Biochar Systems in Smallholder Agriculture

Johannes Lehmann

Department of Crop and Soil Sciences

Cornell University

Early Descriptions of Terra Preta

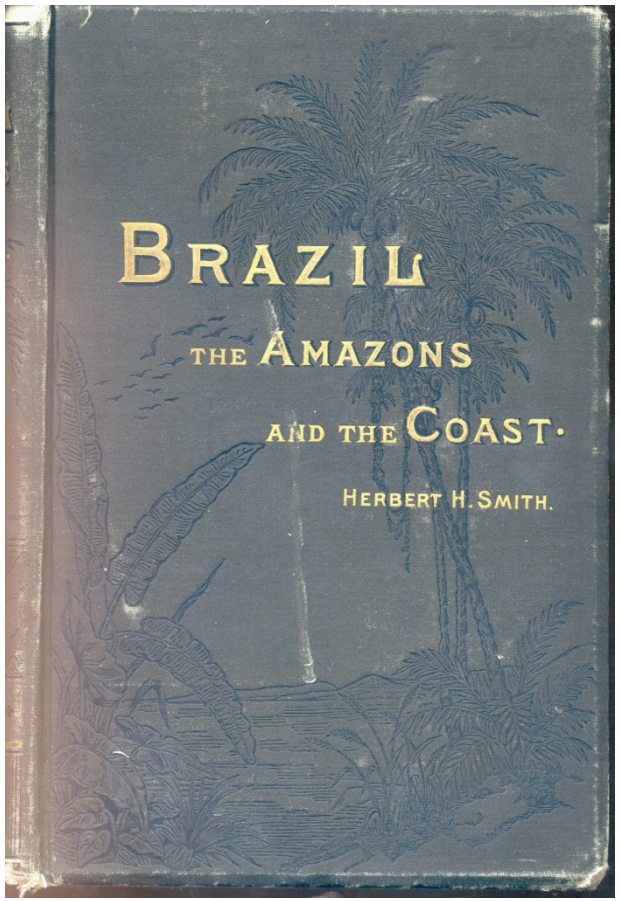
- *Terra Preta* ('black earth') has been radiocarbon dated to be between 500 to 8000 years old.
- Terra Preta is found only where people lived - it is an artificial, human-made soil, rich in minerals. It's most important ingredient is **biochar**, the source of Terra Preta's color.



Early Descriptions of Terra Preta

"The cane field itself is a splendid site; the stalks ten feet high in many places, and as big as one's wrist. This is the rich *terra preta*, 'black land', the best on the Amazons. It is a fine, dark loam, a foot and often two feet thick."
Herbert Smith (1851-1919)

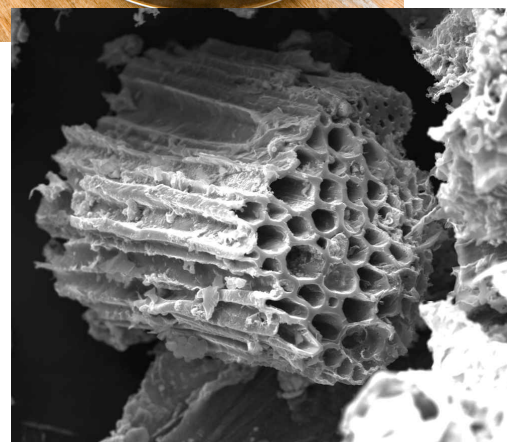
"The soil is black and very fertile. It beats South Carolina, yielding without culture 30 bushels of rice per acre."
James Orton (1830-1877)

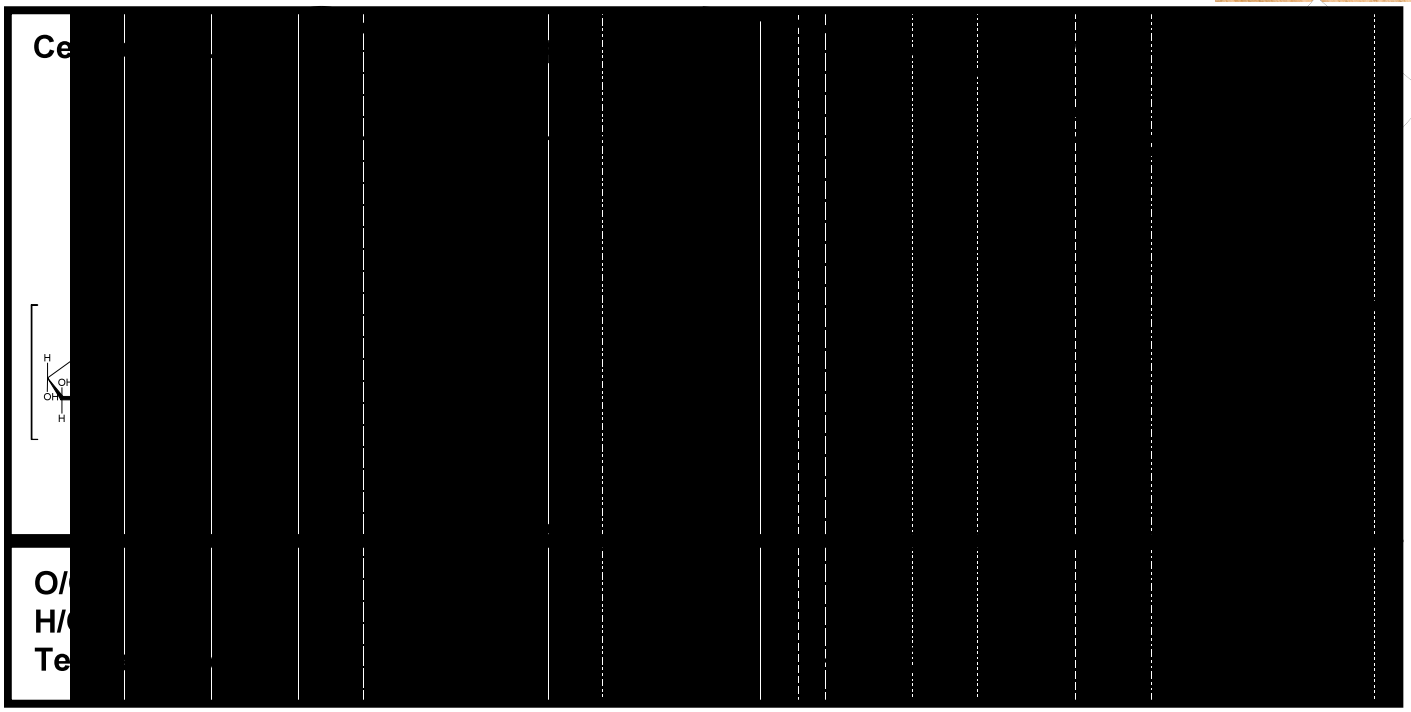


Biochar Conversion

Complete chemical changes
during heating in absence of air (pyrolysis)







Lehmann et al., 2010, in: Imperial College Press, London

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Natural Occurrence

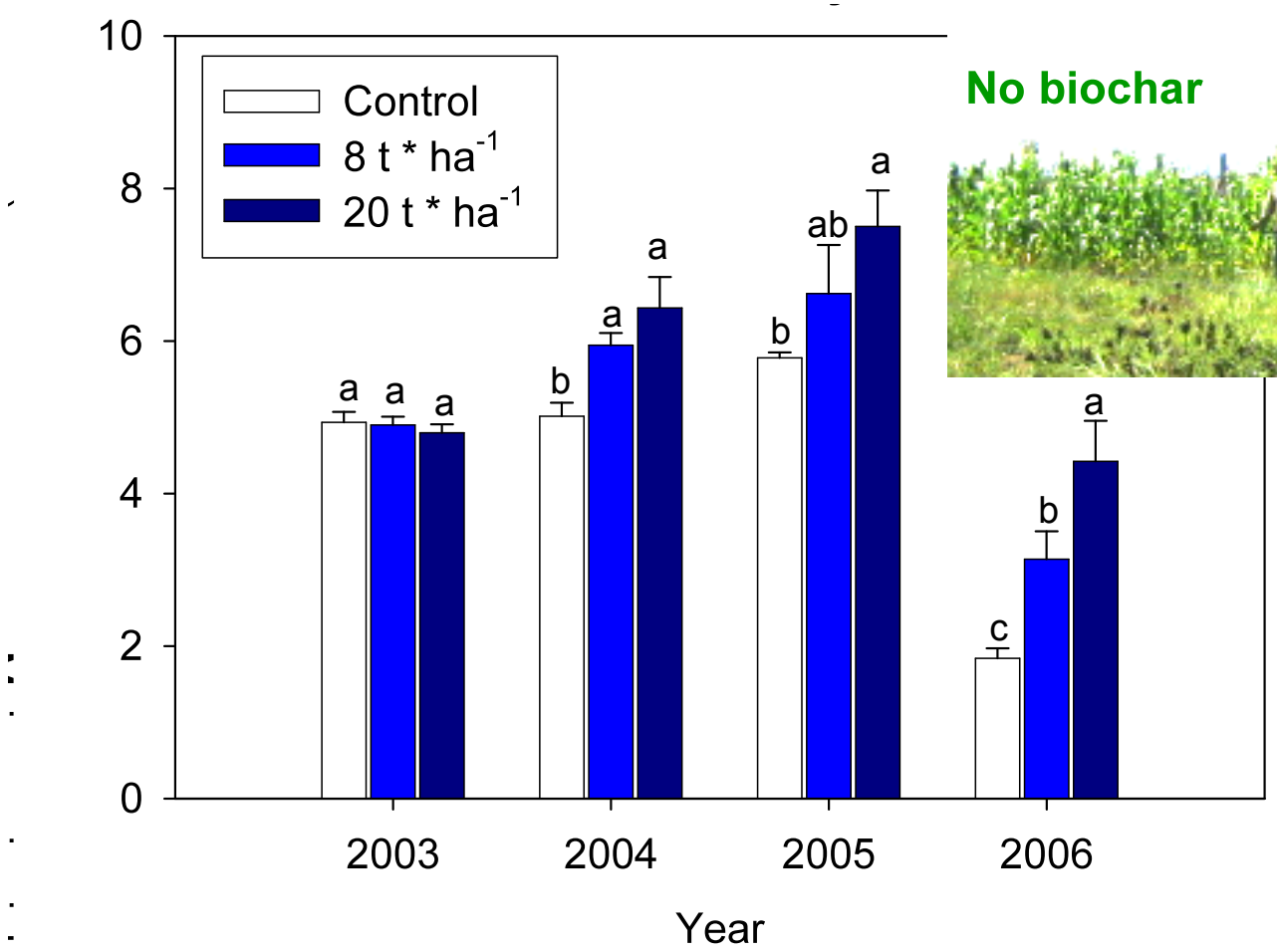








Yield Response



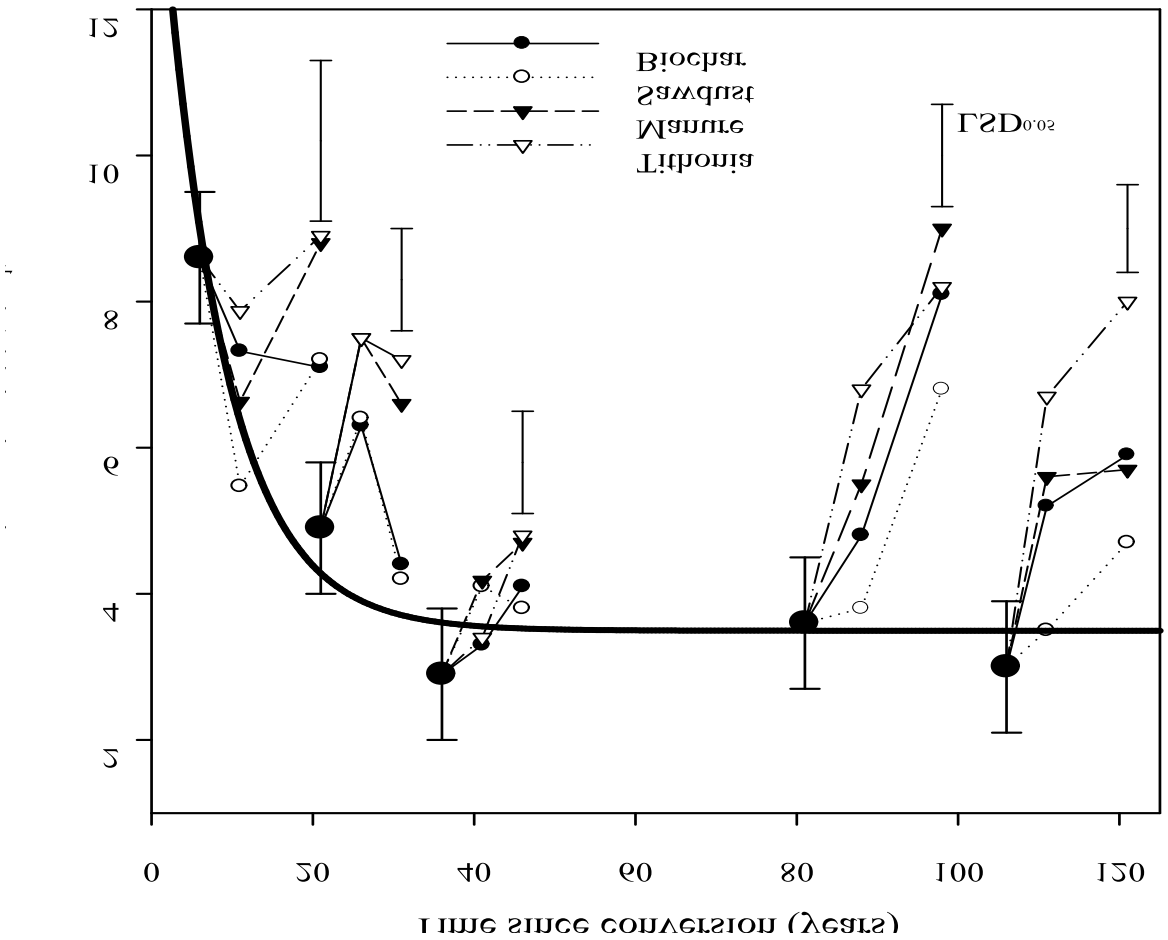


Applied <u>once</u> in 2003
Colombian Llanos
(N=3)

Major et al., 2010, *Plant and Soil* 333, 117-128

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Soil Fertility Dependency

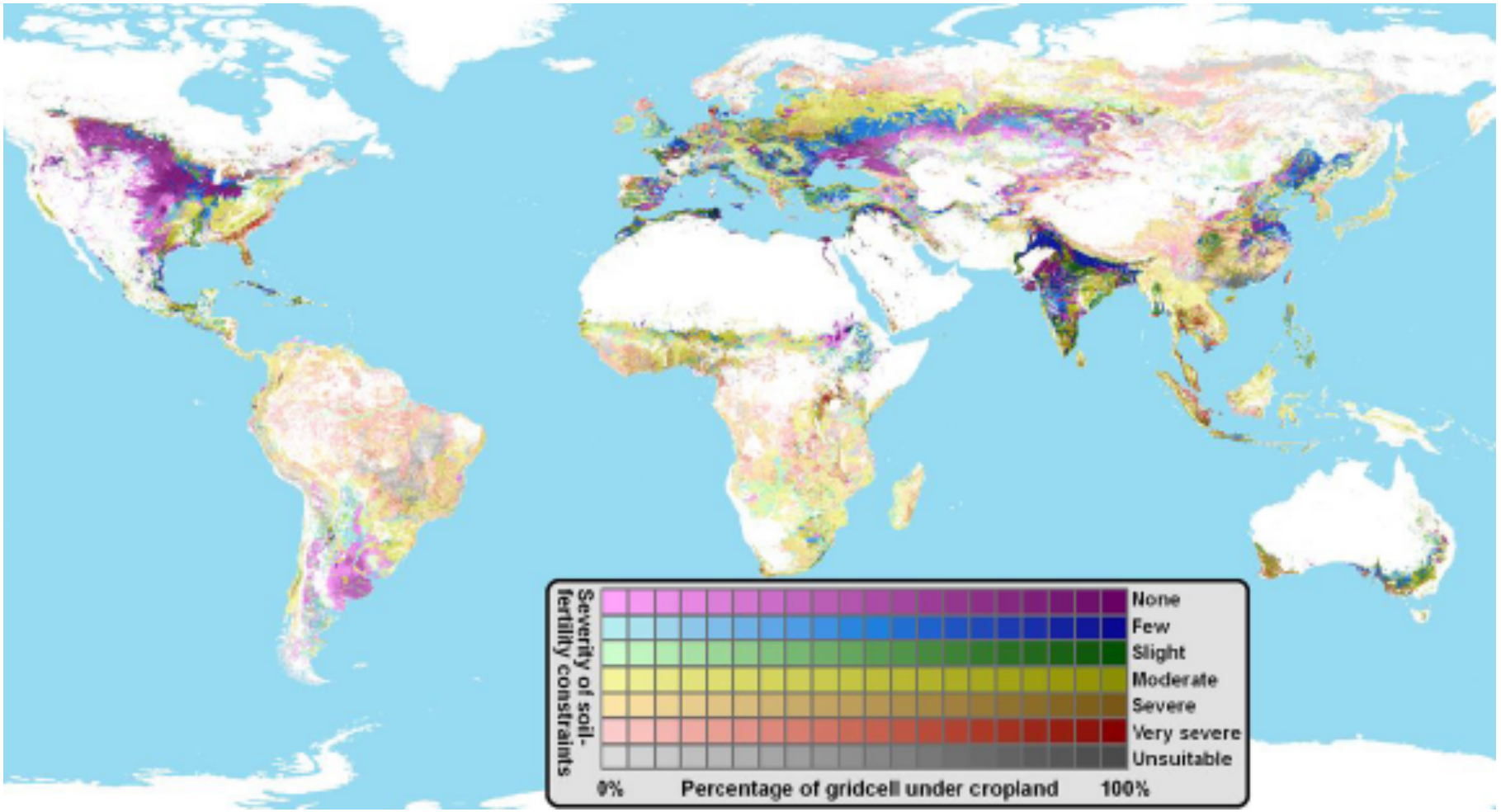


Biochar applied each season
Kenya (n=3)

Kimetu et al., 2008, *Ecosystems* 11: 726-739

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Biochar Soil Improvement Potential



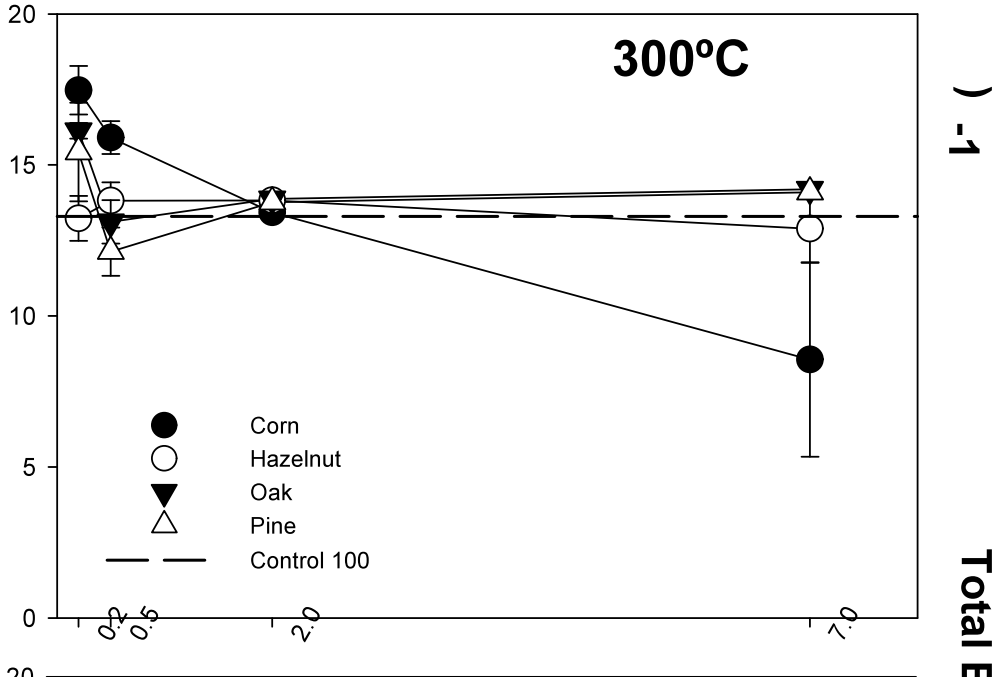
Woolf et al, 2010, *Nature Communications 1, 56*

Biochar Properties and Soil Effects

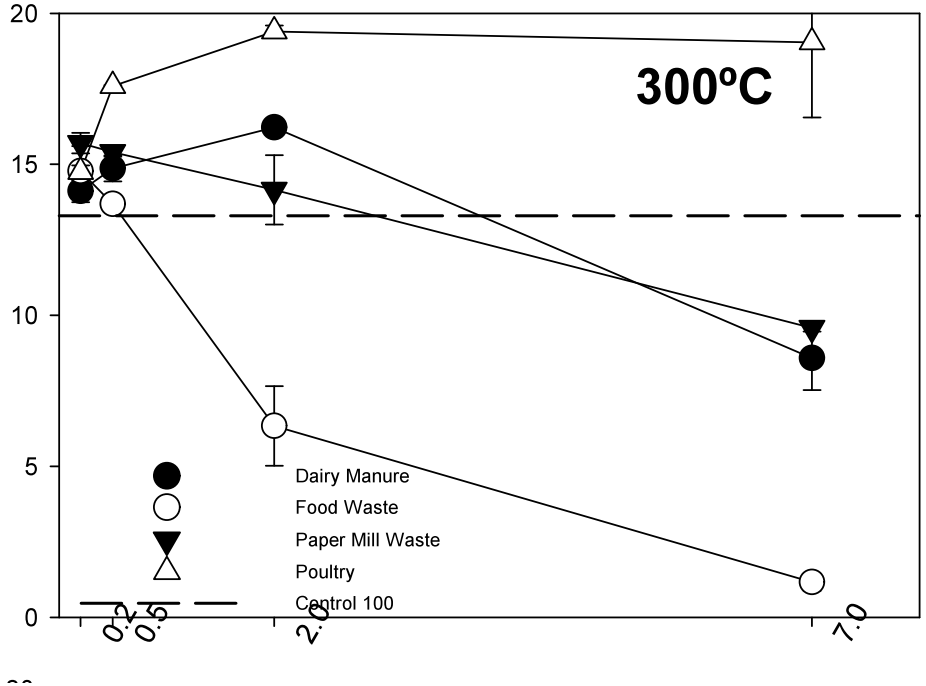


Corn greenhouse trial
Upstate NY loamy soil
N=2 (mean ±SE)

Plant Materials



Waste Materials

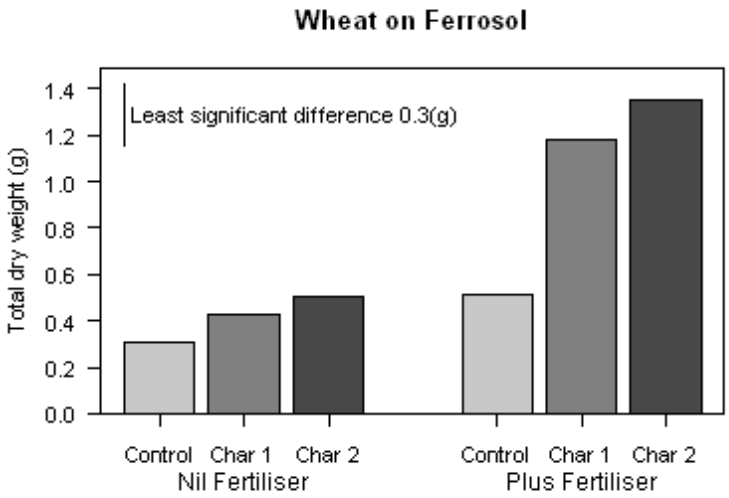


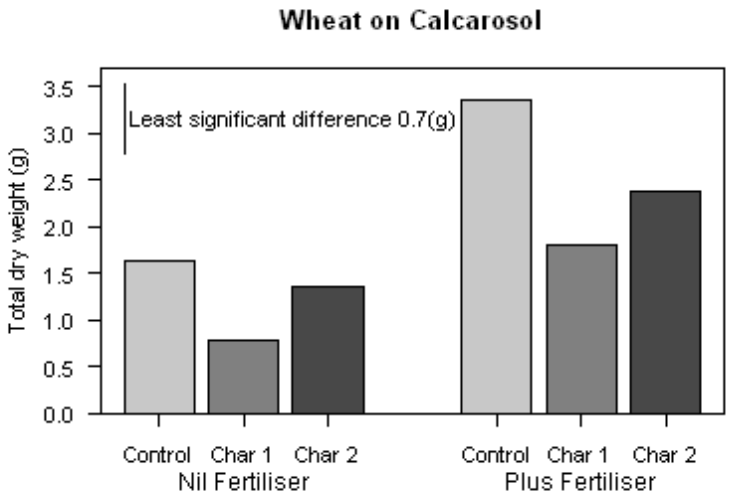
Biochar application rate (% w/w)

Rajkovich et al, unpubl data

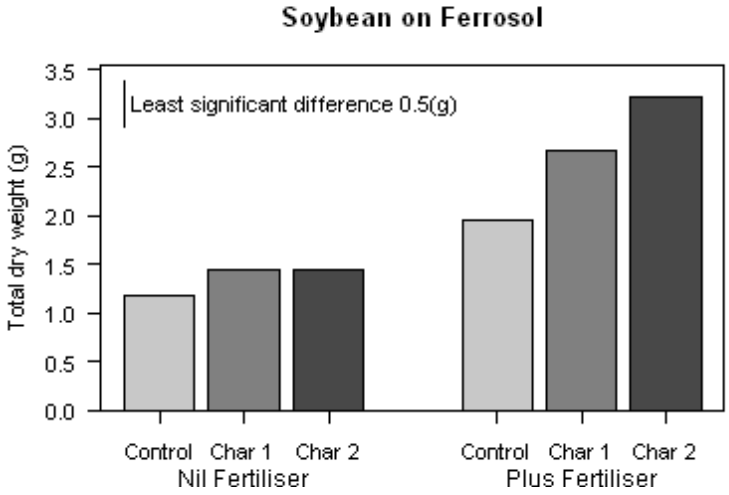
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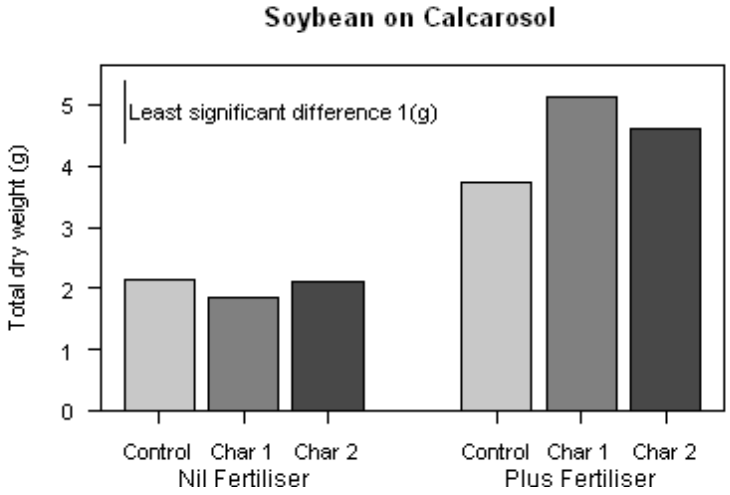
Matching Management to Soil Properties





Variability ≠ Uncertainty





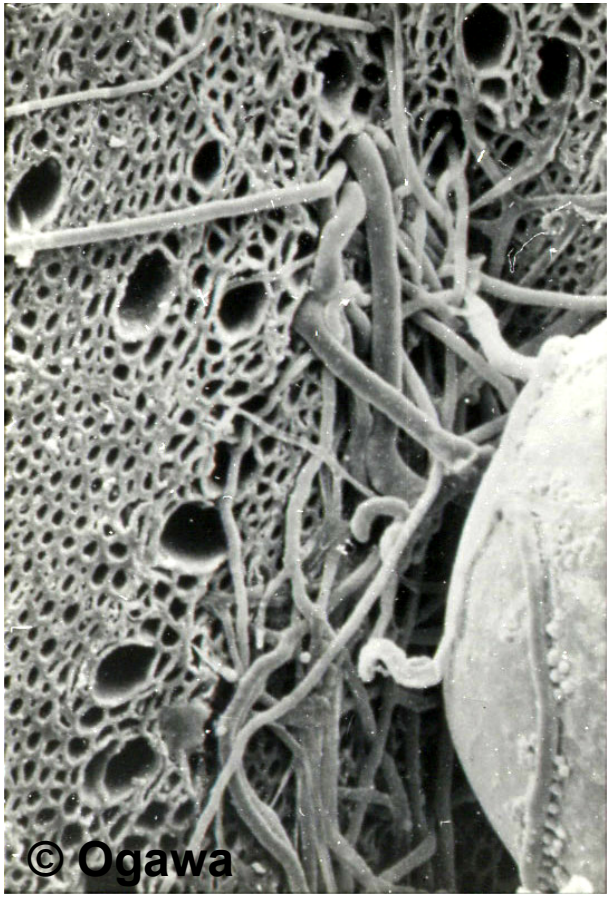
Australia
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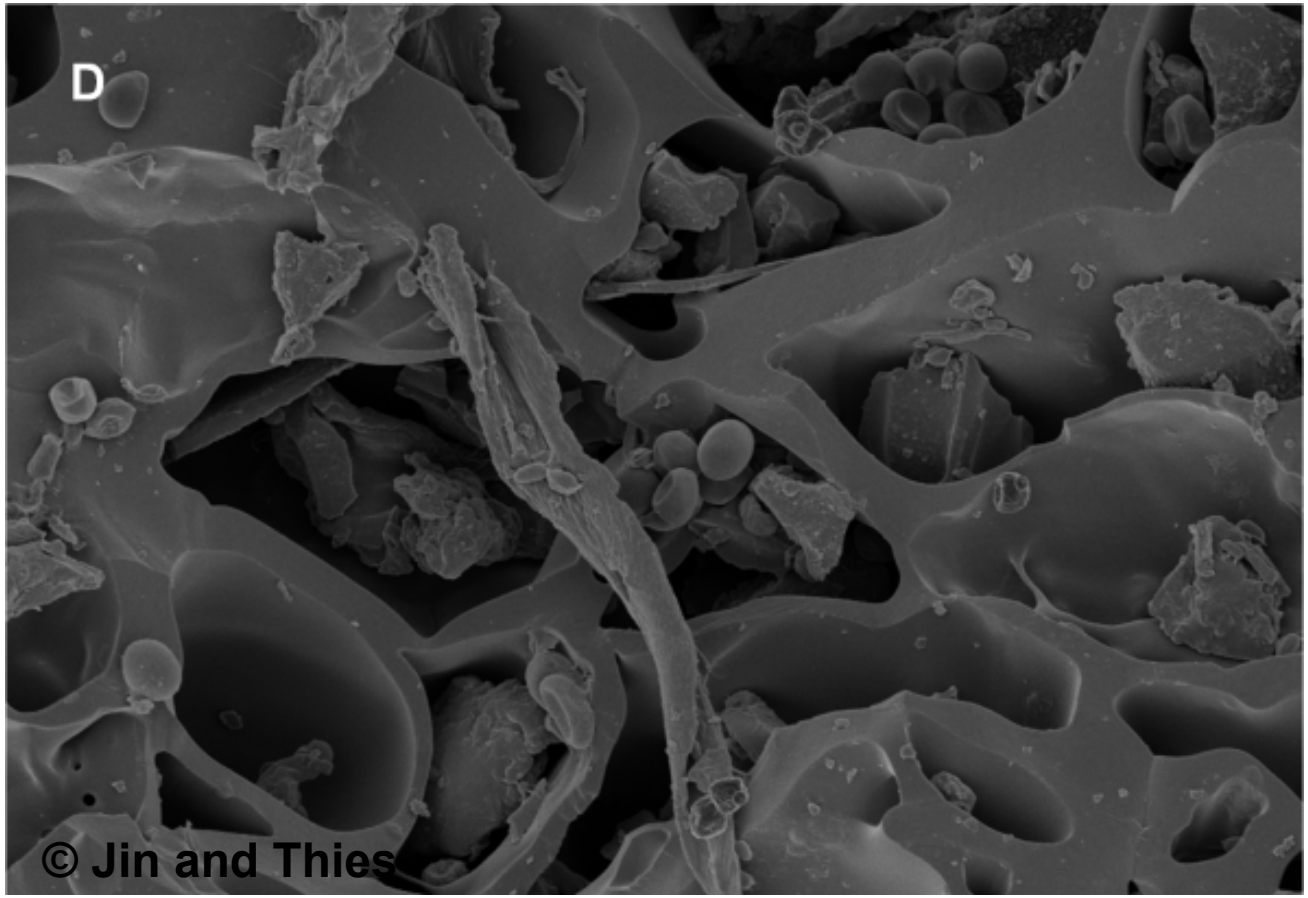
Van Zwieten et al., 2010, *Plant and Soil* 327:235–246

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Soil Biota

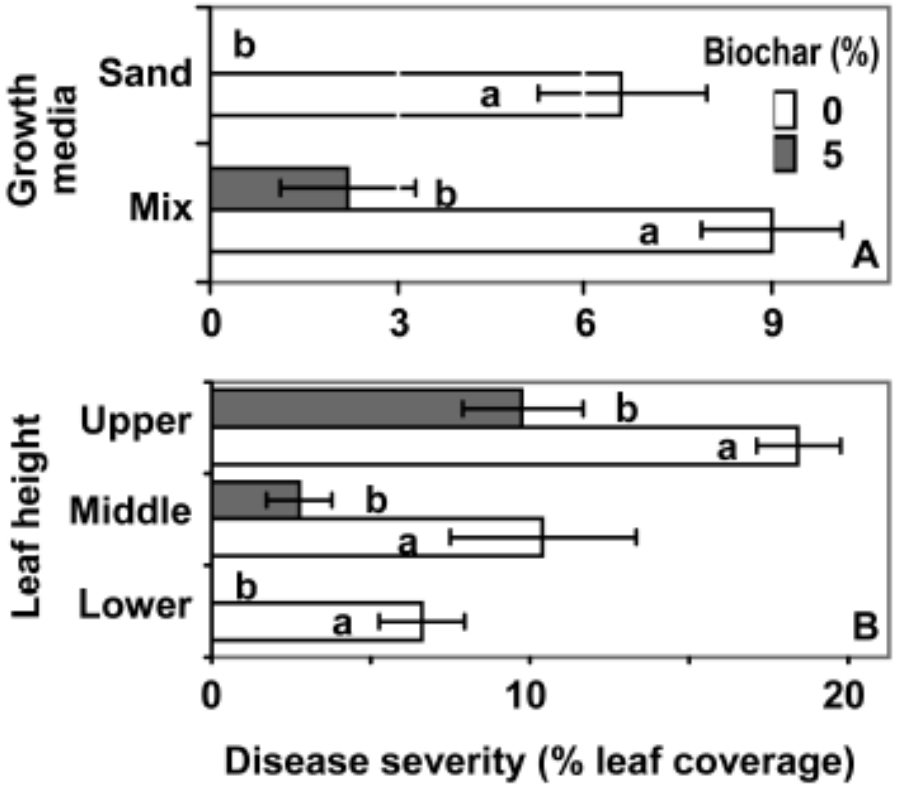
Protection from grazers?

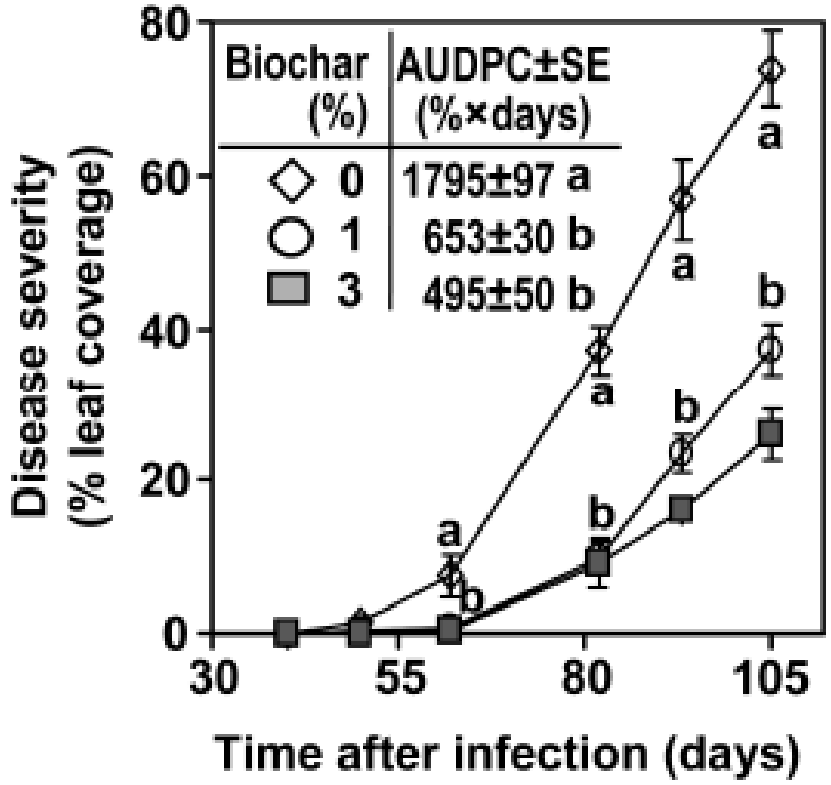




Pathogens

Powdery mildew (*Leveillula taurica*) on tomato

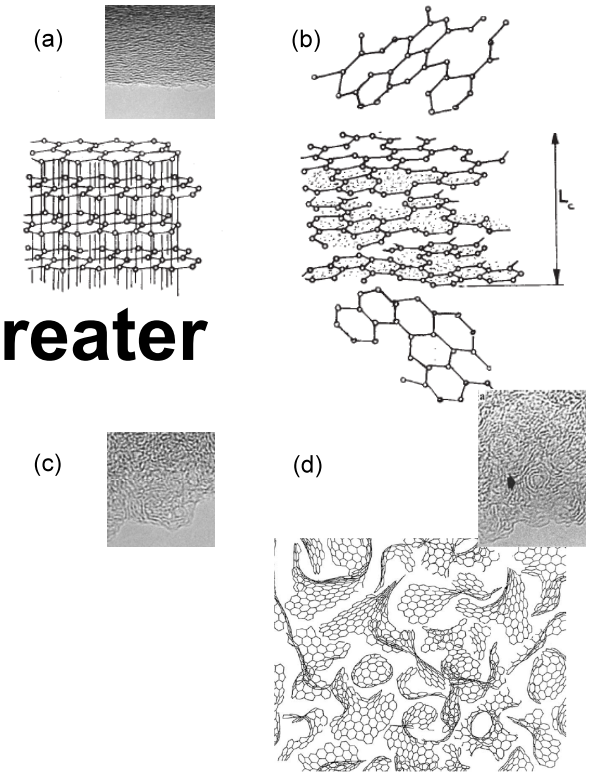




Elad et al, 2010, *Phytopathology* 100, 913-921

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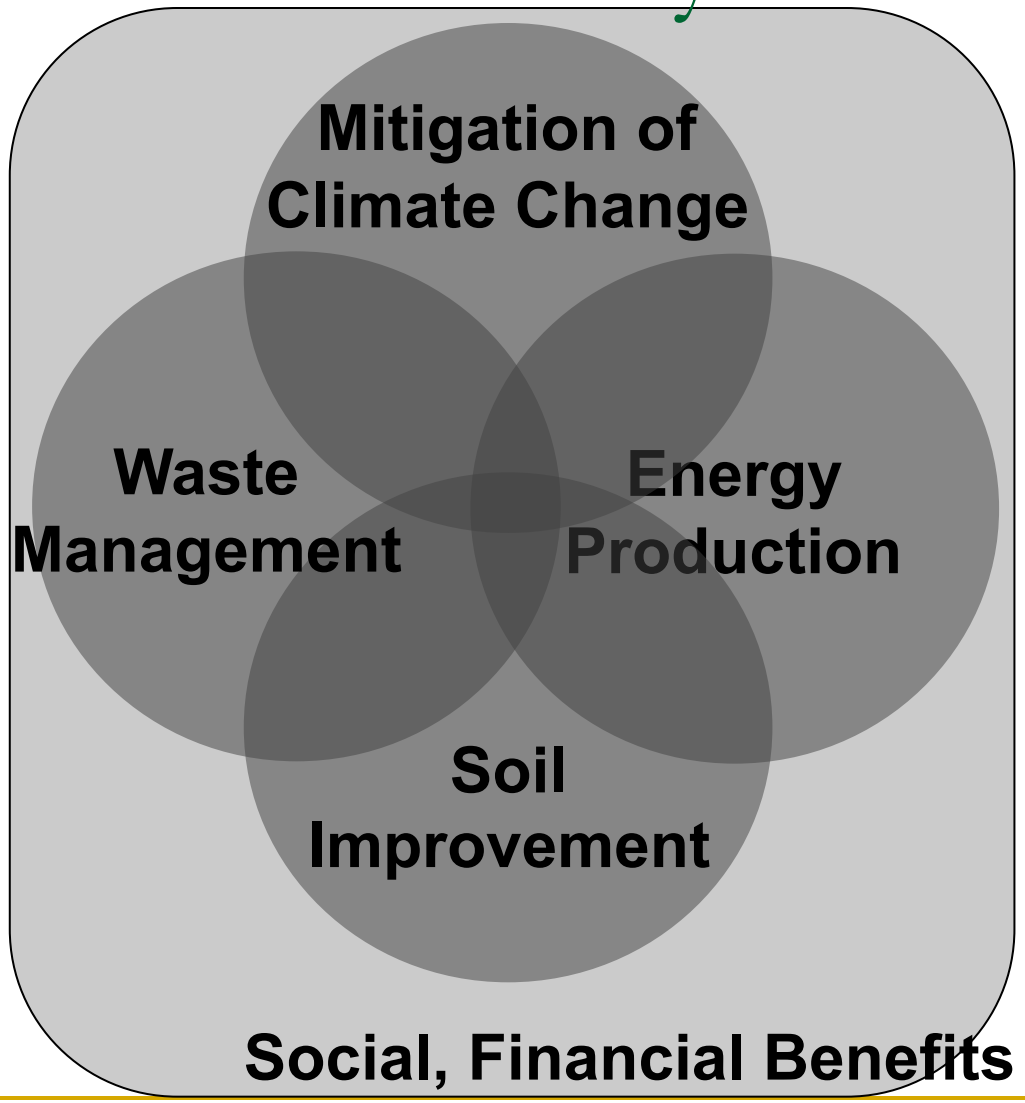
Biochar Stability



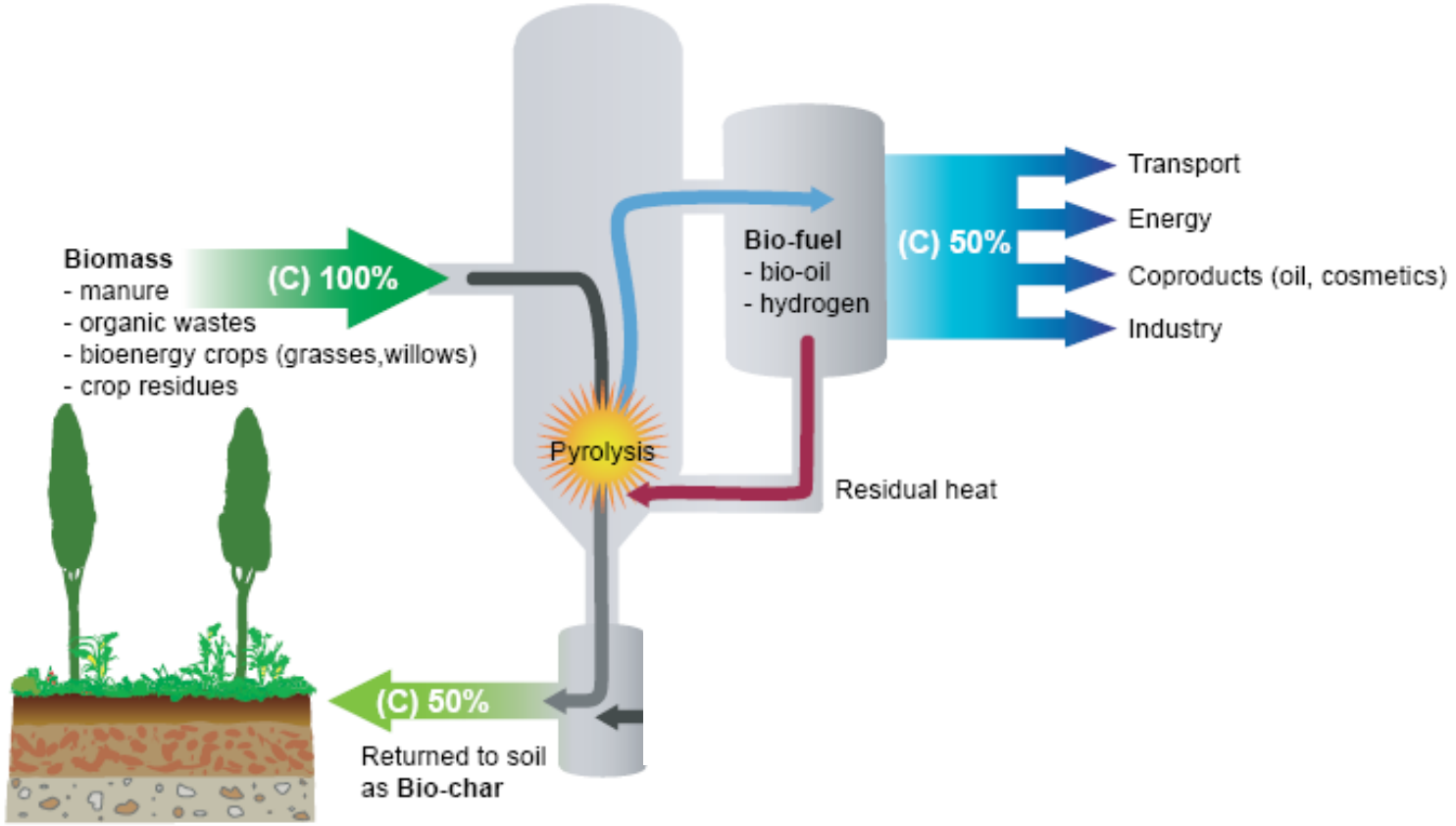
About 1.5 to 2 orders of magnitude greater than uncharred biomass

Baldock and Smernik, 2002, *Organic Geochemistry* 33, 1093-1109
Bruun et al., 2008, *Organic Geochemistry* 39, 839-845
Cheng et al., 2008, *Journal of Geophysical Research*, 113, G02027
Lehmann et al, 2008, *Nature Geoscience* 1, 832 - 835
Liang et al, 2008, *Geochimica et Cosmochimica Acta* 72, 6069-6078
Kuzyakov et al., 2009, *Soil Biology and Biochemistry* 41, 210-219
Major et al., 2010, *Global Change Biology*, 16, 1366-1379
Zimmerman, 2010, *Environmental Science and Technology* 44, 1295-1301

Biochar Benefits – Systems Dimension



Biochar System – Concept



Lehmann, 2007, *Frontiers in Ecology and the Environment* 7, 381-387

From Concept to Practice



Biochar Production



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Biochar Production



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Biochar Production



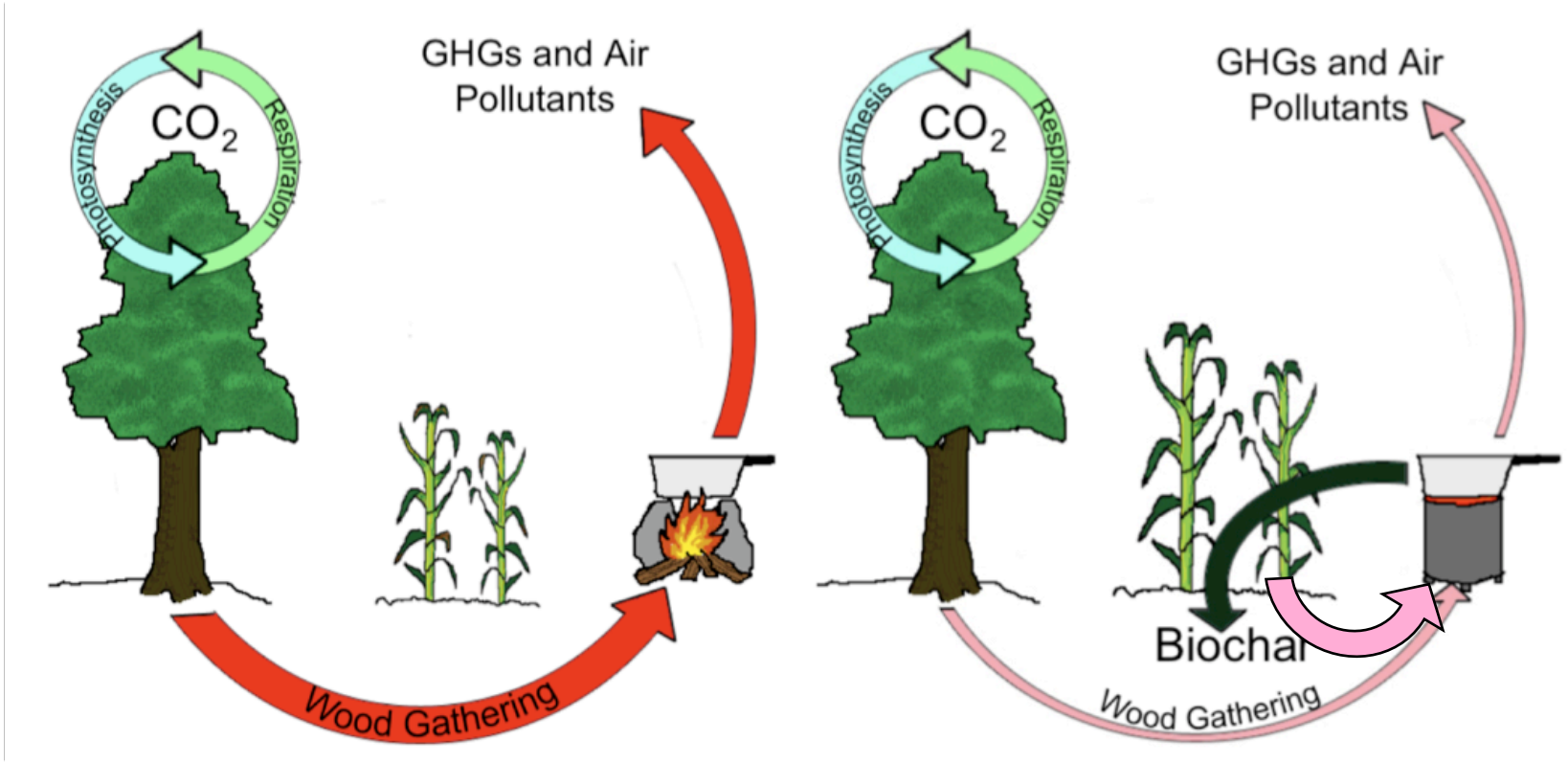
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Biochar Cook Stoves





Biochar Cook Stoves - Principles



Traditional 3-Stone Stove

Biochar Cook Stove

Whitman and Lehmann, 2009, *Environmental Science and Policy* 12, 1024-1027

Biomass availability

Suitable and available for pyrolysis (includes non-traditional feedstocks)

Conversion	Total Standing Biomass ($t\ farm^{-1} yr^{-1}$)	Total Standing Biomass ($t\ ha^{-1} yr^{-1}$)	Total Productivity ($t\ farm^{-1}\ yr^{-1}$)	Total Productivity ($t\ ha^{-1}\ yr^{-1}$)
Recent <20	13.5a	10.91a	6.43a	6.09a (83)*a
Intermediate 21-49	19.8a	10.33a	6.17a	3.52a (43)*b
Old >50	11.7a	9.06a	3.82a	3.02a (37)*b

*main effect significant at $P<0.0029$

Torres, unpubl. data

Biomass availability





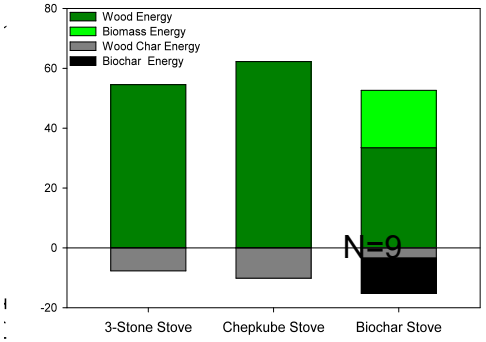
Biomass and Energy

Energy availability and energy needs

Conversion	Energy Available for Pyrolyis (GJ farm^{-1} yr^{-1})	Energy Available for Pyrolysis (GJ ha^{-1} yr^{-1})	Wood Energy Available for Combustion (GJ capita^{-1} yr^{-1})	Energy Available for Pyrolysis (GJ capita^{-1} yr^{-1})	Energy Consumed (GJ capita^{-1} yr^{-1})
Recent <20	100.1a	94.5a	4.58	22.7a	13.0a
Intermediate 21-49	96.1ab	53.9b	7.33	18.7ab	11.4a
Old >50	55.7b	44.2b	3.86	10.1b	8.4a

Torres, unpubl. data

Biomass and Energy



N=10

N=9

N=19

Torres, unpubl. data

Fuel Efficiency

Fuel reduction:

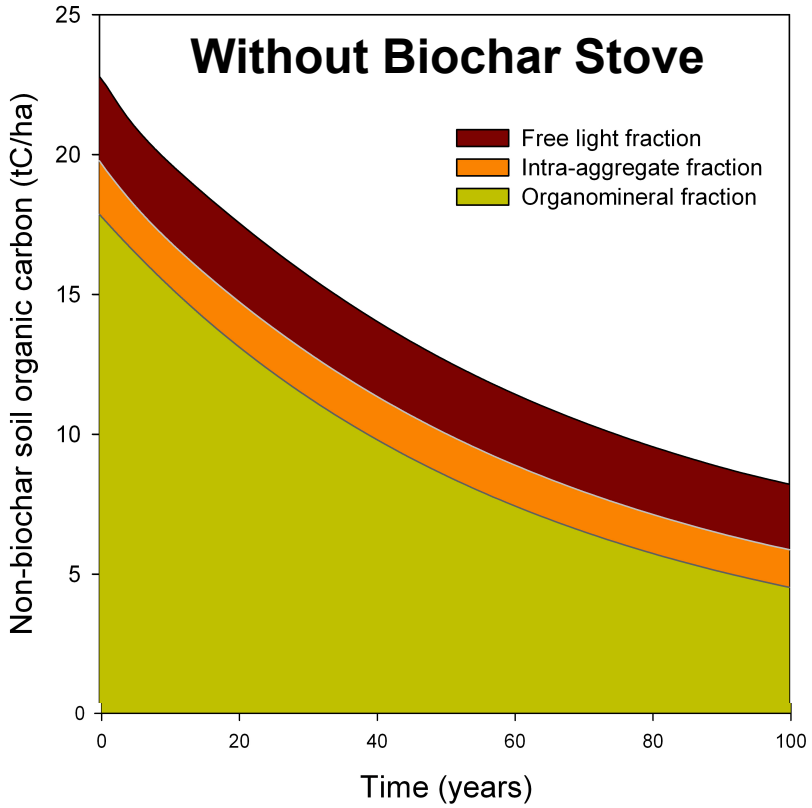
- **Fuel security**
- **Lower fuel acquisition time**
- **Lower pressure on natural resources**

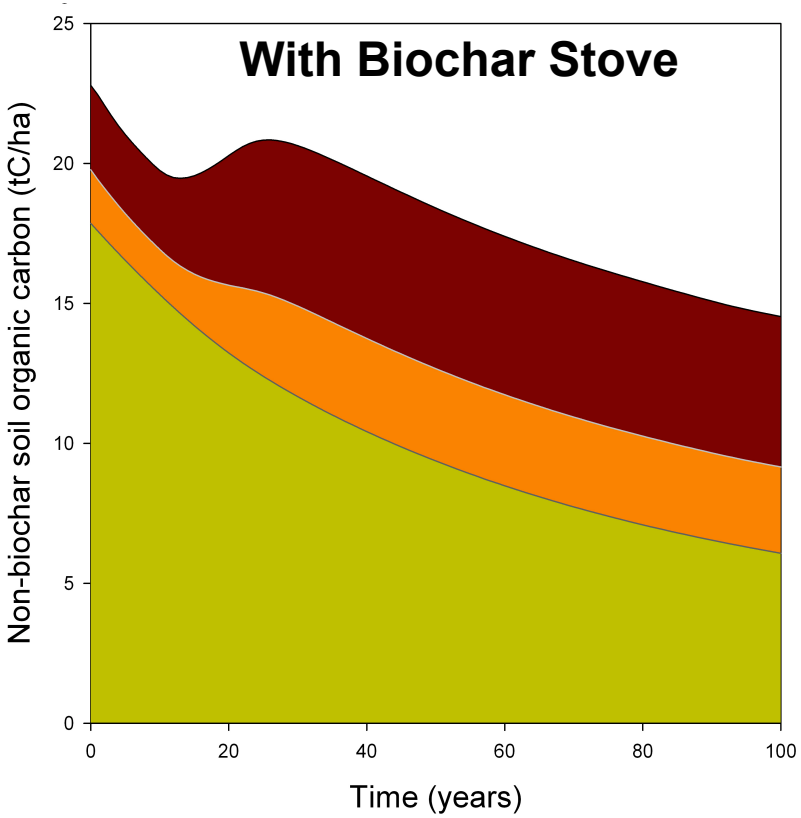


Case Study Kenya:
Distance per headload: 2.1 km (0.1-6.3)
Wood saved: 4.9 t/household/year (0.9-19.2)
Time saved: 6.2 hours/household/week (0.5-32)
(30 households)

Torres, unpubl data

Soil Fertility Feedback





Whitman, unpubl. data

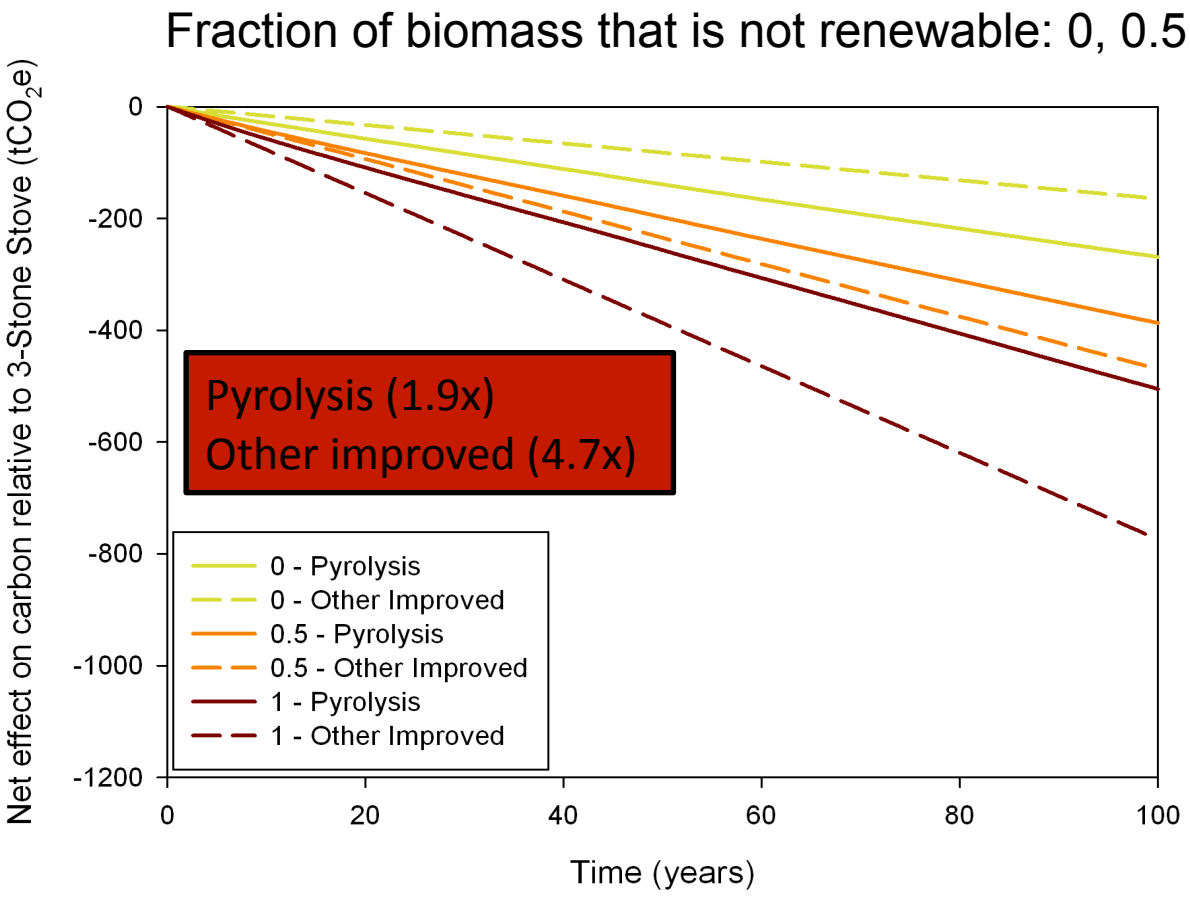
Co-Benefits: Health

Lower indoor pollution=lower respiratory + eye infections





Financing through Carbon Trading?



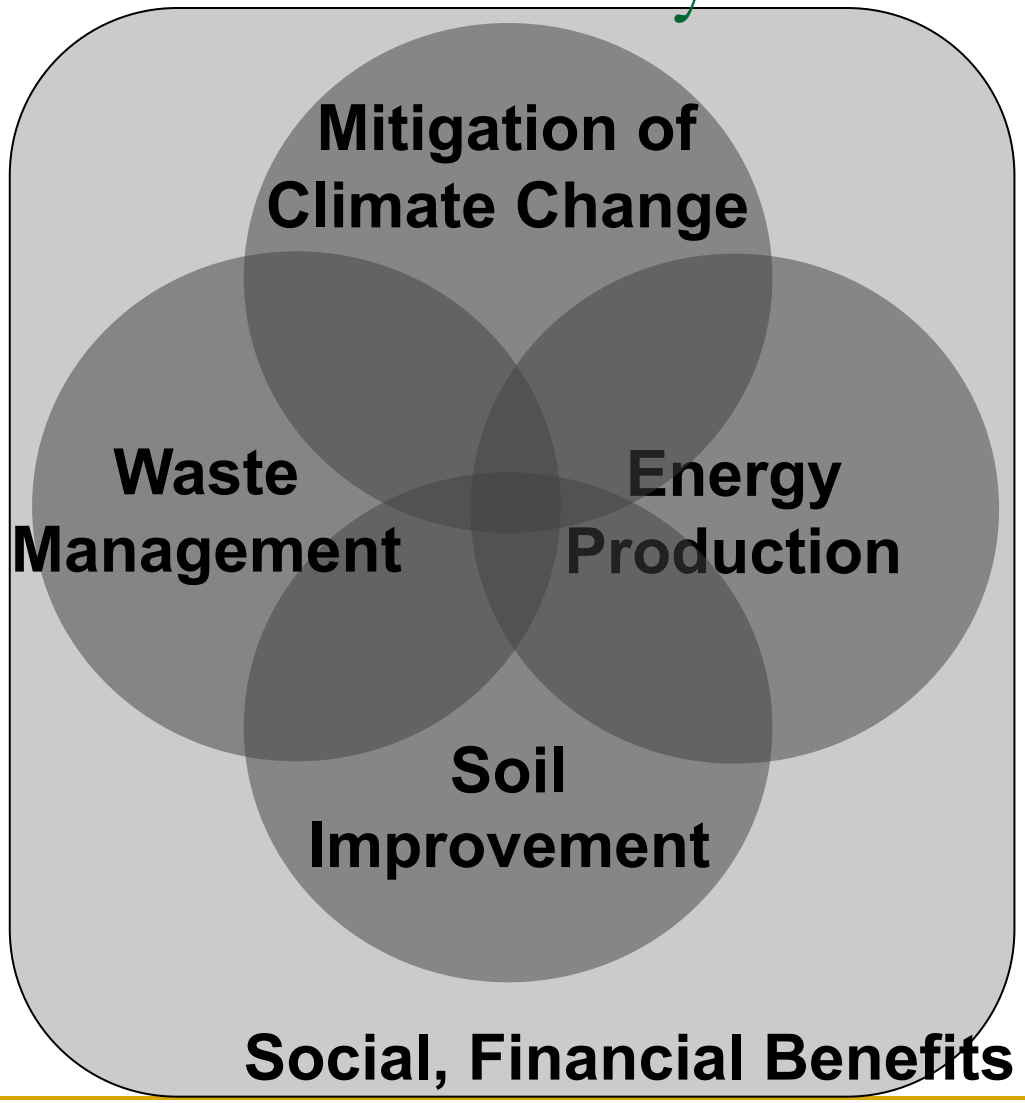
Best preliminary estimate:
Emission reduction: 3-8t CO_2e/yr
Revenue ($10/t CO_2e): $30-80/yr

Emissions from gasifier stove (MacCarty et al 2008)

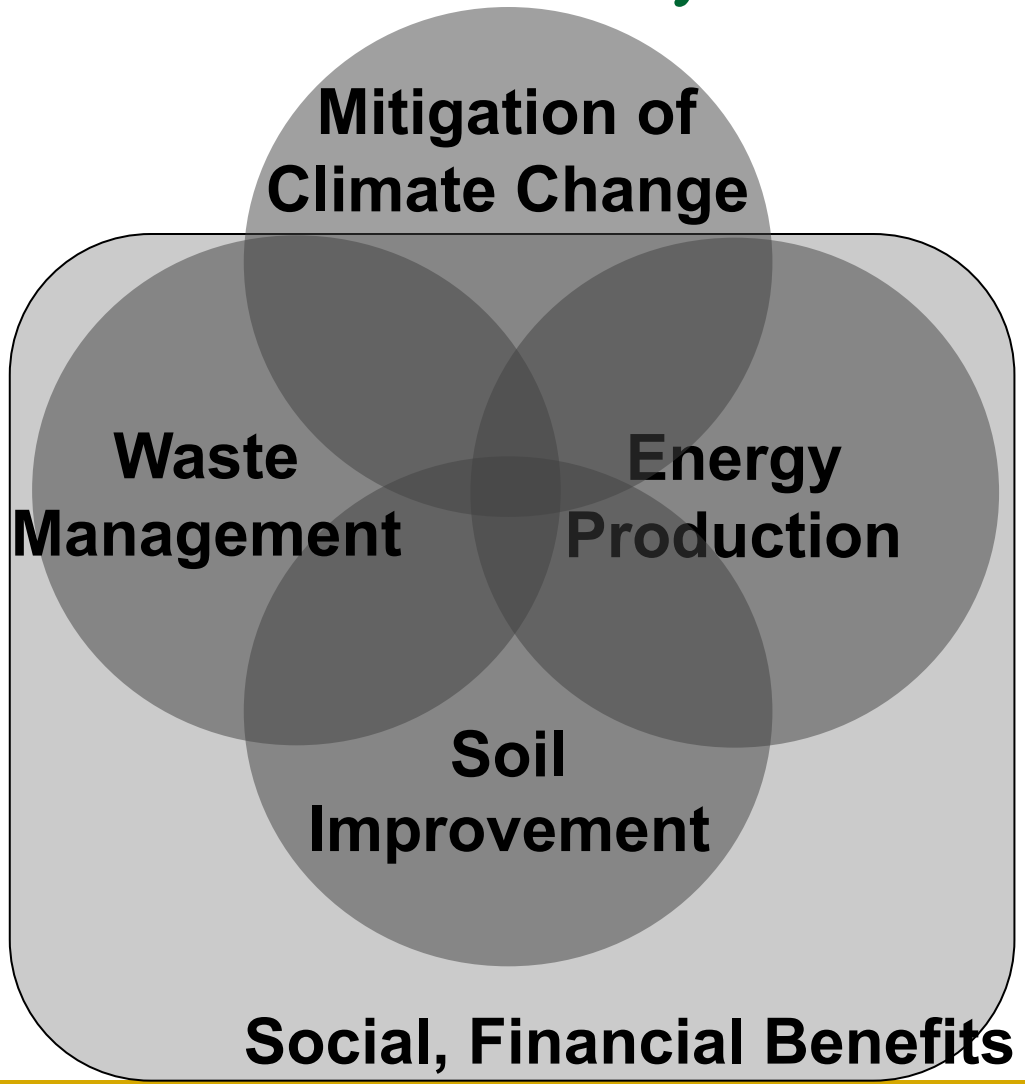
MRT of BC 100-1000yrs
Fraction of passive BC: 0.6-0.9
Fraction converted to BC: 0.15-0.5
Systems dynamics modeling (Vensim)

After Whitman, 2011, MS thesis

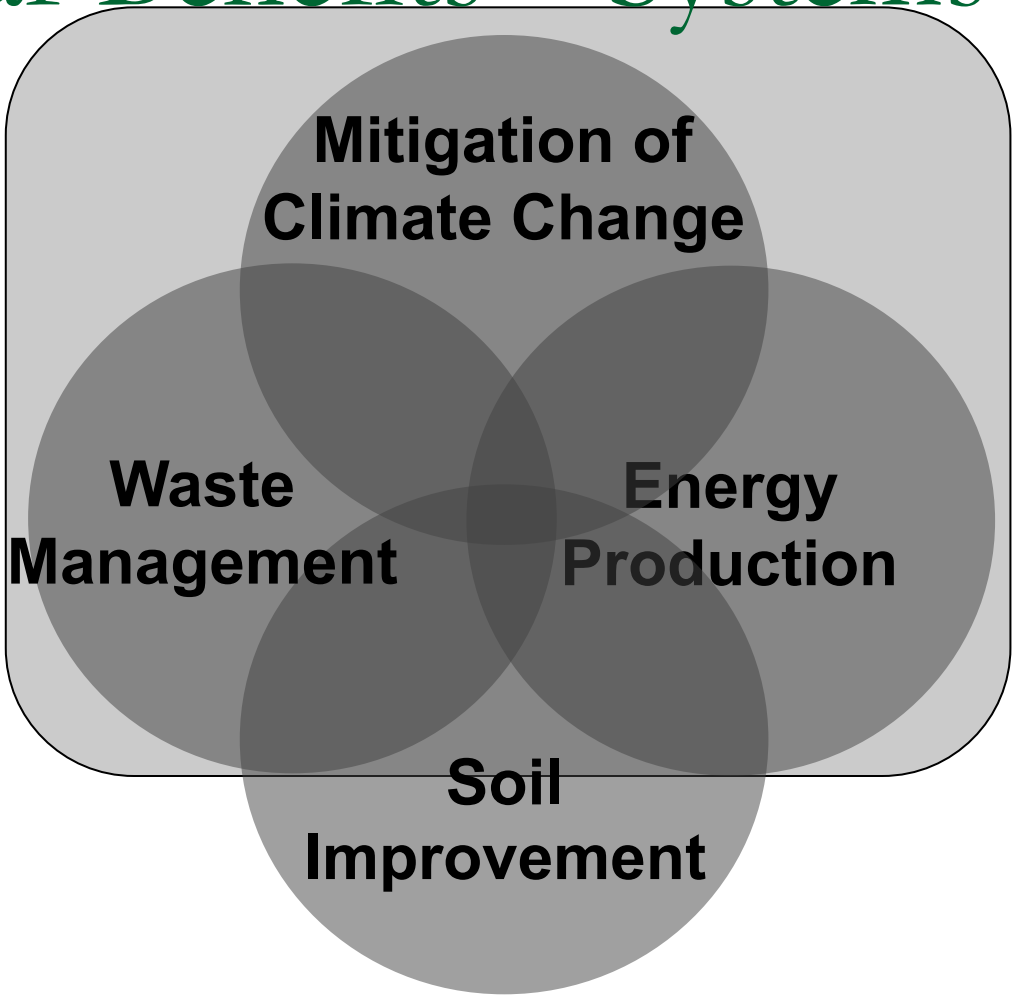
Biochar Benefits – Systems Dimension



Biochar Benefits – Systems Dimension

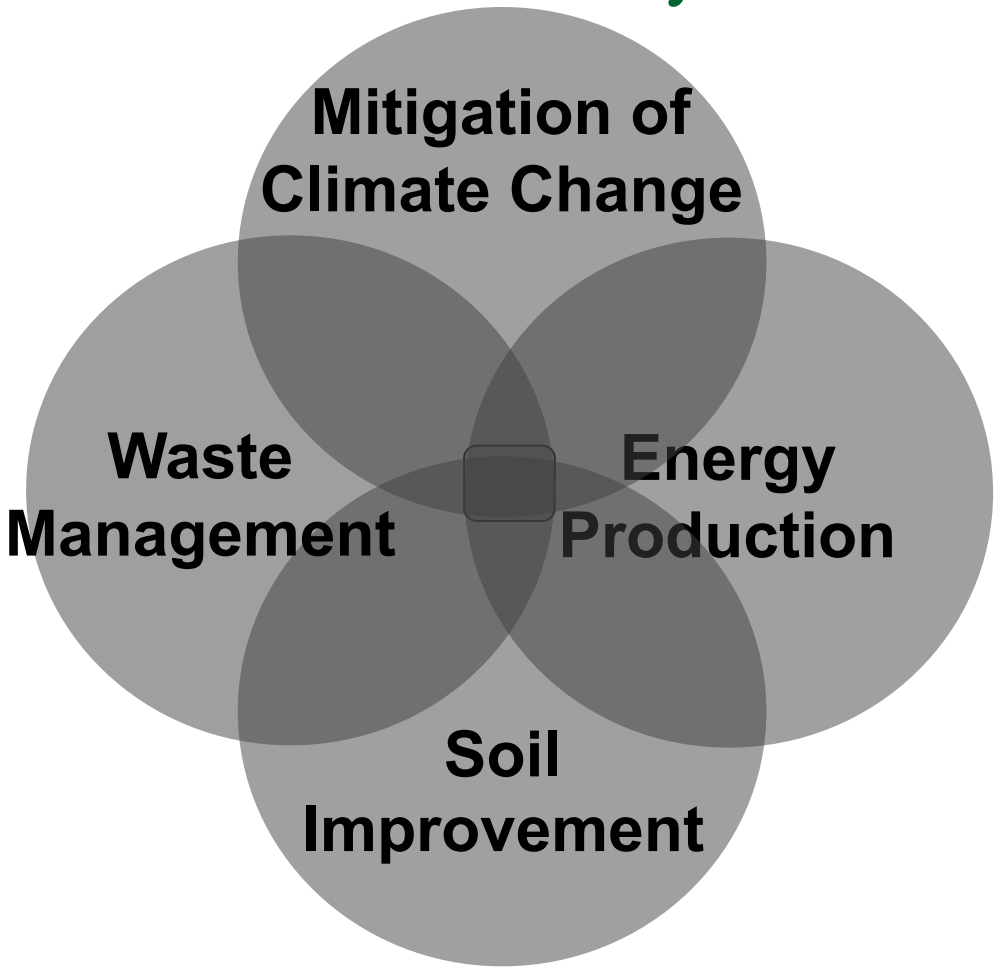


Biochar Benefits – Systems Dimension



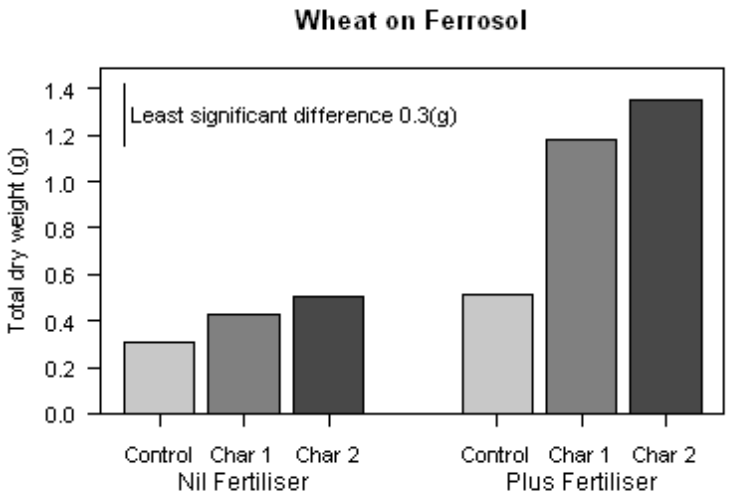
Social, Financial Benefits

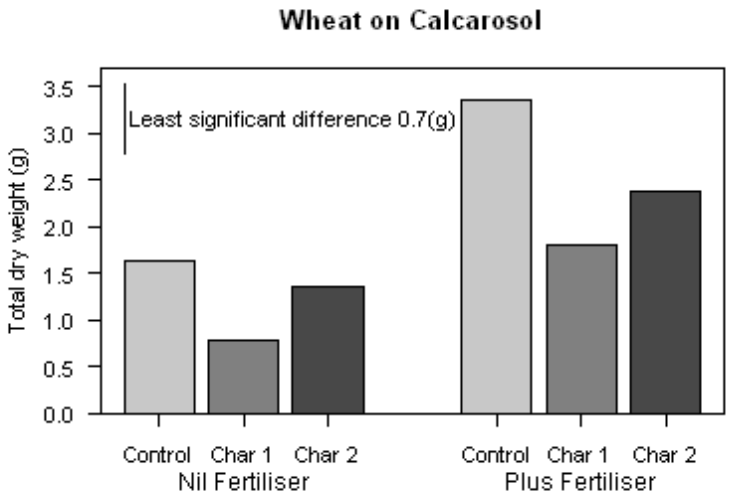
Biochar Benefits – Systems Dimension

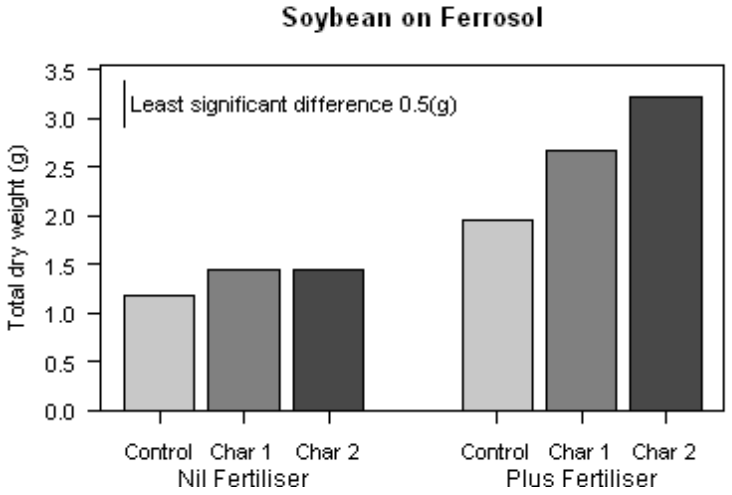


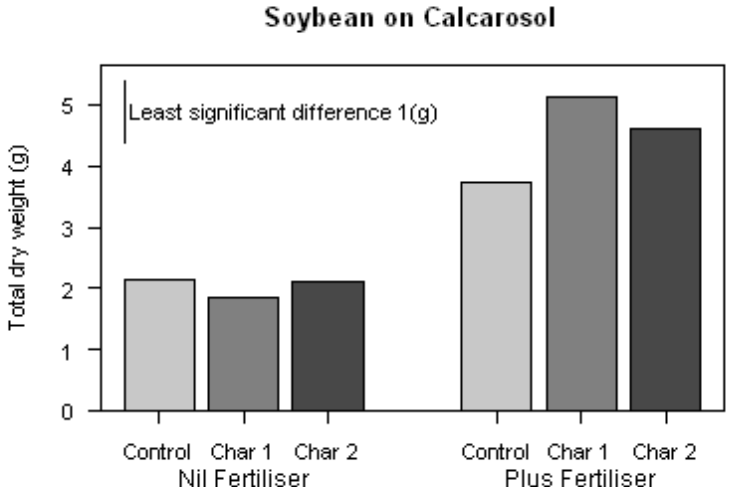
Social, Financial Benefits

Soil Fertility Dependency









Variability ≠ Uncertainty

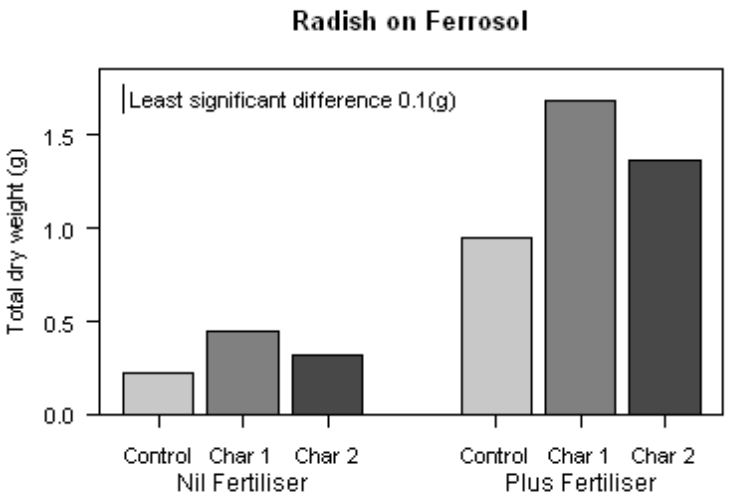
Australia
10 t/ha biochar from paper mill waste+ wood chips (550°C; pH 9.4; 8.2)

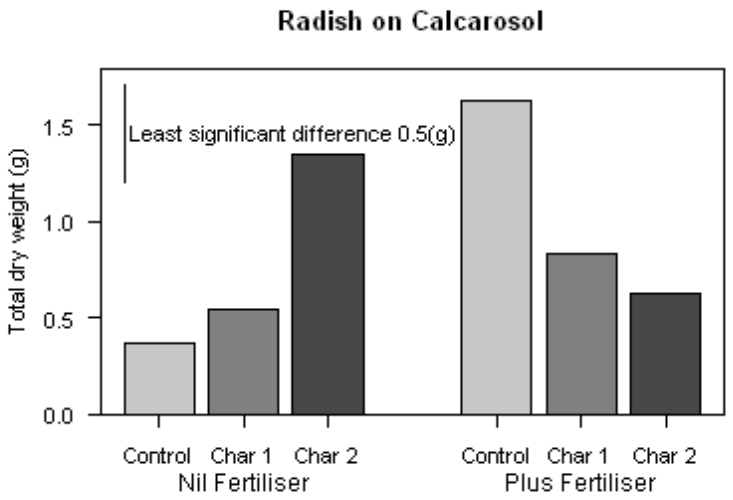
Van Zwieten et al., 2010, *Plant and Soil* 327:235–246

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Soil Fertility Dependency

Variability ≠ Uncertainty



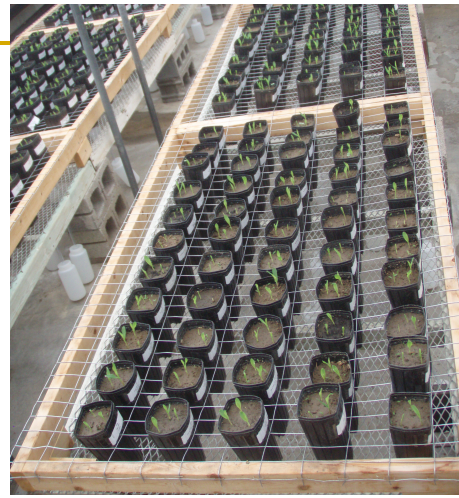


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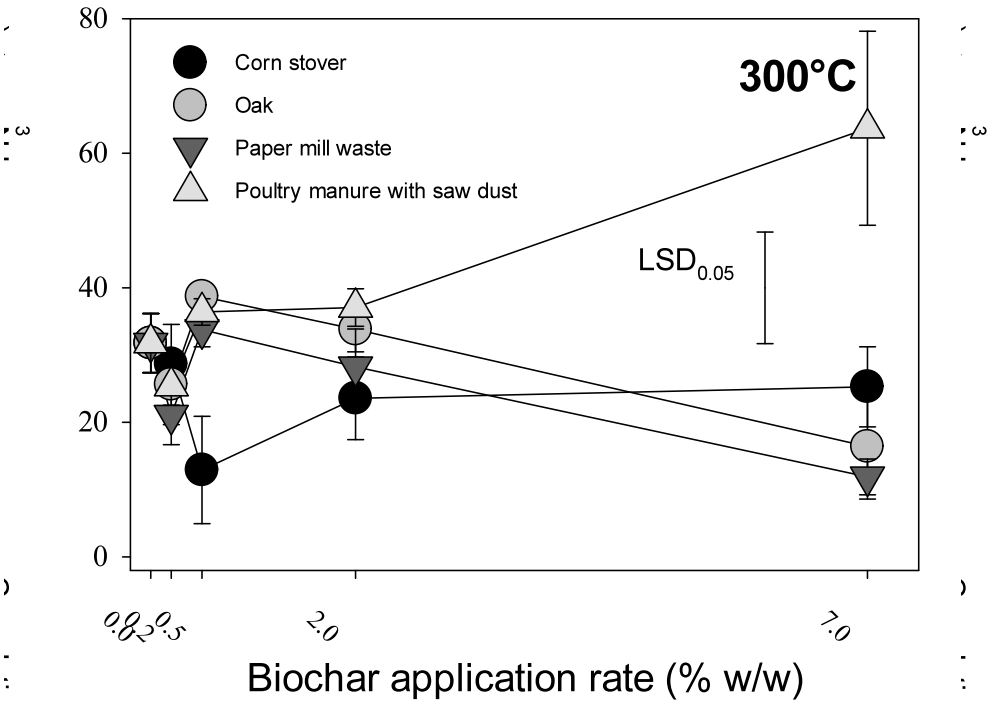
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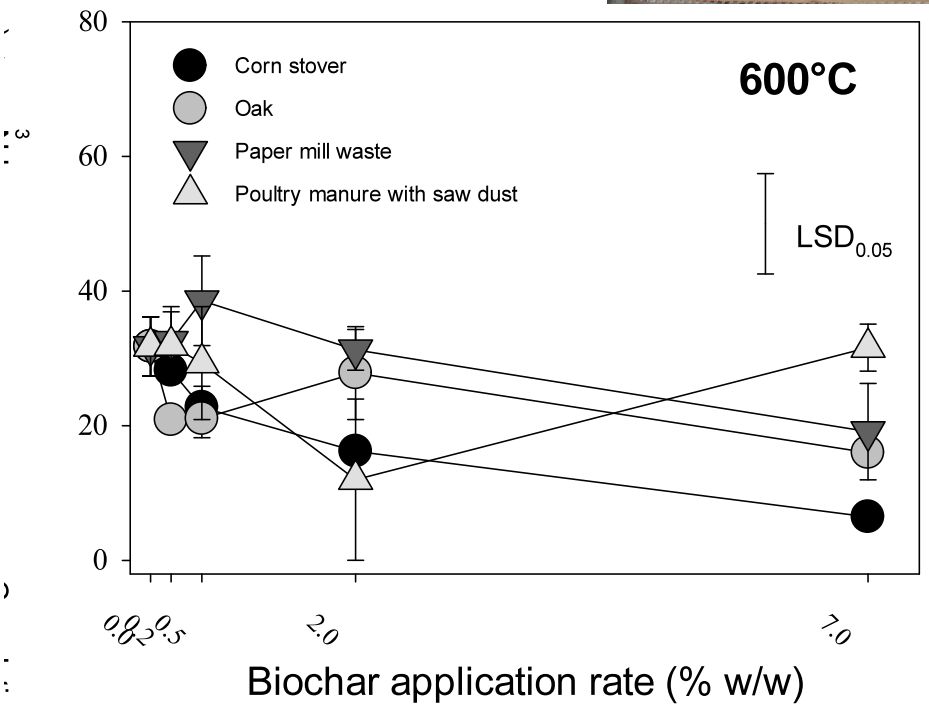
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Biochar Properties and Soil Effects



Nitrate

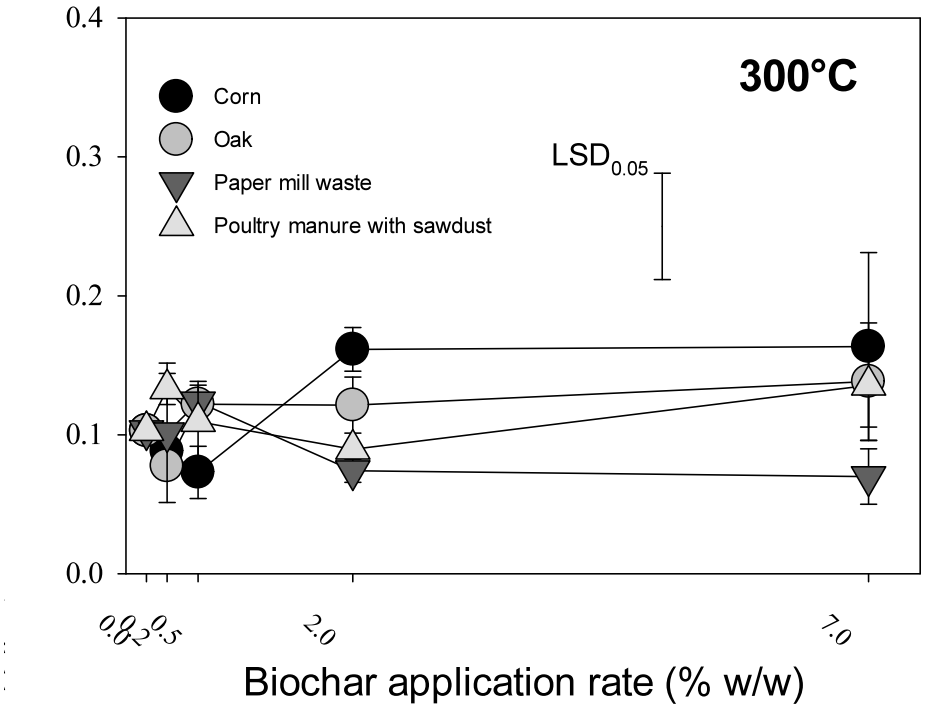


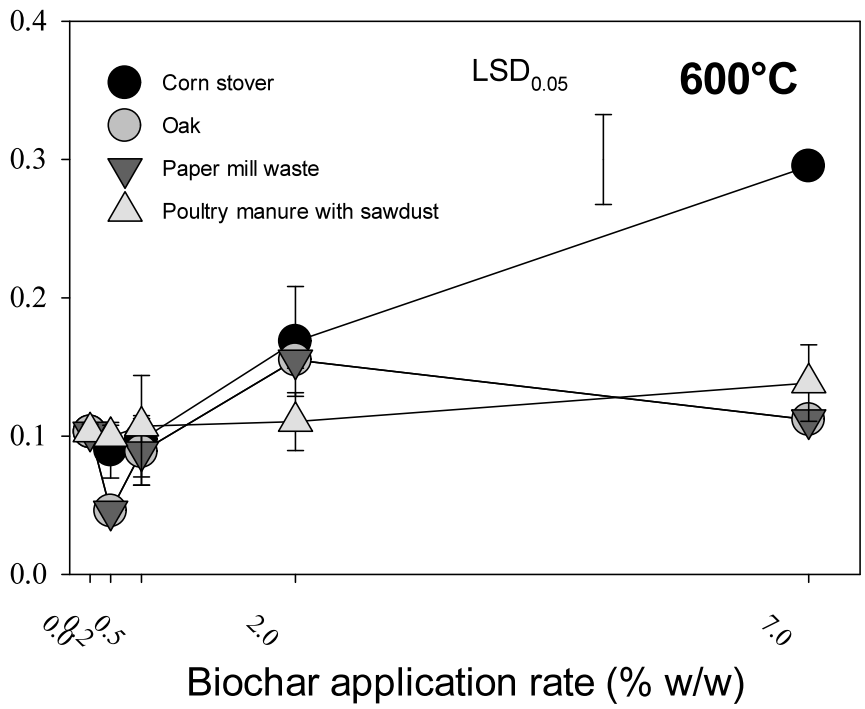


Hyland et al, unpubl data

Biochar Properties and Soil Effects

Plant-available water (FC minus PWP)





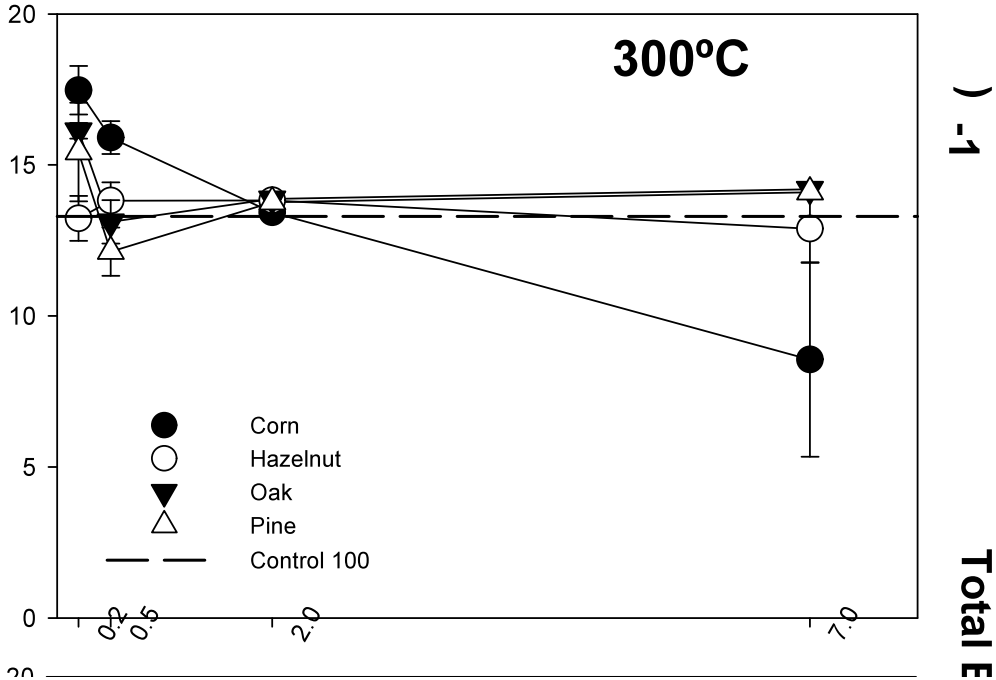
Hyland et al, unpubl data

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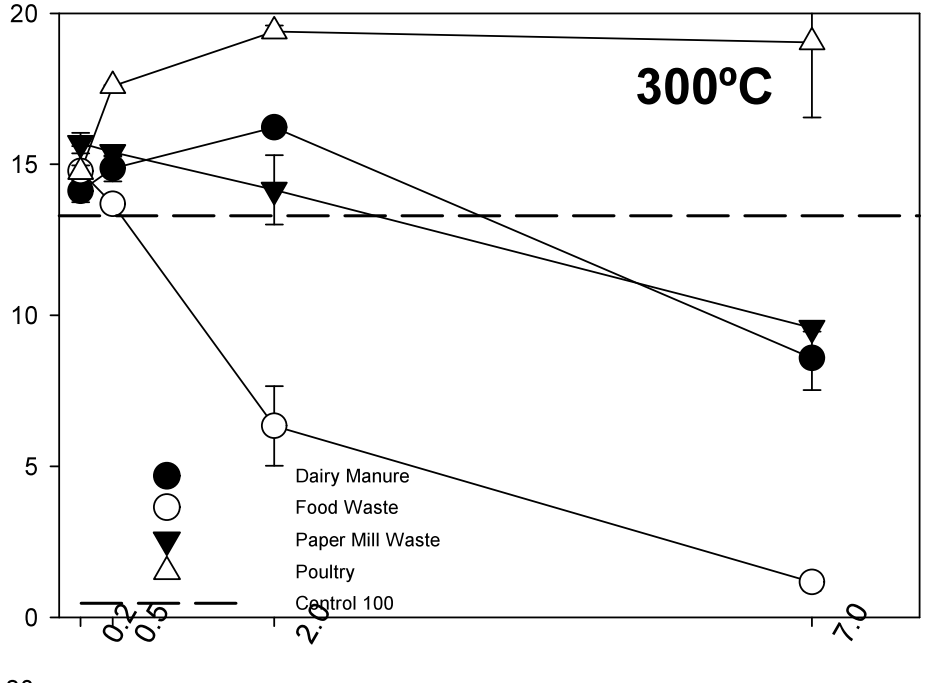


Corn greenhouse trial
Upstate NY loamy soil
N=2 (mean ±SE)

Plant Materials



Waste Materials



Biochar application rate (% w/w)

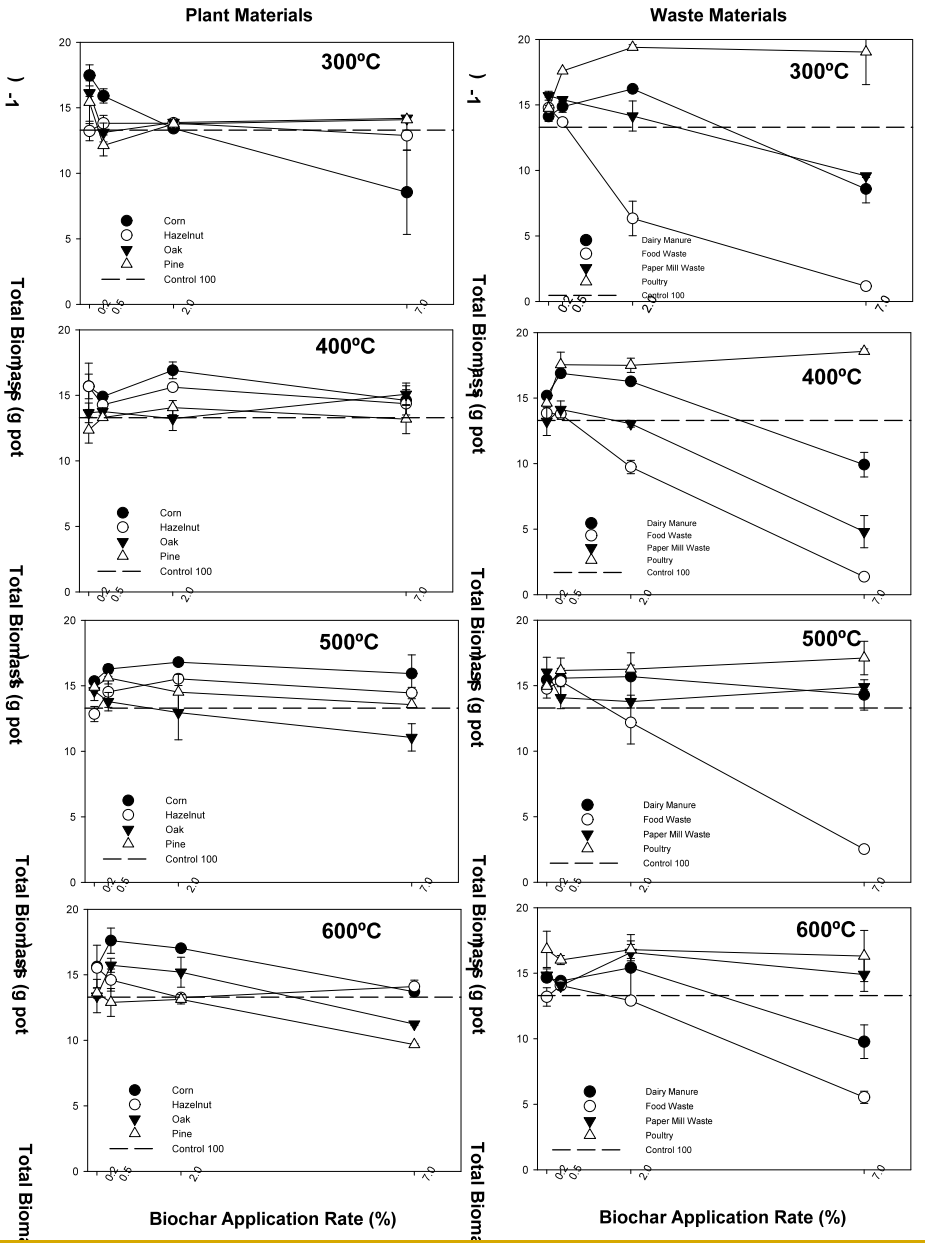
Rajkovich et al, unpubl data

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Biochar Properties

Greatest benefits typically at:

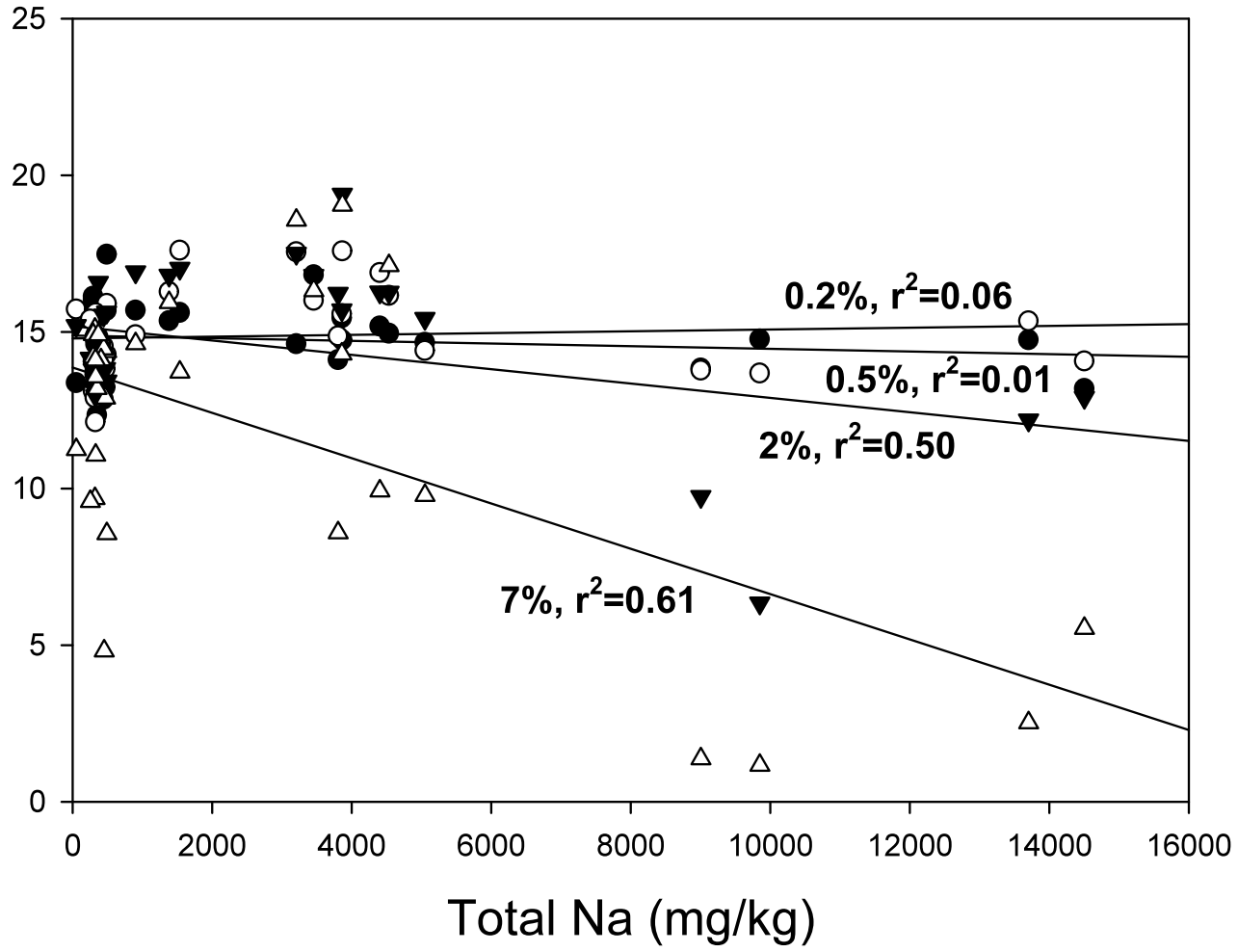
- **0.5% w/w = 6.5 t/ha**
- **Higher pyrolysis temperature**
- **High-P containing poultry biochar**



Rajkovich et al, unpubl data

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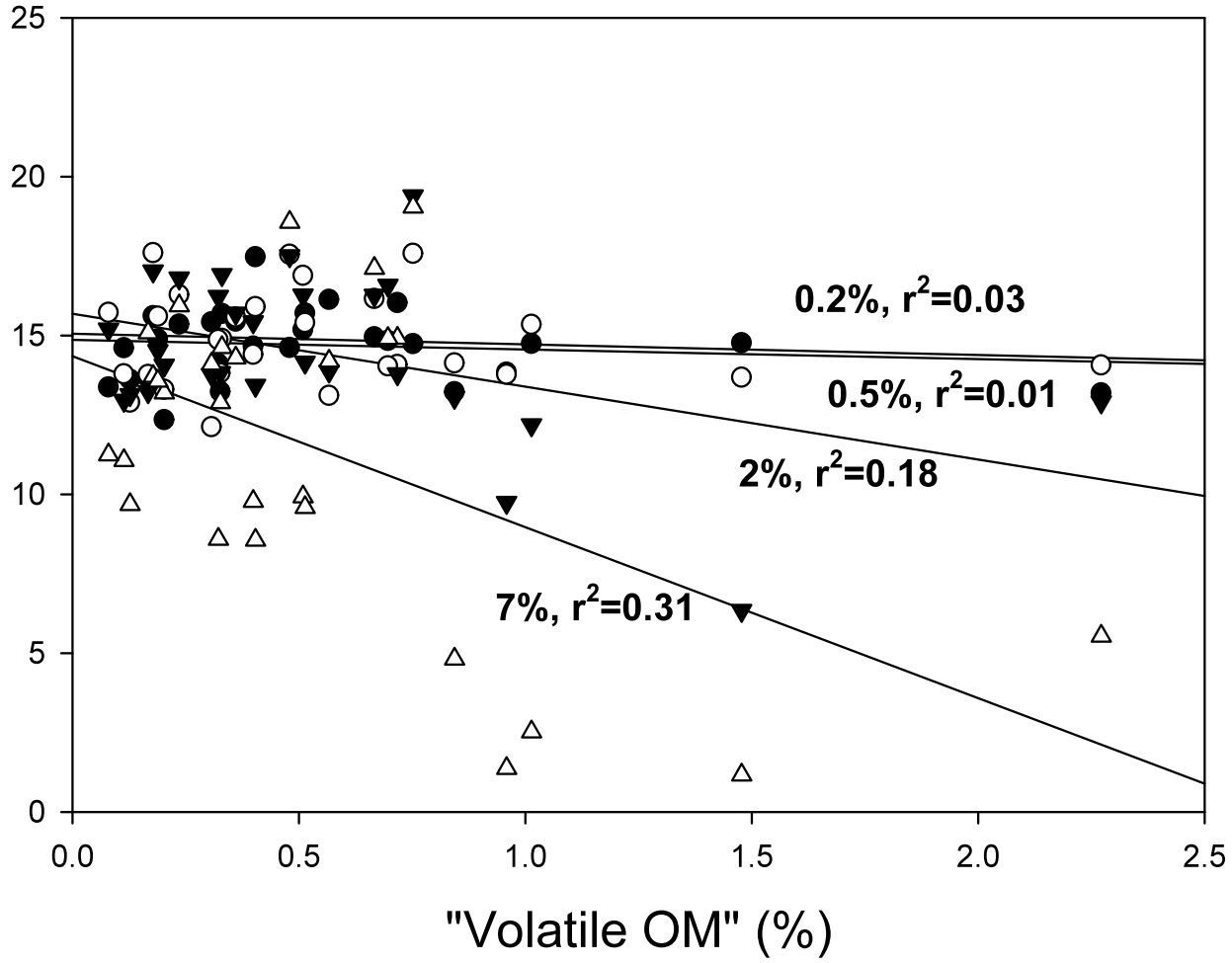
Biochar Properties



Corn greenhouse trial
Upstate NY loamy soil
N=33

Rajkovich et al, unpubl data

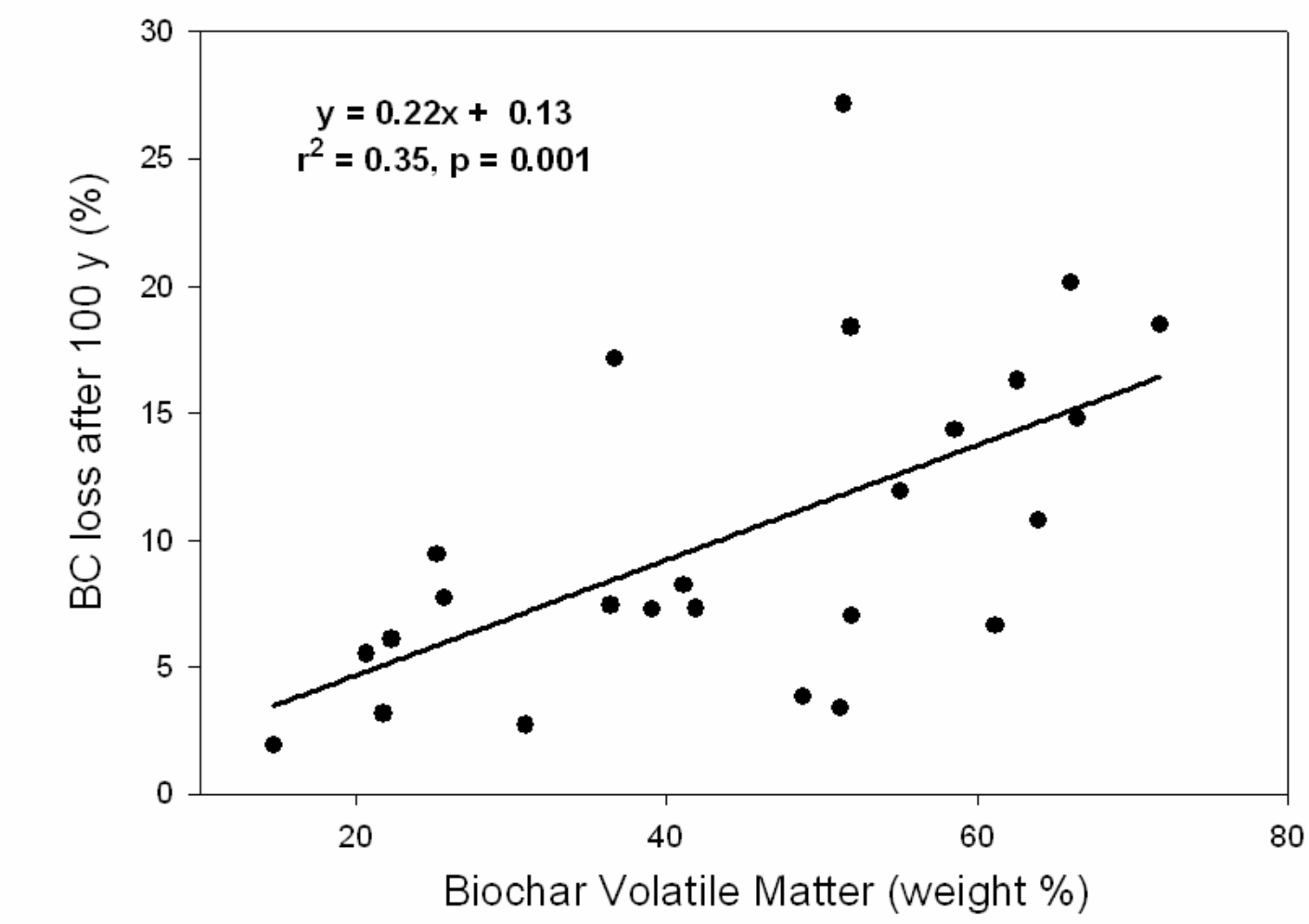
Biochar Properties



Corn greenhouse trial
Upstate NY loamy soil
N=33
Volatile OM from
Joseph et al 2009, Earthscan

Rajkovich et al, unpubl data

Stability of Biochars



Zimmerman, 2010, *EST* 44, 1295-1301

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From Concept to Practice

Biochar production

Biochar application



Biochar budgets and economics

Biochar Production



Biochar Production



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Biochar Production



Biochar Production



Biochar Production





Biochar Application





Blackwell et al., 2009, in Earthscan Publ

Biochar Application



Energy Balance

Energy balance (MJ/MJ), Slow pyrolysis

	Biochar to energy	Biochar to soil
Switchgrass	7.0	5.3
Forage corn	3.0	2.3
Corn stover (crop residue)	9.1	6.9
Wheat straw	9.0	6.9

Gaunt and Lehmann, 2008, *Environmental Science and Technology* 42: 4152-4158

Emission Balance

Avoided Emissions (kg CO_2/ha/yr), Slow pyrolysis

	Biochar to energy	Biochar to soil
Bioenergy crops	4083-7710	12,551-18,595
Crop residues	2002-3736	9575-11,833

Gaunt and Lehmann, 2008, *Environmental Science and Technology* 42: 4152-4158

Co-Benefits: Waste Stream Management

Case Study West-Virginia



West Virginia Poultry Farm

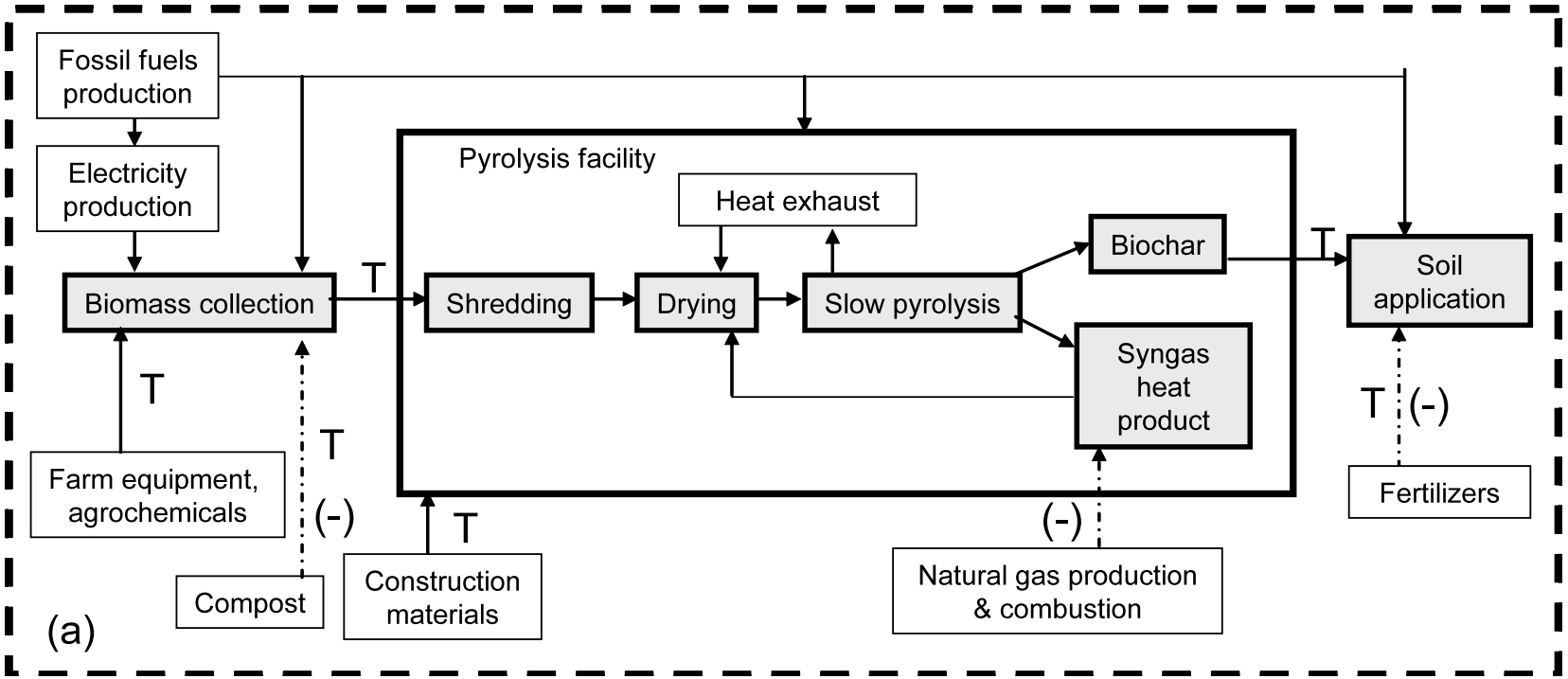
99,000 chickens
125-600 t/yr poultry litter

Pyrolysis of 300 kg/hr dry litter (at 500°C)
Off-sets 114,000L propane gas
US$66,000 /yr

25-120 t/yr biochar

Systems Analysis: Life Cycle Assessment

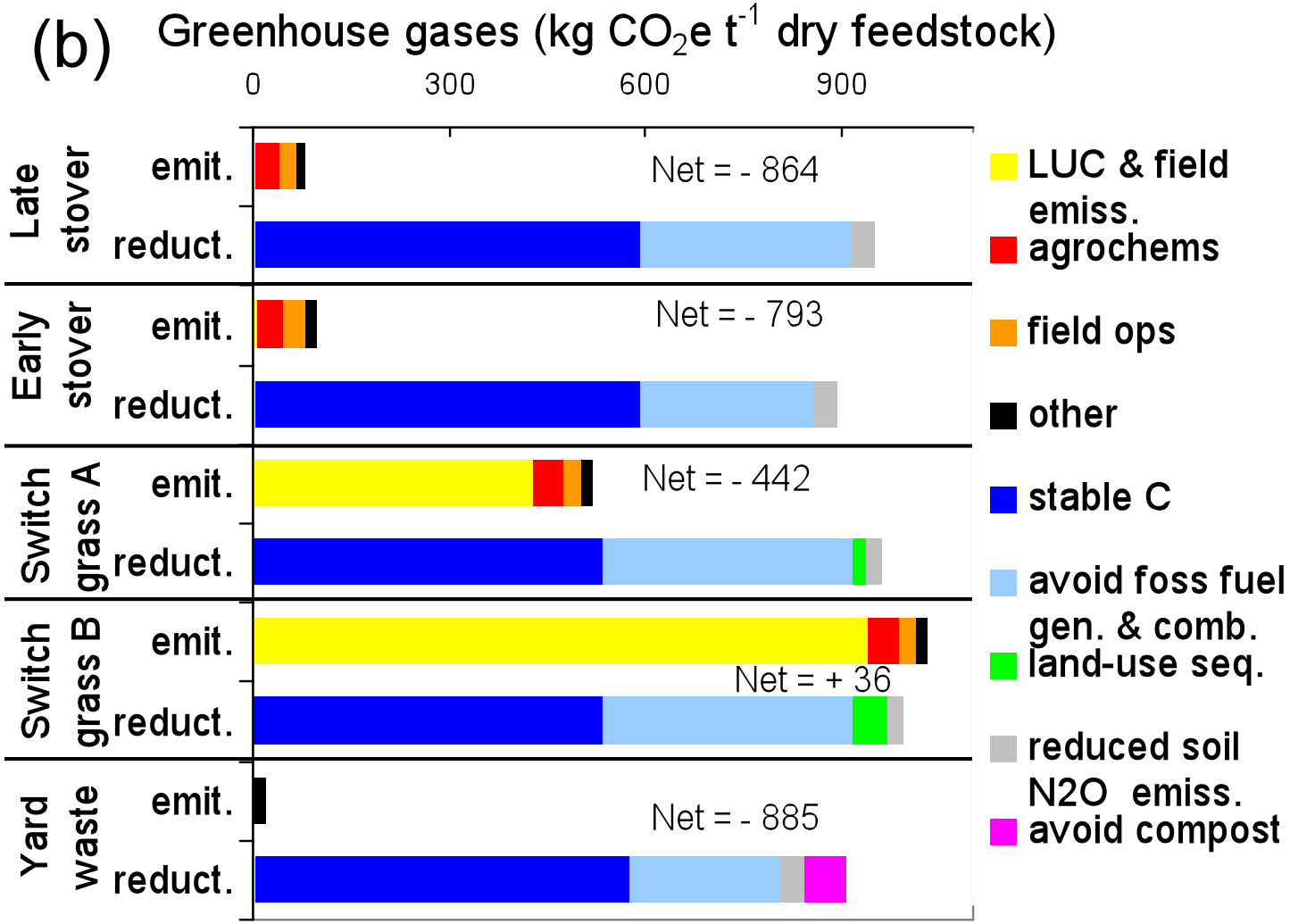
System boundaries



Roberts et al, 2010, *Environmental Science and Technology* 44, 827–833

Cornell University

Systems Analysis: Life Cycle Assessment



Roberts et al, 2010, *Environmental Science and Technology* 44, 827–833

Cornell University

Systems Analysis: Sensitivity Analysis

Stover collection energy sensitivity

Energy per tonne collected (MJ)	723	765 (baseline)	833
Net energy (MJ)	4165	4116	4036
% change	1%	0%	-2%

Stover collection emissions sensitivity

Emissions per tonne collected (kg CO_2e)	-33	58 (baseline)	76
Net CO_2e (kg)	-970	-864	-843
% change	12%	0%	-2%

Late Stover Slow pyrolysis (1-10t/hr)

Roberts et al, 2010, *Environmental Science and Technology* 44, 827–833

Systems Analysis: Sensitivity Analysis

Char yield sensitivity

Char yield input	12 wt %	28.8 wt % (baseline)	35 wt %
Net CO_2e (kg)	-756	-864	-875
% change	-13%	0%	1%

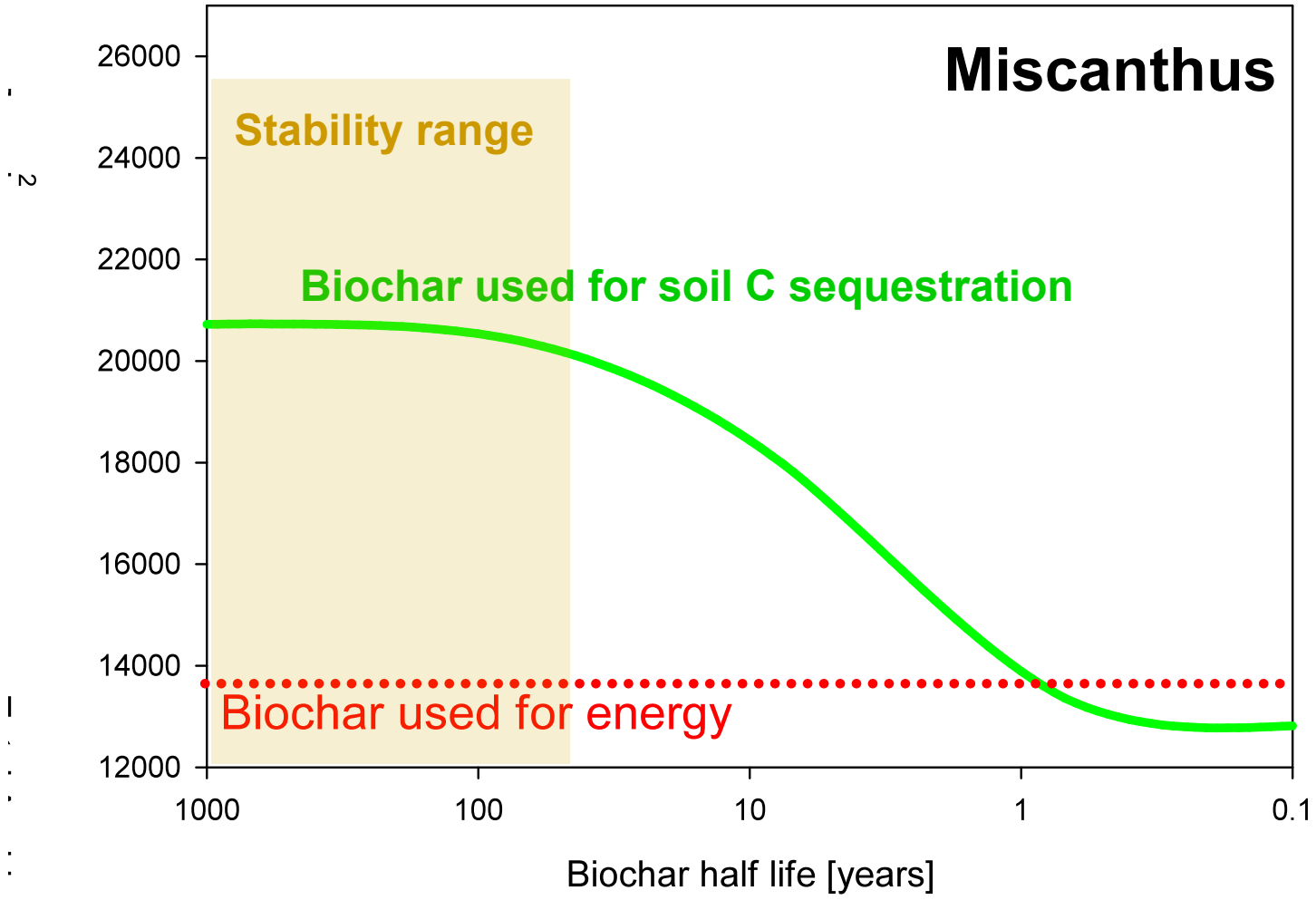
Stable C sensitivity

Stable C content of biochar	0%	50%	80% (baseline)	90%
Net CO_2e (kg)	-275	-643	-864	-938
% change	-68%	-26%	0%	9%

Late Stover
Slow pyrolysis
(1-10t/hr)

Roberts et al, 2010, *Environmental Science and Technology* 44, 827–833

Biochar Stability – Life Cycle Relevance



Gaunt and Lehmann, 2008, *Environ. Sci. Technol.* 42: 4152-4158

Systems Analysis: Sensitivity Analysis

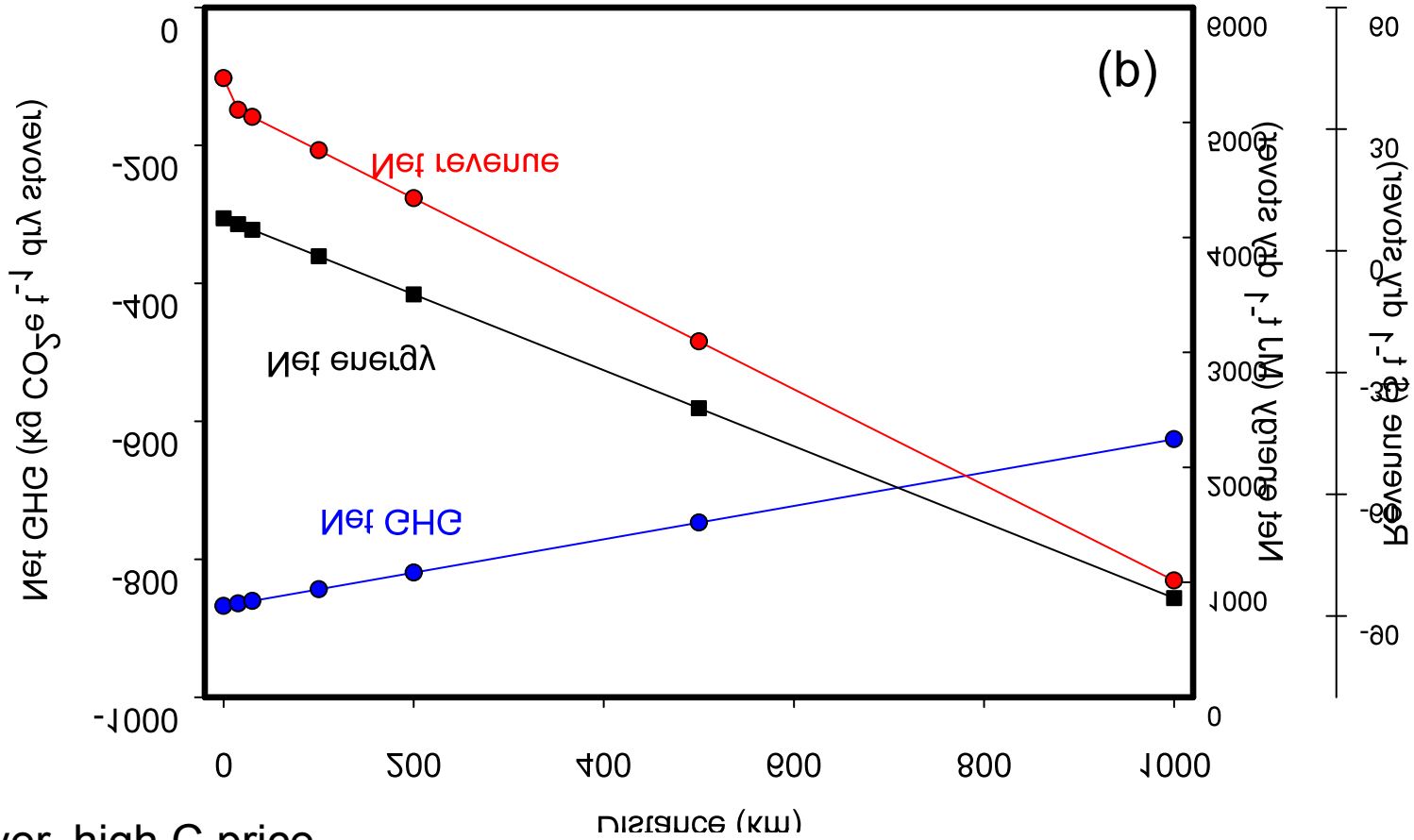
Syngas energy sensitivity

Energy yield input	50% of baseline	(baseline)	150% of baseline
Net energy (MJ)	1509	4116	6722
% change	-63%	0%	63%
Net CO_2e (kg)	-703	-864	-1025
% change	-19%	0%	19%

Late Stover
Slow pyrolysis
(1-10t/hr)

Roberts et al, 2010, *Environmental Science and Technology* 44, 827–833

Costs - transportation

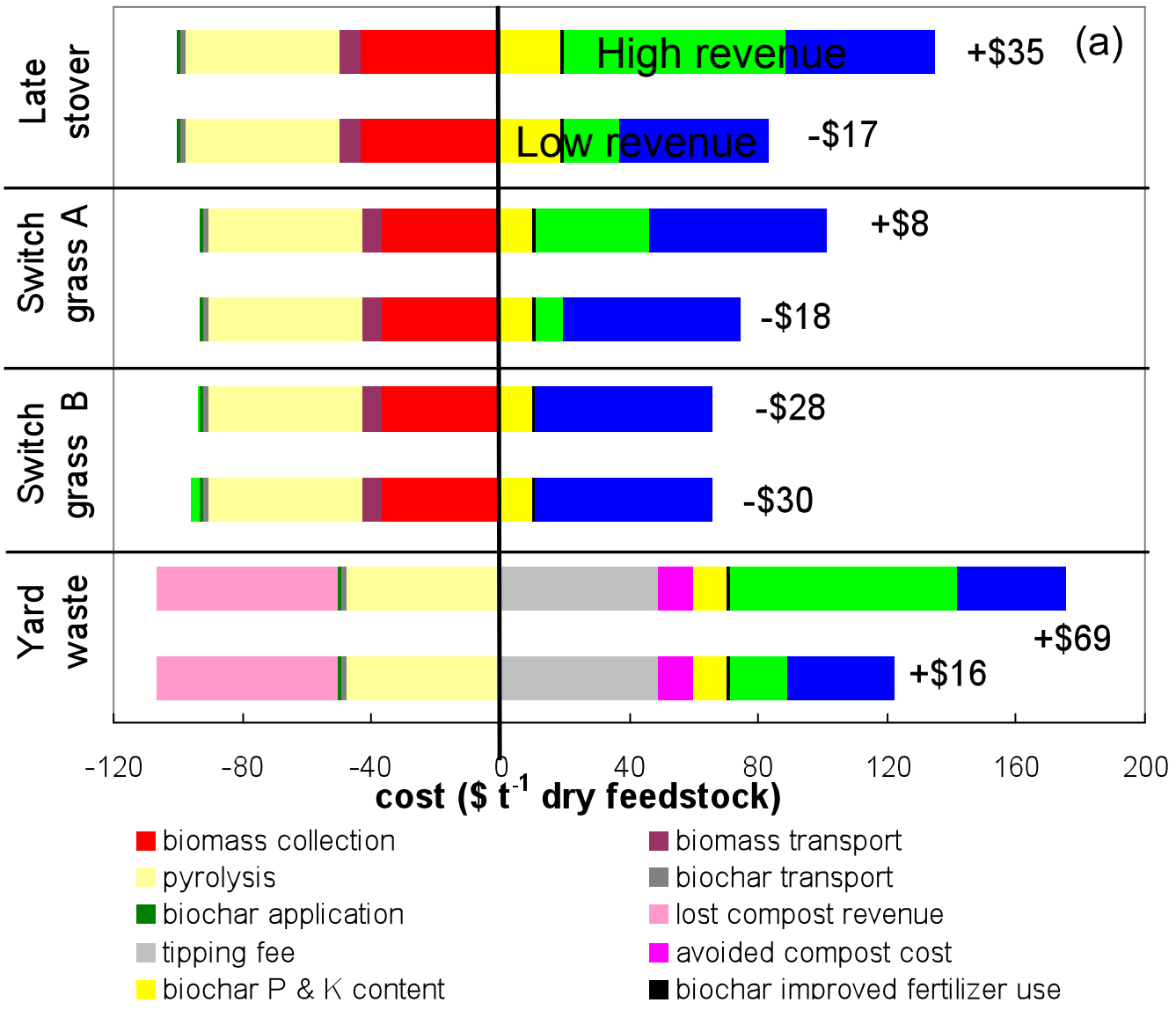


Late stover, high C price
Slow pyrolysis
(1-10 tons/hr capacity)

Roberts et al, 2010, *Environmental Science and Technology* 44, 827–833

Cornell University

Costs



Roberts et al, 2010, *Environmental Science and Technology* 44, 827–833

Cornell University

Biochar Systems across Scales

Stationary, wood, natural gas, asparagus

Stationary, corn stover, propane, corn

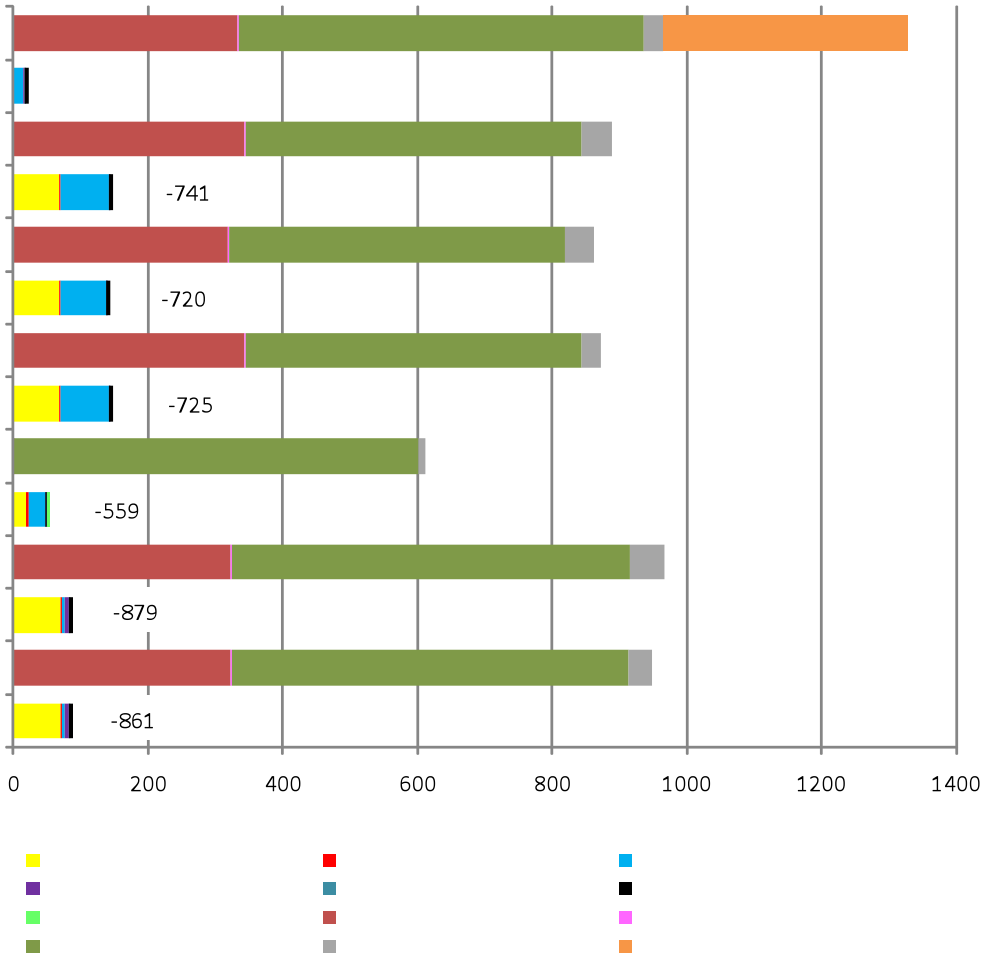
Stationary, corn stover, natural gas, corn

Stationary, corn stover, propane, asparagus

Mobile, beetle kill, none, pine

Large central, corn, natural gas, corn

Large central, corn, natural gas, asparagus



Roberts et al, unpubl. data

Biochar Systems across Scales

Stationary, wood, natural gas, asparagus

Stationary, corn stover, propane, corn

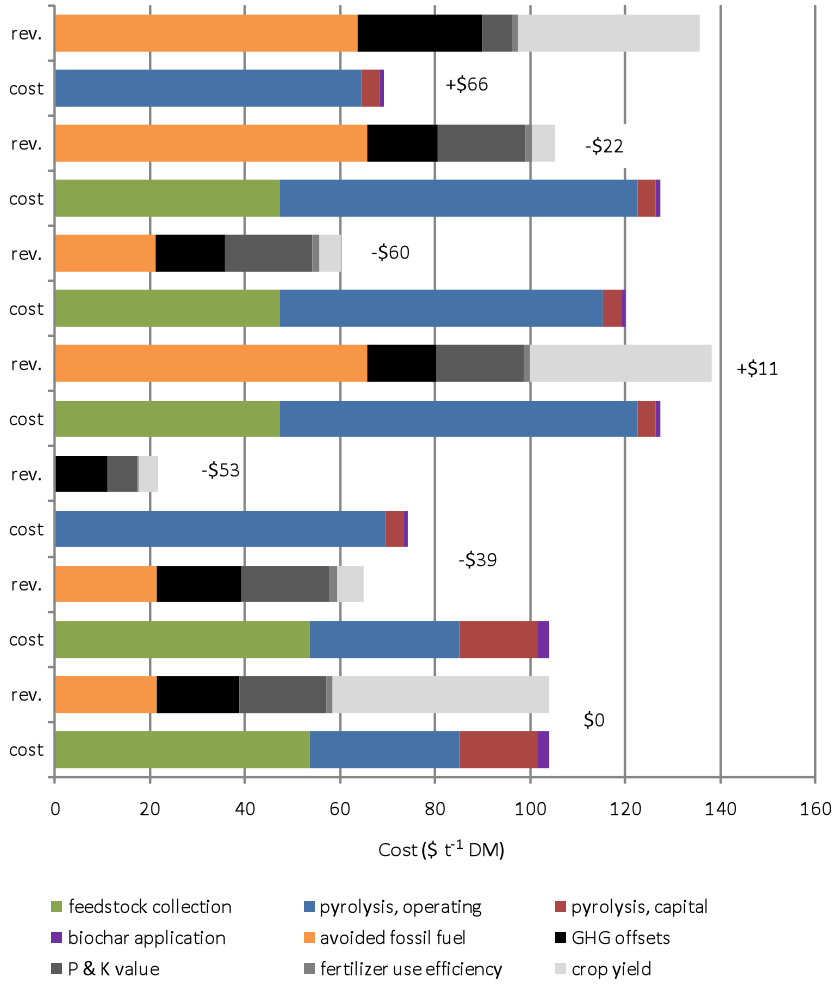
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Stationary, corn stover, propane, asparagus

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Roberts et al, unpubl. data

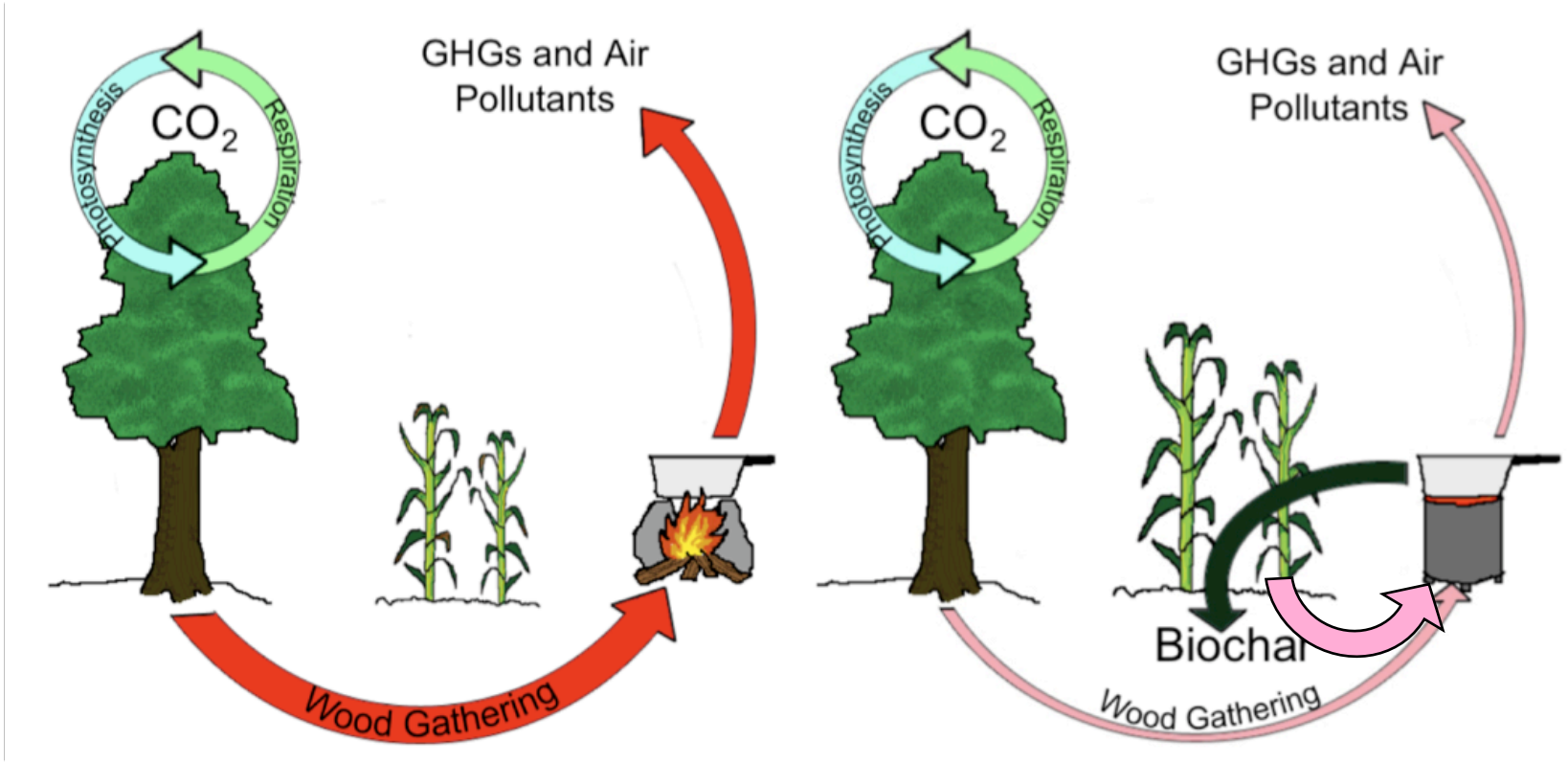
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Biochar Cook Stoves





Biochar Cook Stoves - Principles

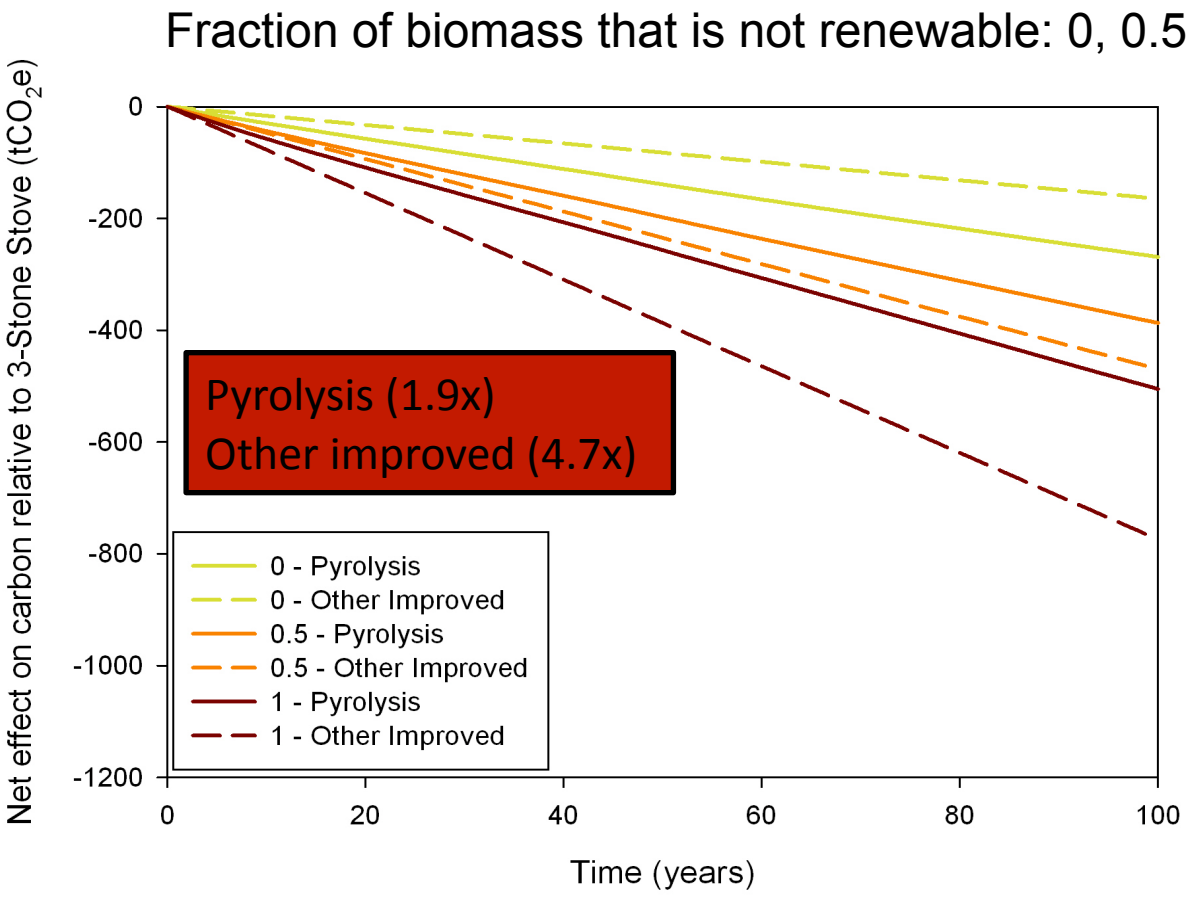


Traditional 3-Stone Stove

Biochar Cook Stove

Whitman and Lehmann, 2009, *Environmental Science and Policy* 12, 1024-1027

Systems Analysis: Household Modeling



Best preliminary estimate:
Emission reduction: 3-8t CO_2e/yr
Revenue ($10/t CO_2e): $30-80/yr

Emissions from gasifier stove (MacCarty et al 2008)

MRT of BC 100-1000yrs
Fraction of passive BC: 0.6-0.9
Fraction converted to BC: 0.15-0.5
Systems dynamics modeling (Vensim)

Whitman, unpubl. data

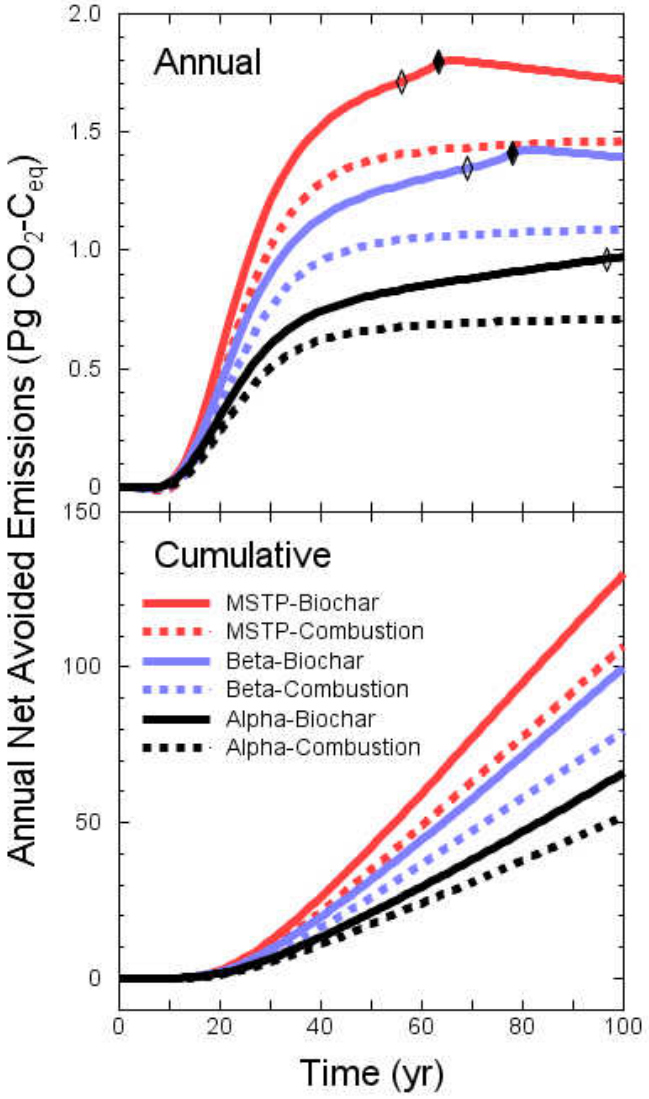
Co-Benefits: Health

Lower indoor pollution=lower respiratory + eye infections



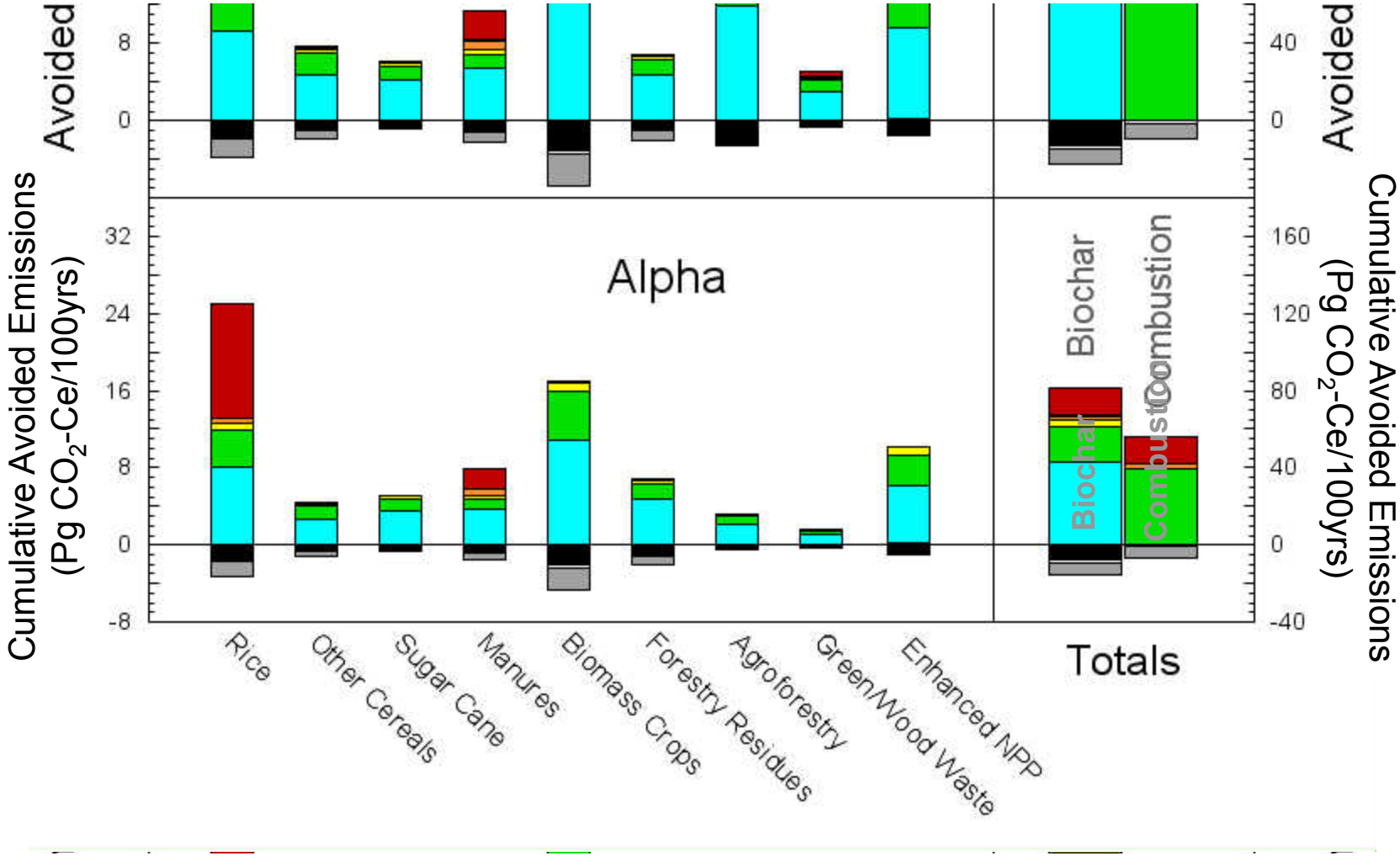


Technical Climate Mitigation Potential



Woolf et al, 2010, *Nature Communications 1, 56*

Technical Climate Mitigation Potential

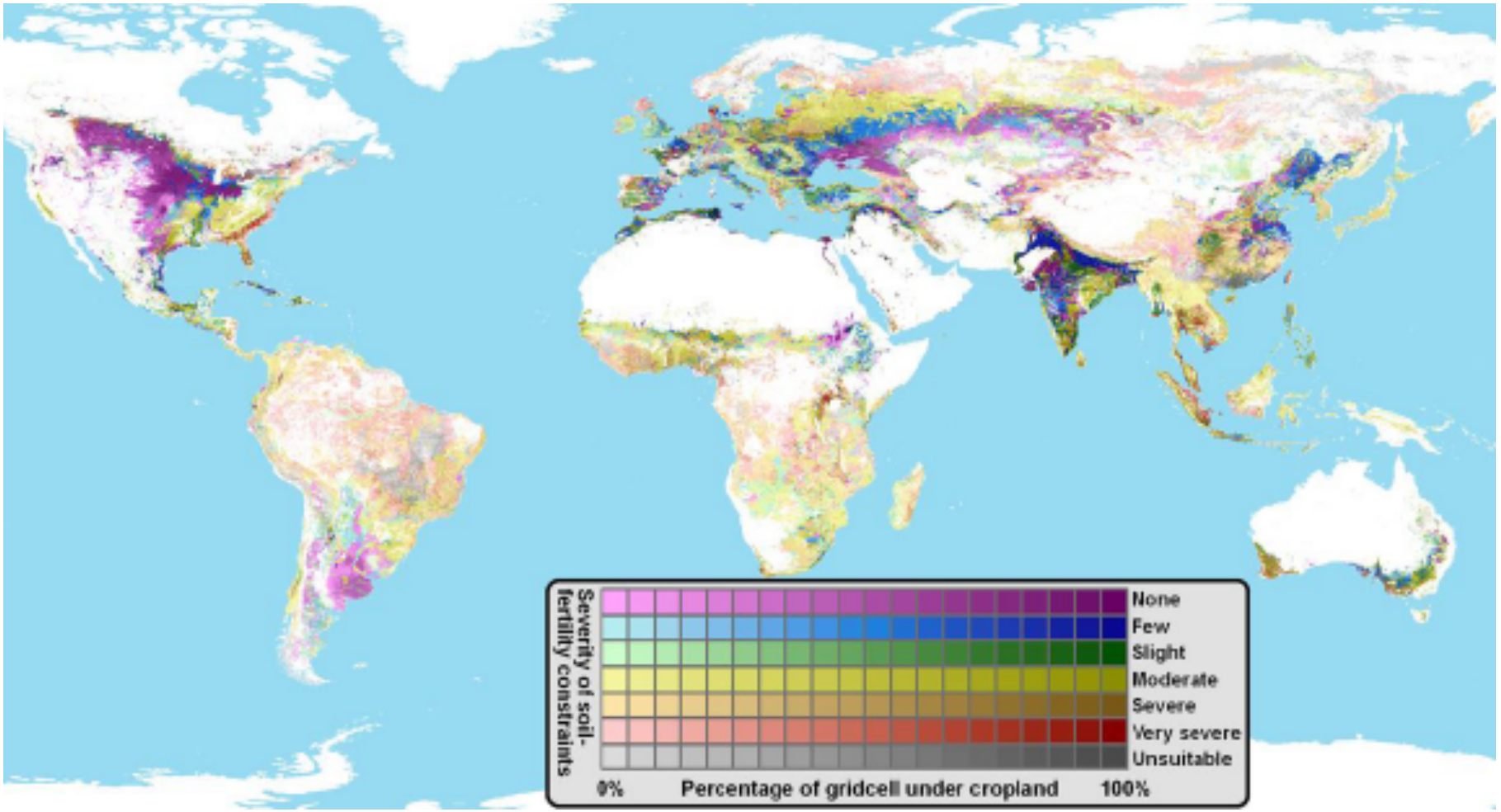


Maximum Sustainable Technical Potential

Woolf et al, 2010, *Nature Communications 1, 56*

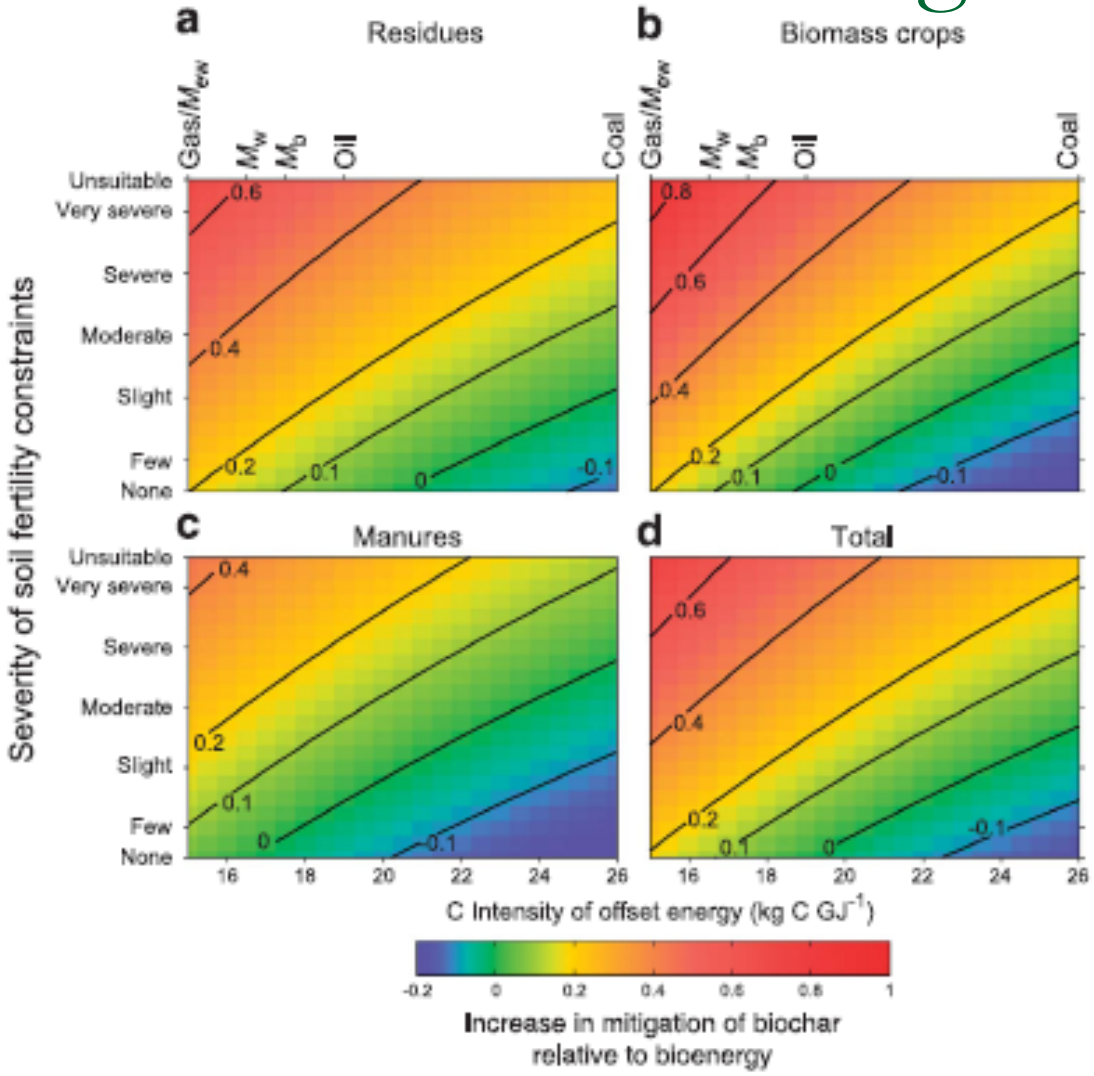
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Technical Climate Mitigation Potential



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Technical Climate Mitigation Potential



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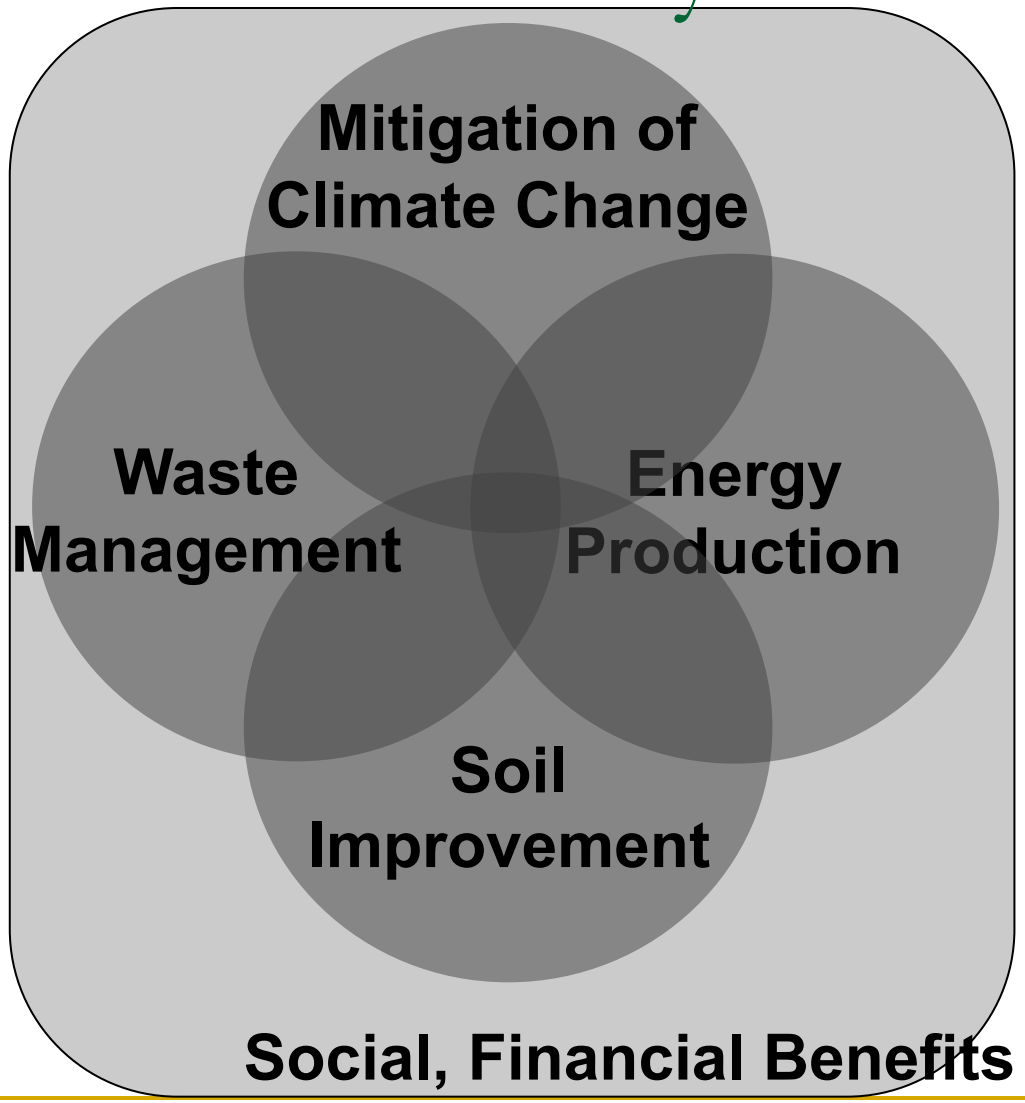
Cornell University

Costs – Carbon Trading Aspects

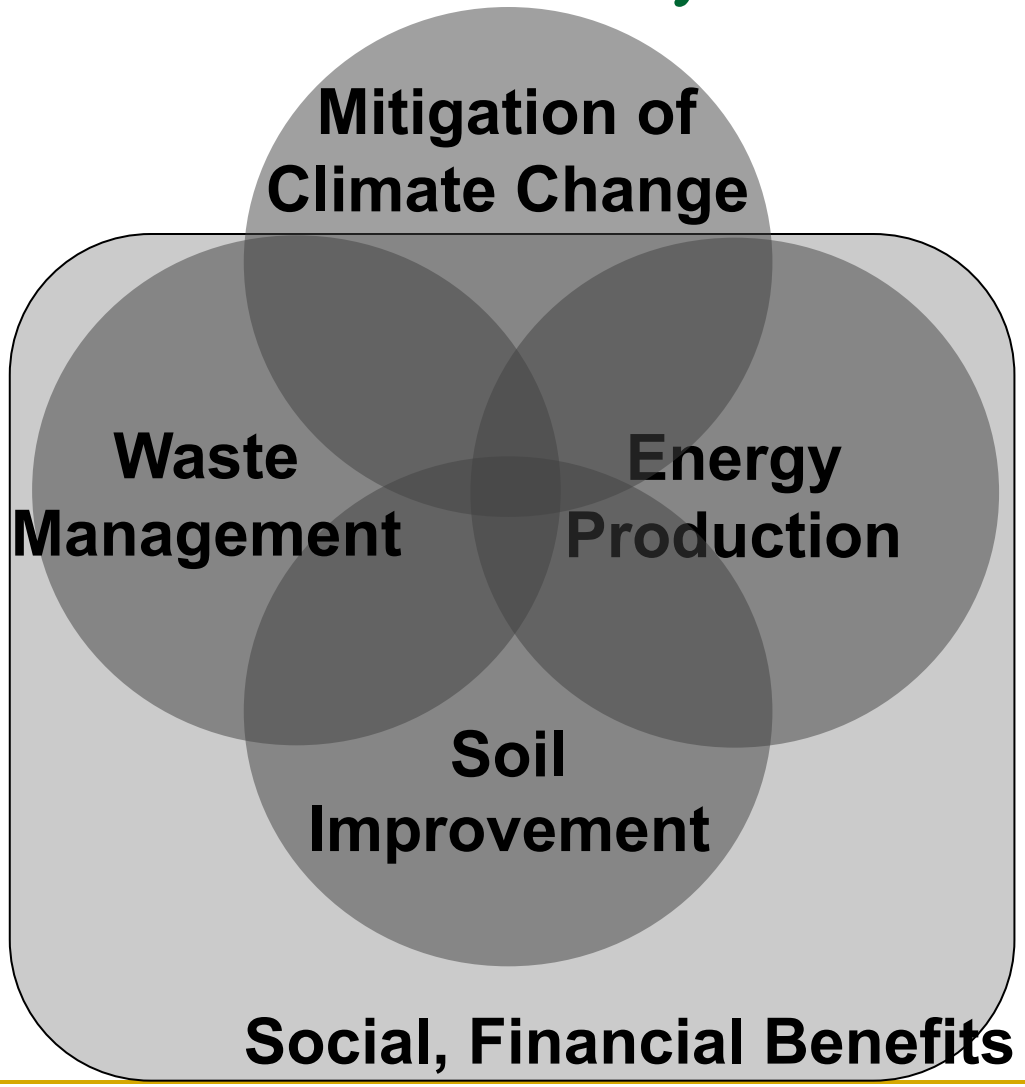
Paraguay



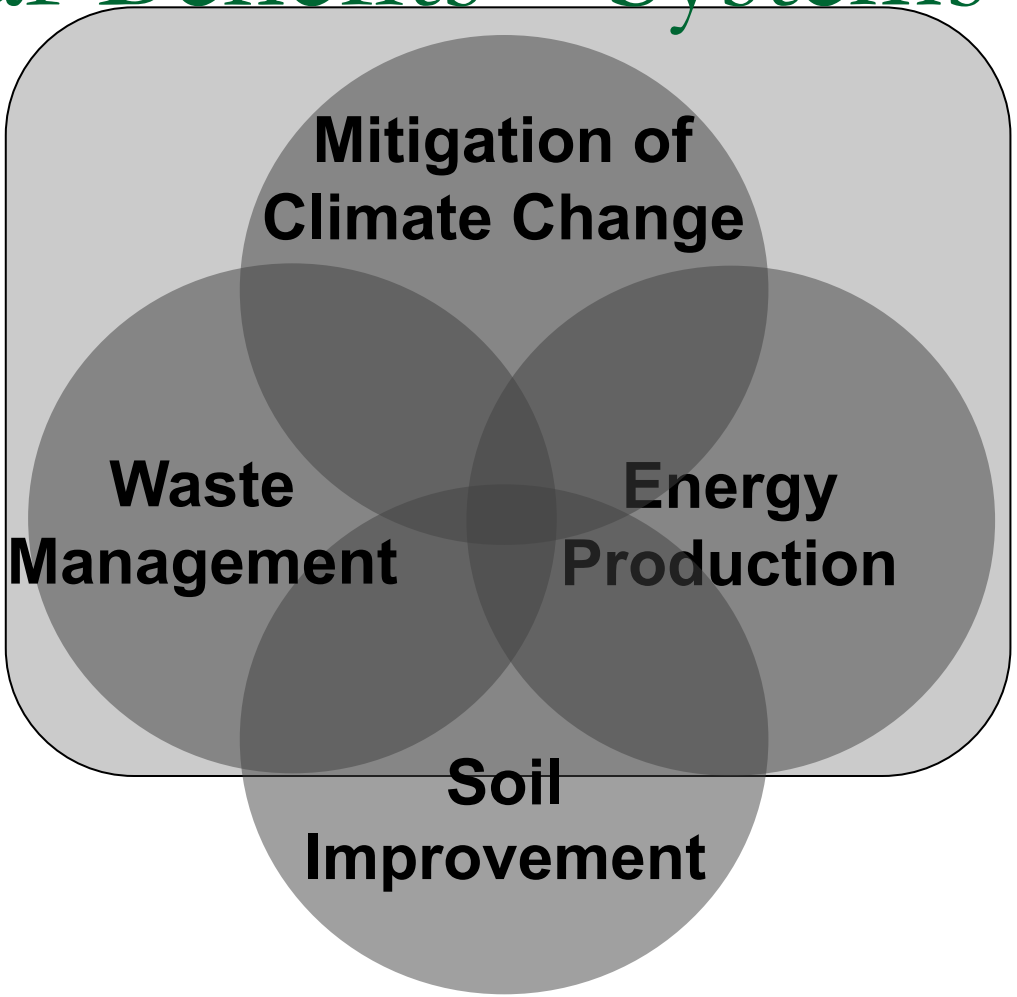
Biochar Benefits – Systems Dimension



Biochar Benefits – Systems Dimension

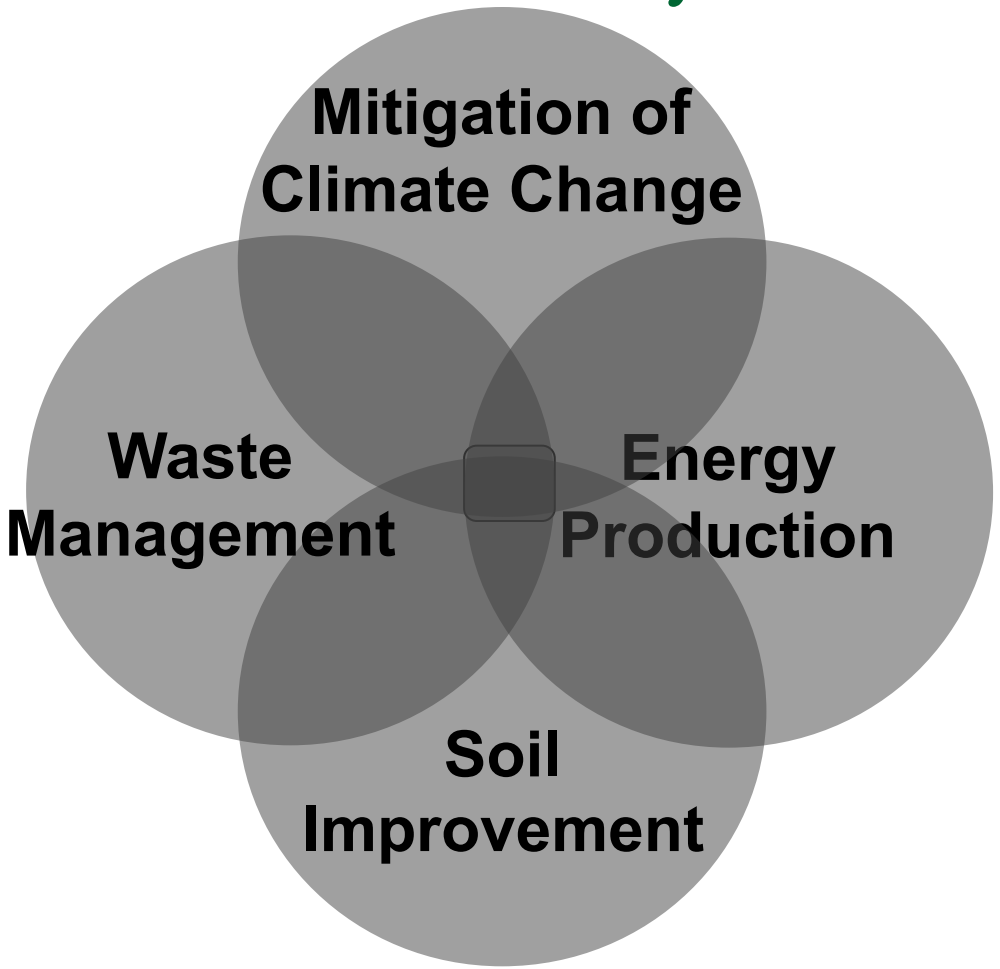


Biochar Benefits – Systems Dimension



Social, Financial Benefits

Biochar Benefits – Systems Dimension



Social, Financial Benefits

Biochar – The Way Forward

Not “WHETHER”, but “WHERE”

The way forward

- **Rigorous system analysis at scale of implementation (economics, emission, etc)**
- **Biochar handling and application**
- **Monitoring and quality control of biochar ("rapid tests")**
- **On-farm field trials**

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