizer and mulch abatements.	1.46	Akala and Lal (2000). Twenty-five year average on pasture in 0-30 cm profile.
Ohio, USA	Mineland reclamation on pasture. Fertilizer and mulch abatements.	3.1	Akala and Lal (2000). Maximum rate recorded in 0-15 cm profile on pasture. Maximum rate was achieved in 11th year of 25-year study.
Northern India	Alkali soil reclamation by afforestation	4.0	Lal (1999) citing Garg (1998)
CO. USA	Biosolids, compost, pellets, limestone, wood chips, manure - 200 tons total added per acre.	8.4	EPA (2011). 0-15 cm. Average over ten years.
CO. USA	Biosolids, compost, pellets, limestone, wood chips, manure - 200 tons total added per acre.	9.0	EPA (2011). 15-30 cm. Average over ten years.
Northern Great Plains, USA	Switchgrass grown for bioenergy	2.9	Liebig et al. (2008). 0-120 cm.
Northern Great Plains, USA	Switchgrass grown for bioenergy	4.3	Liebig et al. (2008). 0-120 cm. Highest reading.
Mandan, ND, USA	Switchgrass experimental plot	10.0	Frank, Berdahl, Hanson, Liebig, and Johnson (2004). Given as 1.01 kg C m-2/yr to a depth of 0.9 m.

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Table 6: Sequestration Potential - Lal & Bruce 1999

Methodology	Low (Pg/yr)	High (Pg/yr)
Erosion control	0.08	0.12
Restoration of severely degraded soils	0.02	0.03
Reclamation of salt-affected soil	0.02	0.04
Conservation tillage and crop residue management	0.15	0.17
Improved cropping system	0.18	0.24
C offset through biofuel production	0.3	0.4
Total	**0.75**	**1.0**
Source: (Lal & Bruce, 1999)		

Table 7: Sequestration Potential - Lal 1999

Methodology	Low (Pg/yr)	High (Pg/yr)
Soil erosion control	0.6	1.1
Restoration of extremely/strongly degraded soils	0.1	0.3
Adoption of recommended agricultural practices	0.2	0.5
Biofuel production on severely degraded soils	0.3	0.7
Total	**1.2**	**2.6**
Source: Lal (1999)		

Table 8: Restoration Potential Detail – Lal 2011

Agroecosystem	Area Mha	Low (Pg/yr)	High (Pg/yr)
Croplands	1300	0.4	1.2
Savanna and grasslands	2900	0.3	0.5
Salt affected soils	955	0.3	0.7
Desertification control	3500	0.2	0.7
Total		**1.2**	**3.1**
Source: Lal (2011)			

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Table 9: Yearly Global SOC Sequestration Potential

Potential	Source	Notes
0.75 – 1.0 Pg/yr	Lal (1999)	1
0.9 – 1.9 Pg/yr	Lal et al. (1999)	2
1.2 – 2.6 Pg/yr	Lal (1999)	3
3.0 Pg/yr	Lal (2001a)	4
1.2 – 3.1 Pg/yr	Lal (2011)	5
5.65 – 10.1 Pg/yr	DOE (1999)	6

Notes
1. World cropland soils (includes numerous restoration methods, including erosion control and conservation tillage).
2. A mean of 1.4 Pg/yr. Includes all dry areas of the world. Traditional methodologies including biofuel offsets. No restoration through grazing.
3. Includes enhanced values for erosion control.
4. “Maximum potential rate of SOC sequestration”
5. Includes savanna and grasslands restoration on 2900 Mha. Estimated restoration of 200 to 500 kg C/ha/yr (0.2 to 0.5 Mg). Methodologies include: water conservation, erosion control, soil fertility improvement, establishment of adaptable species, fire management, controlled grazing (reduction or exclusion).
6. Includes 1 to 3 Pg/yr for reforestation and 1.2 Pg/yr for rangelands.

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