Savannas and Global Climate Change:
Source or Sink of Atmospheric CO$_2$
Outline

• History of climate change
• Carbon sink capacity of terrestrial ecosystems
• World savannas
• Ecosystem carbon budget of savannas
• Cerrados
• Land use conversion in cerrados and C budget
• Strategies to harness carbon sink capacity of savannas
• Tenets of sustainable land use

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Historical Development In Global Warming

• **1783**: Volcanic fog caused by eruption in Iceland.
• **1850**: Joseph Fourier: Energy balance of earth.
• **1859**: John Tyndall: Not all gases are transparent to heat (H₂O, CH₄, CO₂).
• **1896**: Svante Arrhenius suggested the effect of CO₂ on global temperature.
• **1897**: Avrid Högboom: The biogeochemical cycles of CO₂.
• **1897**: Chamberlain’s model of global C exchange including feedback.
Historical Development (Cont.)

- 1938: Guy Stewart Callendar calculated the warming effect of CO2 emissions.
- 1979: The Gaia hypothesis.
- 1988: IPCC.
- 1992: UNFCCC.
Abrupt Climate Change (ACC) and the Biosphere

- For each 1 °C increase in global temperature, the vegetational zones may move poleward by 200 to 300 km

- Ecosystems cannot adjust to the “abrupt climate change”.
Climate Change

$\Delta T$ over 20th century. . . . . . . . . . . . +0.6$\pm$0.2°C

Rate of $\Delta T$ since 1950. . . . . . . . . . . . 
+0.17°C/decade

Sea level rise over 20th century. . . . +0.1-0.2m

Change in precipitation. . . . . . . . . . . . +0.5-1%/decade

Extreme events in Northern Hemisphere. . . +2-4% in frequency of heavy precipitation
On-set of Anthropogenic Emissions

A trend of increase in atmospheric concentration of CO$_2$ began 8000 years ago, and that in CH$_4$ 5000 years ago, corresponding with the dawn of settled agriculture with attendant deforestation, soil cultivation, spread of rice paddies and raising cattle.

...Ruddiman (2003)
Anthropogenic Emissions (1850-2000)

(a) Pre-Industrial era
   (i) 320 Pg (Ruddiman, 2003)

(b) Post-Industrial era
   (i) Fossil fuel: $270 \pm 30$ Pg
   (ii) Land use change: $136 \pm 55$ Pg
       Soil: $78 \pm 12$
Terrestrial C Sink Capacity

• Historic Loss from Terrestrial Biosphere = 456 Pg with 4 Pg of C emission = 1 ppm of CO₂

• The Potential Sink of Terrestrial Biospheres = 114 ppm

• Assuming that up to 50% can be resequestered = 45 – 55 ppm

• The Average Sink Capacity = 50 ppm over 50 yr.
Potential of Mitigating Atmospheric CO$_2$

(Hansen, 2008)
Potential carbon sink capacity of global ecosystems. (USDOE, 1999).

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Potential Carbon Sink Capacity (Pg C yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grasslands</td>
<td>0.5</td>
</tr>
<tr>
<td>Rangelands</td>
<td>1.2</td>
</tr>
<tr>
<td>Forests</td>
<td>1-3</td>
</tr>
<tr>
<td>Urban forests and grasslands</td>
<td>-</td>
</tr>
<tr>
<td>Deserts and degraded lands</td>
<td>0.8 – 1.3</td>
</tr>
<tr>
<td>Agricultural lands</td>
<td>0.85 – 0.9</td>
</tr>
<tr>
<td>Biomass croplands</td>
<td>0.5 – 0.8</td>
</tr>
<tr>
<td>Terrestrial sediments</td>
<td>0.7 – 1.7</td>
</tr>
<tr>
<td>Boreal peatlands and other wetlands</td>
<td>0.1 – 0.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>CMASC 10/08</strong> 5.65 – 10.1</td>
</tr>
</tbody>
</table>
## Predominant Regions of Savannas

<table>
<thead>
<tr>
<th>Climate</th>
<th>Regions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropics</td>
<td>Africa, South America, Australia, South Asia</td>
</tr>
<tr>
<td>Temperate</td>
<td>North America, Russia, Europe</td>
</tr>
</tbody>
</table>
## Land Area of Savannas

<table>
<thead>
<tr>
<th>Climate</th>
<th>Area ($10^6$ km$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropics</td>
<td>20</td>
</tr>
<tr>
<td>Temperate</td>
<td>9</td>
</tr>
<tr>
<td>Total</td>
<td>29</td>
</tr>
</tbody>
</table>

% of World Area 20%
## Tropical Savannas

<table>
<thead>
<tr>
<th>Region</th>
<th>Area ($10^6 \text{ km}^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Africa</td>
<td>15.1</td>
</tr>
<tr>
<td>South America</td>
<td>2.1</td>
</tr>
<tr>
<td>Australia</td>
<td>2.0</td>
</tr>
<tr>
<td>Others</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>20.0</strong></td>
</tr>
</tbody>
</table>

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Grasslands & Savannas of Tropical America

http://www.conservegrassland.org/images/maps/grassland_map_small.gif
CMASC 10/08
Land area and total net primary productivity of tropical savannas and other ecosystems (adapted from Grace et al., 2006).

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>Area ($10^6$ km²)</th>
<th>Total C Pool (Pg C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical savannas &amp; grasslands</td>
<td>27.6</td>
<td>326</td>
</tr>
<tr>
<td>Temperate grasslands</td>
<td>15.0</td>
<td>182</td>
</tr>
<tr>
<td>Tropical forests</td>
<td>17.5</td>
<td>553</td>
</tr>
<tr>
<td>Temperate forests</td>
<td>10.4</td>
<td>292</td>
</tr>
<tr>
<td>Boreal forests</td>
<td>13.7</td>
<td>395</td>
</tr>
<tr>
<td>Crops</td>
<td>13.5</td>
<td>15</td>
</tr>
<tr>
<td>World</td>
<td>149.1</td>
<td>2137</td>
</tr>
</tbody>
</table>

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Climate Change and Savannas

- Projected climate change may reduce the total C pool in savanna biomes by 4 Pg C over 50 yrs (Scurlock and Hall, 1998).

- The loss may be due to
  (i) Increase in respiration
  (ii) Acceleration of soil erosion

- In some cases CO₂ fertilization effect may make TS a modest C sink
Ecosystem C Pool in Savannas

ECP = AGB + BGB + DM + SOC

AGB = Above ground biomass
BGB = Below ground biomass
DM = Detritus material
SOC = Soil C pool
C Pool & Fluxes in Natural Savannas

Emissions of CO₂, CH₄, N₂O

Above ground Biomass

Below ground Biomass

SOC

GPP

Humification

Erosion & Leaching
Deforestation of Tropical Savannas (TS)

- Removal of tree cover can deplete the ecosystem C pool over years

- The loss is more from biomass C than SOC pool
C Pool & Fluxes in Agricultural Ecosystems
Ecosystem C Pool Changes by Land Use Conversion and Deforestation

Ecosystem C Pool

Biomass C

Soil C Pool

C Sink Capacity

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Fire and the Savanna Ecosystems

http://earthobservatory.nasa.gov/Library/BiomassBurning/Images/figure1.jpg

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Fire and Ecosystem

iomass burning = 5 – 8 Pg C yr\(^{-1}\)

mission = Aerosol, POM, Soot (Black C)

erosol in tropics = 30 Tg yr\(^{-1}\)
Land Area Affected by Burning During 20th Century

Global area burnt = 608 Mha yr\(^{-1}\)

Area burnt in tropical savannas = 523 Mha yr\(^{-1}\) (86%)

(Fire in TRF = 70.7 Mha yr\(^{-1}\))

Mouillet and Field (2005)
Smoke Plume

Area covered in South America = \(4 - 5 \times 10^6 \text{ km}^2\)
Cerrado

Area = $2 \times 10^6 \text{ km}^2$

Suitable for Agric. = 62%

Rainfall = 600 mm – 2000 mm per annum

Dry season = 4 to 7 months

Mean annual temperature = 22° to 27° C

Pastures = 66 Mha

Cropland = 18 Mha

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Cerrados of Brazil

http://www.worldfoodprize.org/assets/pressroom/2006/June/brazil_map.jpg

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Savanna To Tree Plantations

Mean C Pool in Native Tropical Savannas  =  67 Mg ha\(^{-1}\)

Mean C Pool in Improved Tree Plantations  =  150 Mg ha\(^{-1}\)

Area Convertible to Tree Plantations  =  11.5 \times 10^6 \text{ km}^2

Carbon Sequestration Potential  =  94.3 \text{ Pg over } 50 \text{ yrs}

=  \sim 2 \text{ Pg C yr}^{-1}

Scurlock and Hall (1998)
Savanna To Pastures

- Degraded pastures deplete Soc pool: Source of CO\(_2\)

- Improved pastures can enhance SOC pool: Sink of CO\(_2\)
Conversion of Savannas to Pastures


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Degraded Pastures are Indicated by Termite Mounds

http://upload.wikimedia.org/wikipedia/commons/e/e4/Termite_mounds_NT.JPG
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SOC Sequestration In Improved Pastures

Pasture Area in Cerrados $= 0.6 \text{ – } 0.8 \times 10^6 \text{ km}^2$

Rate of C Sequestration $= 1.5 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$

Total Potential $= 0.05 \text{ – } 0.1 \text{ Pg C yr}^{-1}$
# Rate of soil carbon sequestration by no-till farming in the Brazilian Cerrados.

<table>
<thead>
<tr>
<th>Cropping System</th>
<th>Duration (yrs)</th>
<th>Soil Depth (cm)</th>
<th>C Sequestration (Mg C ha-1 yr-1)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean</td>
<td>12</td>
<td>20</td>
<td>0.83</td>
<td>Corbeels et al. (2006)</td>
</tr>
<tr>
<td>Soybean</td>
<td>12</td>
<td>40</td>
<td>0.7-1.15</td>
<td>Corbeels et al. (2006)</td>
</tr>
<tr>
<td>Corn-Soybean</td>
<td>2</td>
<td>30</td>
<td>- 1.5</td>
<td>San José and Montes (2001)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tiessen et al. (1999)</td>
</tr>
<tr>
<td>Rice (upland)</td>
<td>5</td>
<td>10</td>
<td>0.35</td>
<td>Lilienfein and Wilcke (2003)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Zinn et al. (2005)</td>
</tr>
<tr>
<td>Soybean-Maize</td>
<td>8</td>
<td>20</td>
<td>0.3-0.6</td>
<td>Metay et al. (2007a)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bayer et al. (2006)</td>
</tr>
</tbody>
</table>

CMASC 10/08
Soil carbon pool in different land uses in cerrado region of Minas Gerais (Recalculated from Lilienfein and Wilcke, 2003).

<table>
<thead>
<tr>
<th>Land use</th>
<th>Age (yrs)</th>
<th>Soil Organic Carbon Pool (Mg ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0 – 0.3 m</td>
</tr>
<tr>
<td>Cerrado</td>
<td>-</td>
<td>55 ± 2.3 (^{ab})</td>
</tr>
<tr>
<td>Pinus</td>
<td>20</td>
<td>49 ± 2.9 (^{b})</td>
</tr>
<tr>
<td>Degraded Pasture</td>
<td>14</td>
<td>60 ± 4.7 (^{ab})</td>
</tr>
<tr>
<td>Productive Pasture</td>
<td>14</td>
<td>64 ± 8.1 (^{a})</td>
</tr>
<tr>
<td>No-till</td>
<td>2</td>
<td>58 ± 5.3 (^{ab})</td>
</tr>
<tr>
<td>Plow tillage</td>
<td>12</td>
<td>61 ± 3.2 (^{ab})</td>
</tr>
</tbody>
</table>

Figures in the column followed by the same letters are statistically similar.

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Savanna To Croplands

- Plow till croplands = Source
- NT croplands = Possible sink
Conversion of Savanna to No-till Farming


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Rate of SOC Sequestration by NT Farming

Conversion to NT = 0.5 – 1.2 Mg C ha\(^{-1}\) yr\(^{-1}\)

Total potential on 18 Mha = 10 – 15 Tg C yr\(^{-1}\)
Eucalyptus Savannas of Australia

http://upload.wikimedia.org/wikipedia/en/thumb/1/14/9706101.jpg/240px-9706101.jpg

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C Pool & Fluxes in Eucalyptus Savanna, Australia (Grace et al., 2006)

Above ground Biomass
32.3 ± 12.2 Mg C ha\(^{-1}\)

Below ground Biomass
20.7 ± 6.0 Mg C ha\(^{-1}\)

SOC Pool
151 ± 33 Mg C ha\(^{-1}\)

14.3 Mg C ha\(^{-1}\) yr\(^{-1}\)
GPP 20.8 Mg C ha\(^{-1}\) yr\(^{-1}\)
5.6 Mg C ha\(^{-1}\) yr\(^{-1}\)
15.2 Mg C ha\(^{-1}\) yr\(^{-1}\)
Carbon pools and fluxes in savanna ecosystems (Grace et al., 2006).

- Atmospheric C Pool: 780 (+ 3.5) tC
- Above-Ground C Pool: 26 tC
- Below-Ground C Pool: 52 tC
- Soil Organic Carbon Pool: 480 tC

Flows:
- Fire: 4.5
- Litter Fall: 15
- NPP: 20
- Land Use Change: 0.4 – 0.8
- Soil Respiration?
# Hidden C Cost of Fuel Sources

<table>
<thead>
<tr>
<th>Source/ Practice</th>
<th>Equivalent carbon emission (kg C E)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>I. Fuel (kg of fuel)</strong></td>
<td></td>
</tr>
<tr>
<td>1. Diesel</td>
<td>0.94</td>
</tr>
<tr>
<td>2. Gasoline</td>
<td>0.59</td>
</tr>
<tr>
<td>3. Oil</td>
<td>1.01</td>
</tr>
<tr>
<td>4. Natural gas</td>
<td>0.85</td>
</tr>
</tbody>
</table>

# Hidden C Costs of Tillage Methods

<table>
<thead>
<tr>
<th>Source/ Practice</th>
<th>Equivalent carbon emission (kg C E)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>II. Tillage (per ha)</strong></td>
<td></td>
</tr>
<tr>
<td>1. Moldboard plowing</td>
<td>15.2</td>
</tr>
<tr>
<td>2. Chisel plowing</td>
<td>7.9</td>
</tr>
<tr>
<td>3. Disking</td>
<td>8.3</td>
</tr>
<tr>
<td>4. Cultivation</td>
<td>4.0</td>
</tr>
</tbody>
</table>

# Hidden C Costs of Fertilizer

<table>
<thead>
<tr>
<th>Source/ Practice</th>
<th>Equivalent carbon emission (kg C E)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>III. Fertilizers (Per kg)</strong></td>
<td></td>
</tr>
<tr>
<td>1. Nitrogen</td>
<td>1.3</td>
</tr>
<tr>
<td>2. Phosphorus</td>
<td>0.2</td>
</tr>
<tr>
<td>3. Potash</td>
<td>0.15</td>
</tr>
<tr>
<td>4. Lime</td>
<td>0.16</td>
</tr>
</tbody>
</table>

# Hidden C Costs of Pesticides

<table>
<thead>
<tr>
<th>Source/ Practice</th>
<th>Equivalent carbon emission (kg C E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IV. Pesticides</td>
<td></td>
</tr>
<tr>
<td>1. Herbicides</td>
<td>6.3</td>
</tr>
<tr>
<td>2. Insecticides</td>
<td>5.1</td>
</tr>
<tr>
<td>3. Fungicides</td>
<td>3.9</td>
</tr>
</tbody>
</table>

Land area and total net primary productivity of tropical savannas and other ecosystems (adapted from Grace et al., 2006).

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>C Sink Capacity (Pg C yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical savannas &amp; grasslands</td>
<td>0.39</td>
</tr>
<tr>
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<td>0.21</td>
</tr>
<tr>
<td>Tropical forests</td>
<td>0.66</td>
</tr>
<tr>
<td>Temperate forests</td>
<td>0.35</td>
</tr>
<tr>
<td>Boreal forests</td>
<td>0.47</td>
</tr>
<tr>
<td>Crops</td>
<td>0.02</td>
</tr>
<tr>
<td>World</td>
<td>2.55</td>
</tr>
</tbody>
</table>
Strategies to make TS biomes a net C sink

- **Restoring Degraded Ecosystems**
  - Afforestation
  - Reforestation
  - Species selection
  - Stand management
  - Fire management
  - GM crops/biotech
  - Deep root system
  - Improved pasture species
  - Controlled grazing
  - Soil fertility management

- **Tropical Savannas**
  - Above ground biomass
  - Below ground biomass
  - Soil C pool
  - Creating positive C and nutrient budgets
  - Reducing losses
  - Enhancing biodiversity
  - NT farming
  - Cover cropping
  - Precision farming
  - INM/IPM
  - Nano-enhanced materials

- **Restoring Cropland**
  - NT
  - INM, IPM
  - Enhancing use efficiency

- **Restoring Pastures**
  - Species
  - Management
  - Grazing
  - Improved pasture species
  - Controlled grazing
  - Soil fertility management

- **Biofuel plantations**
- **Tree plantations**
- **Native savannas**
- **NT farming**
- **Cover cropping**
- **Precision farming**
- **INM/IPM**
- **Nano-enhanced materials**

Creating positive C and nutrient budgets
Reducing losses
Enhancing biodiversity
Enhancing use efficiency
Enhancing biodiversity
Enhancing use efficiency
Enhancing biodiversity
Enhancing use efficiency
Land area and total net primary productivity of tropical savannas and other ecosystems (adapted from Grace et al., 2006).

<table>
<thead>
<tr>
<th>Ecosystem</th>
<th>C Sink Capacity (Pg C yr(^{-1}))</th>
<th>C Sequestration Rate (Mg C ha(^{-1}) yr(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical savannas &amp; grasslands</td>
<td>0.39</td>
<td>0.14</td>
</tr>
<tr>
<td>Temperate grasslands</td>
<td>0.21</td>
<td>0.14</td>
</tr>
<tr>
<td>Tropical forests</td>
<td>0.66</td>
<td>0.37</td>
</tr>
<tr>
<td>Temperate forests</td>
<td>0.35</td>
<td>0.34</td>
</tr>
<tr>
<td>Boreal forests</td>
<td>0.47</td>
<td>0.34</td>
</tr>
<tr>
<td>Crops</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>World</td>
<td>2.55</td>
<td>2-3</td>
</tr>
</tbody>
</table>
# Savannas And Climate Change

<table>
<thead>
<tr>
<th>Era</th>
<th>Sink Capacity (Pg C yr⁻¹)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present</td>
<td>0.74</td>
<td>Thornley et al. (1991)</td>
</tr>
<tr>
<td></td>
<td>0.1 – 0.5</td>
<td>Fisher et al. (1994, 1995)</td>
</tr>
<tr>
<td>Future</td>
<td>-1.0 to -2.0</td>
<td>Paston et al. (1995)</td>
</tr>
<tr>
<td></td>
<td>1.5 – 1.6</td>
<td>Lutz and Gifford (1995)</td>
</tr>
<tr>
<td></td>
<td>~ 2.0</td>
<td>Scholes and Hall (1995)</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>Scurlock and Hall (1998)</td>
</tr>
</tbody>
</table>

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Strategies To Harness C Sink Capacity of Savannas

• Stop further conversion of native TS to agricultural ecosystems

• Promote conversion of degraded pastures to tree plantations

• Adopt NT system with cover crops and residue mulch

• Follow integrated nutrient management and integrated pest management practices to reduce dependence on fertilizers and pesticides

• Use slow release formulations of fertilizers with nano-enhanced materials, and grow genetically modified plants to enhance use efficiency of input

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Strategies To Harness C Sink Capacity of Savannas (Cont.)

- Adopt land-saving practices of agricultural intensification for increasing production from existing lands so that natural TS biomes can be preserved for nature conservancy.

- Create another income stream for farmers through making payments for ecosystem services (e.g., trading C credits).

- Establish biofuel and timber plantations.

- Regulate fire or biomass burning.

- Adopt measures to reduce runoff and control soil erosion.
Ten
Tenets of Soil and Water Management
The biophysical process of soil degradation is driven by economic, social and political forces.
Law #2

Soil Stewardship and Human Suffering

When people are poverty stricken, desperate and starving, they pass on their sufferings to the land.
Law #3

Nutrient, Carbon and Water Bank

It is not possible to take more out of a soil than what is put in it without degrading its quality.
The Ultimate Recycling

Energy flow

Mosquito bites frog
Mosquito gains energy

Frog eats mosquito
Frog gains energy

An Impossible Ecosystem
Law #4

Marginality Principle

Marginal soils cultivated with marginal inputs produce marginal yields and support marginal living.
Plants cannot differentiate the nutrients supplied through inorganic fertilizers or organic amendments.
Law #6

Soil Carbon and Greenhouse Effect

Mining C has the same effect on global warming whether it is through mineralization of soil organic matter and extractive farming or burning fossil fuels or draining peat soils.
Law #7

Soil Versus Germplasm

Even the elite varieties cannot extract water and nutrients from any soil where they do not exist.
Law #8

Soil As Sink For Atmospheric CO2

Soil are integral to any strategy of mitigating global warming and improving the environment
Law #9

**Engine of Economic Development**

Sustainable management of soils is the engine of economic development, political stability and transformation of rural communities in developing countries.
Law #10
Traditional Knowledge and Modern Innovations

• Sustainable management of soil implies the use of modern innovations built upon the traditional knowledge.

• Those who refuse to use modern science to address urgent global issues must be prepared to endure more suffering.
Soil Carbon and Greenhouse Effect
Organic Versus Inorganic Source of Nutrients
Sustainable Management of Soil
Engine of Economic Development
Traditional Knowledge and Modern Innovations
Causes of Soil Degradation
Soil Stewardship and Human Suffering
Marginality Principle
Nutrient, Carbon and Water Bank
Soil Versus Germplasm
Soil As Sink For Atmospheric CO₂
A Precious Resource

Irrespective of the climate debate, soil quality and its organic matter content must be restored, enhanced and improved.
Not Taking Soils for Granted

If soils are not restored, crops will fail even if rains do not; hunger will perpetuate even with emphasis on biotechnology and genetically modified crops; civil strife and political instability will plague the developing world even with sermons on human rights and democratic ideals; and humanity will suffer even with great scientific strides. Political stability and global peace are threatened because of soil degradation, food insecurity, and desperateness. The time to act is now.

Lal (Science, 2008)