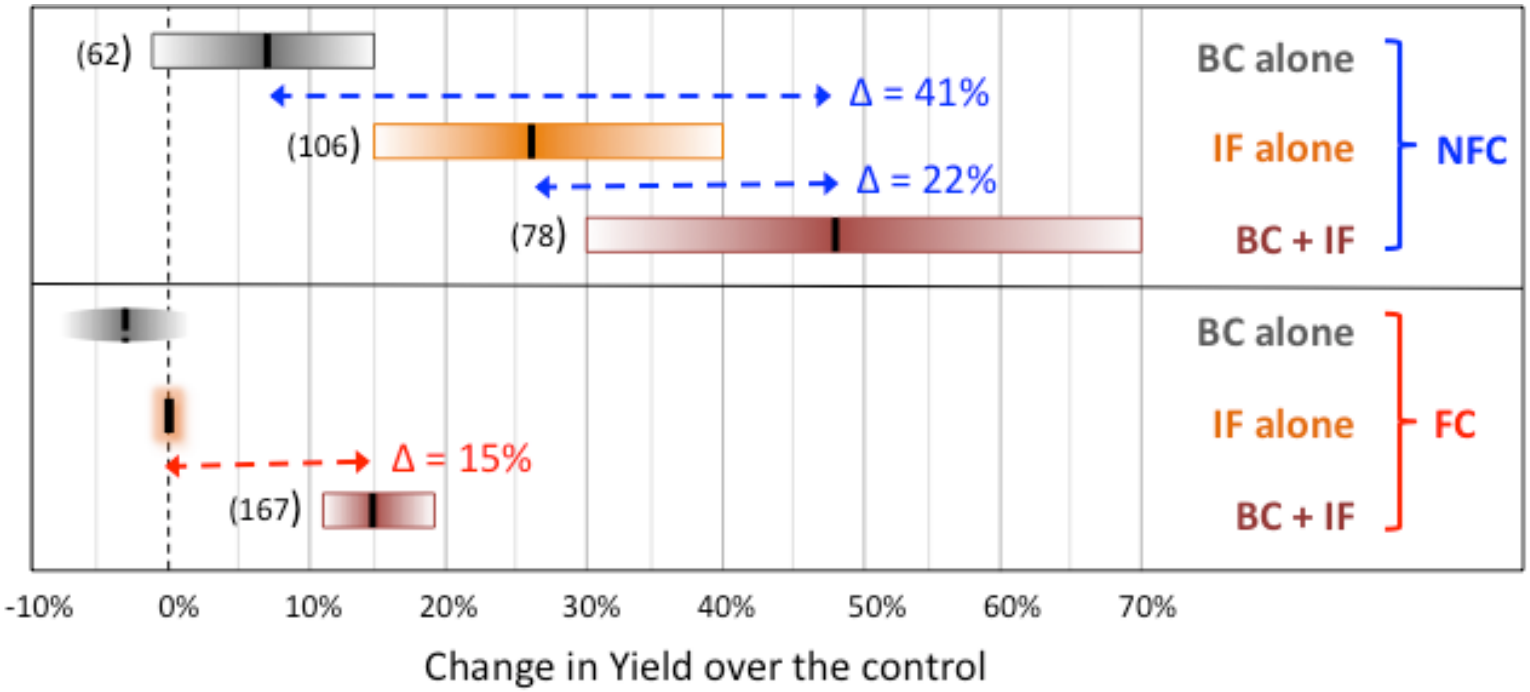
How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar.

Stephen Joseph PhD, AM, FIE

An Overview of the Research; Results From Meta-Analysis



- Biochar added with fertiliser can increases average crop yield by 42% compared to an unfertilised and can increase yields by 22% compared to fertilisation alone.

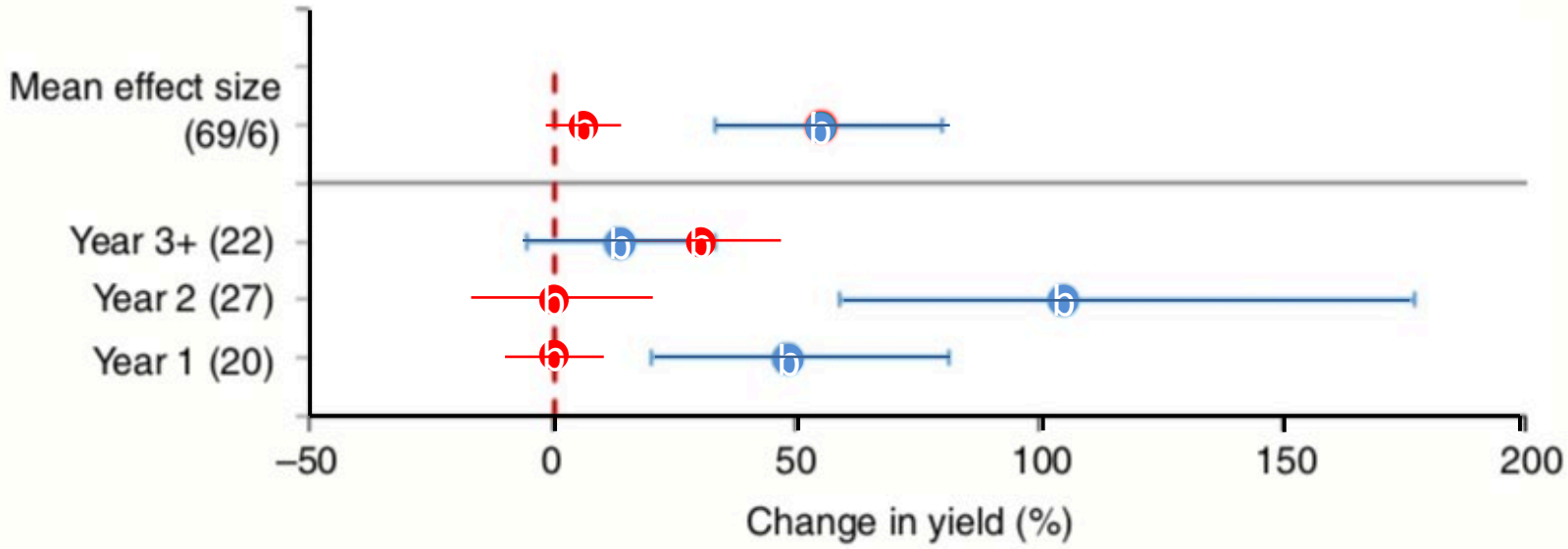
- Biochar applied with fertiliser can increase average yields by 15% compared to a fertilised control

Joseph, S., Cowie, A.L., Van Zwieten, 2021. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy.* 00:1–34
) Ye, L, et al2019, 'Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls', in LM Condron (ed.), *Soil Use and Management*, vol. 36, no. 1, pp. 2–18

The Highest Increases In Crop Yields Occur When;

1. BC are produced at low temperatures (<400C),
2. BC contains a high concentration of nutrients,
3. Applied to low nutrient P-sorbing acidic soils (common in the tropics) and in sandy soils in drylands due to increase in nutrient retention and water holding capacity.
4. Applied at low application rates in the rhizosphere

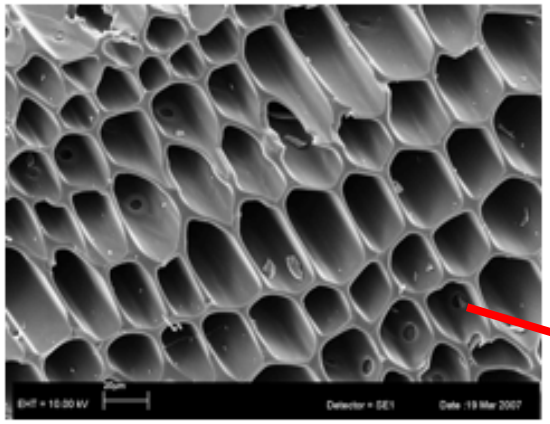
The Highest Increases In Crop Yields Often Occur After The Biochar Has Been In The Ground For More Than 1 Year.

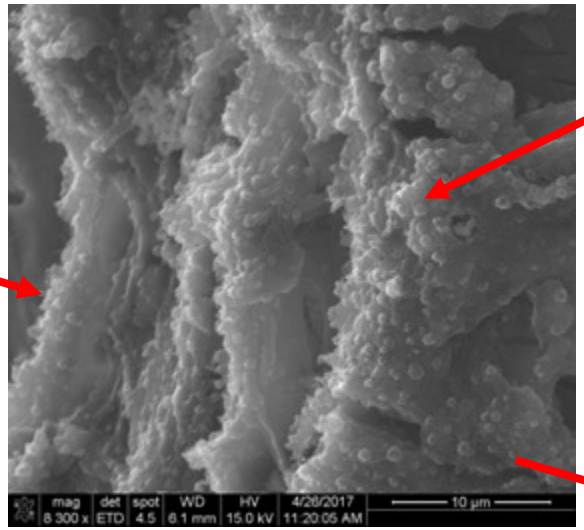


Highest increase in yields for trials with fertilized control occurs in year 3.

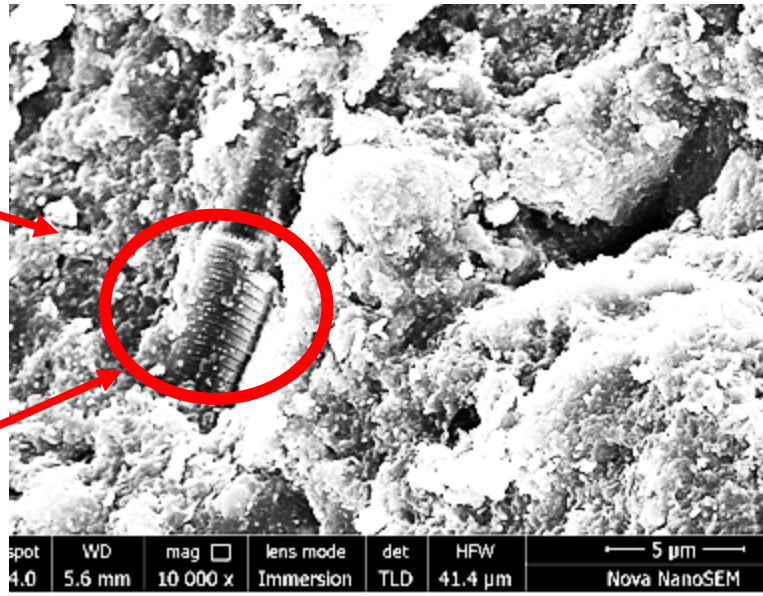
Highest increase in yields for trials with non fertilized control occurs in year 1 and 2

Many Beneficial Properties of Biochar Improve as they Age. Aging Involves the Formation of Organo-mineral Micron size Cluster on The Surface of The Biochar





Minerals bonded by organic compounds forming clusters on the surface

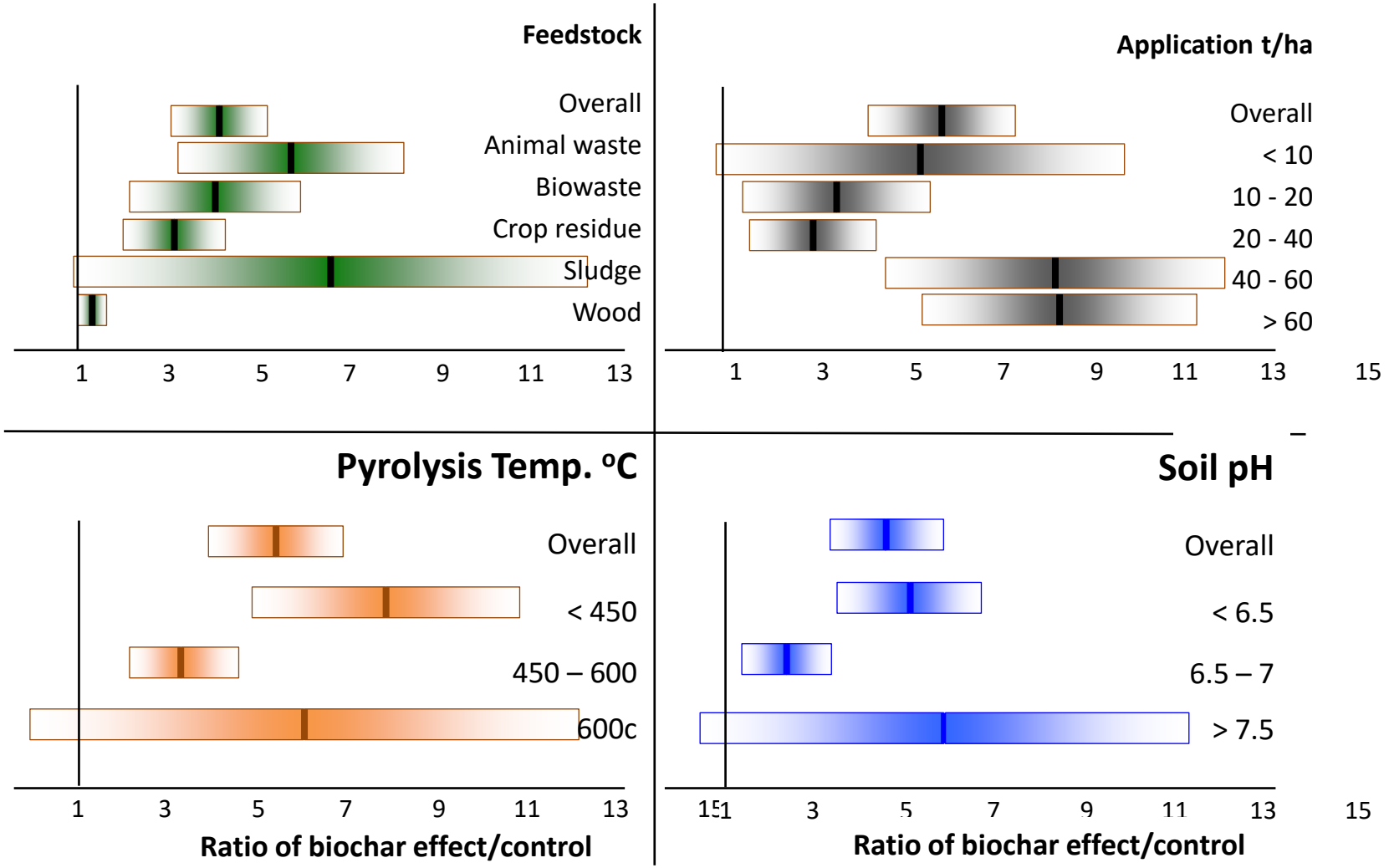


Biochar accelerates the formation of microaggregates via organo-mineral interactions, resulting in the stabilization and accumulation of SOC in the soil

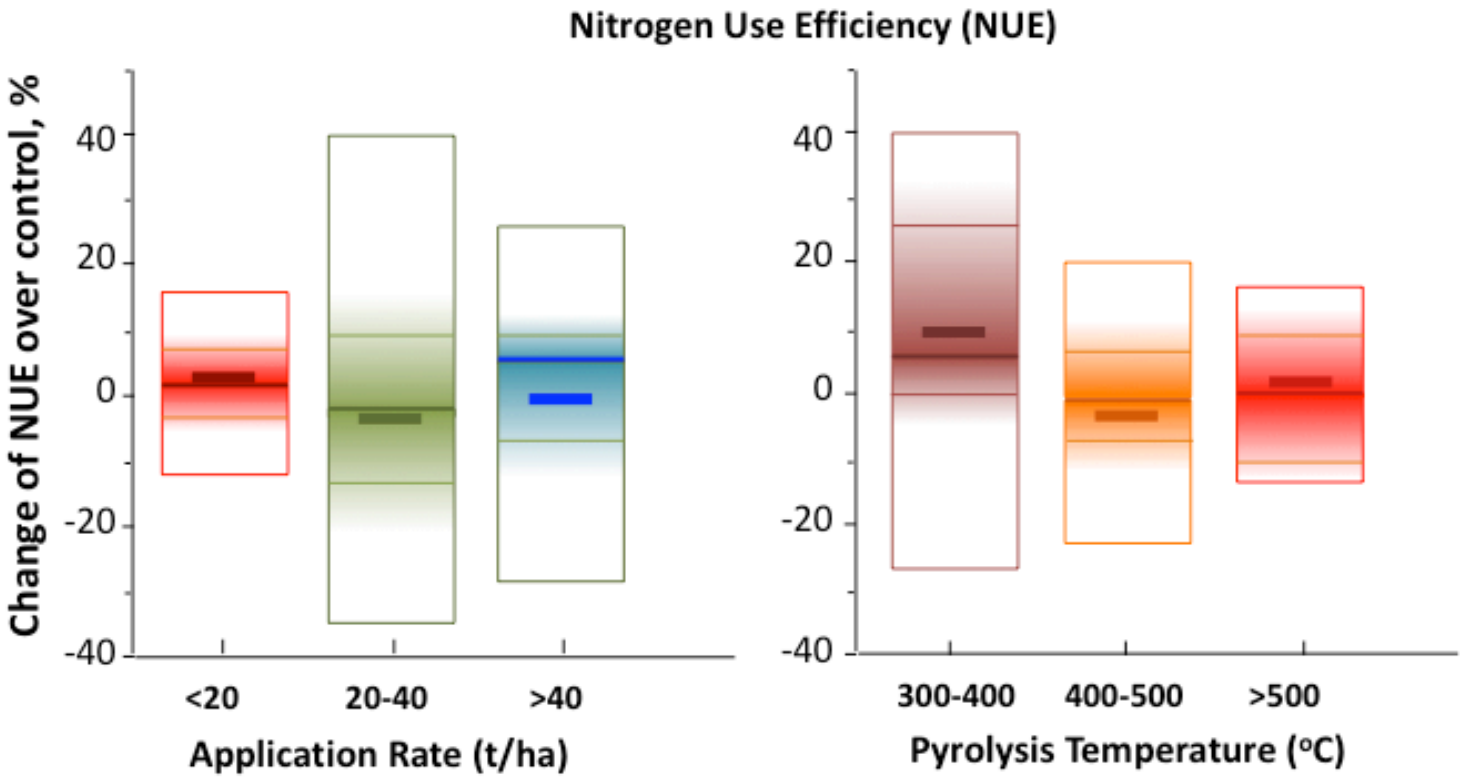
Weng et al 2017 Nature Climate Change

The Effect of Biochar on Phosphorous Availability

1. Produced at low temperatures (<400C),
2. Contain a high concentration of nutrients,
3. Applied to either acid or basic soils at either low or very high application rates



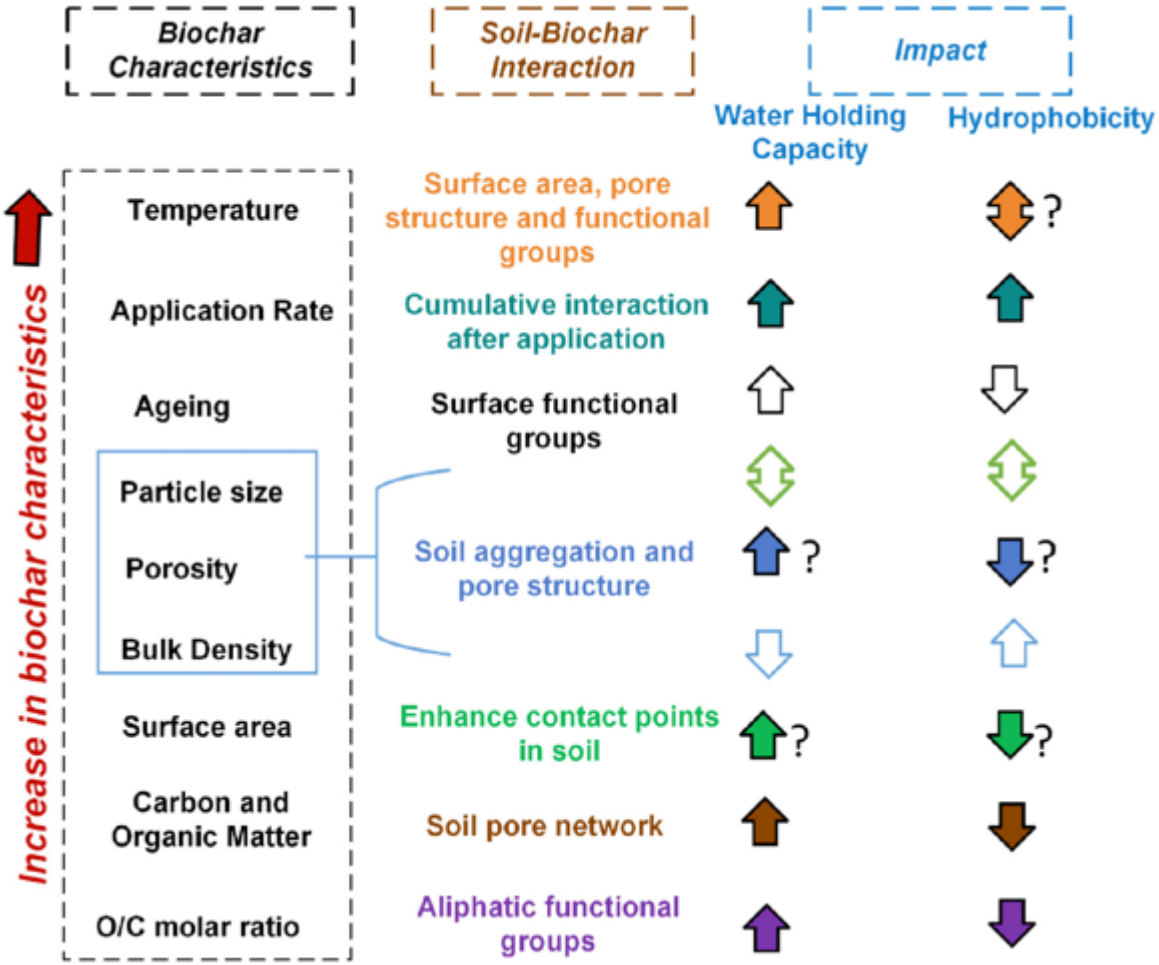
Biochar Effects on Nitrogen Use Efficiency Can Be Positive or Negative



Key Points

- Large applications of woody biochar can increase the C:N ratio, reducing the availability of nitrogen, and increase loss through volatilisation of ammonia.
- Add an additional source of N to bring the C:N ratio to around 30:1 and limit application rates to below 10 tonnes/ha or us high N feedstock.

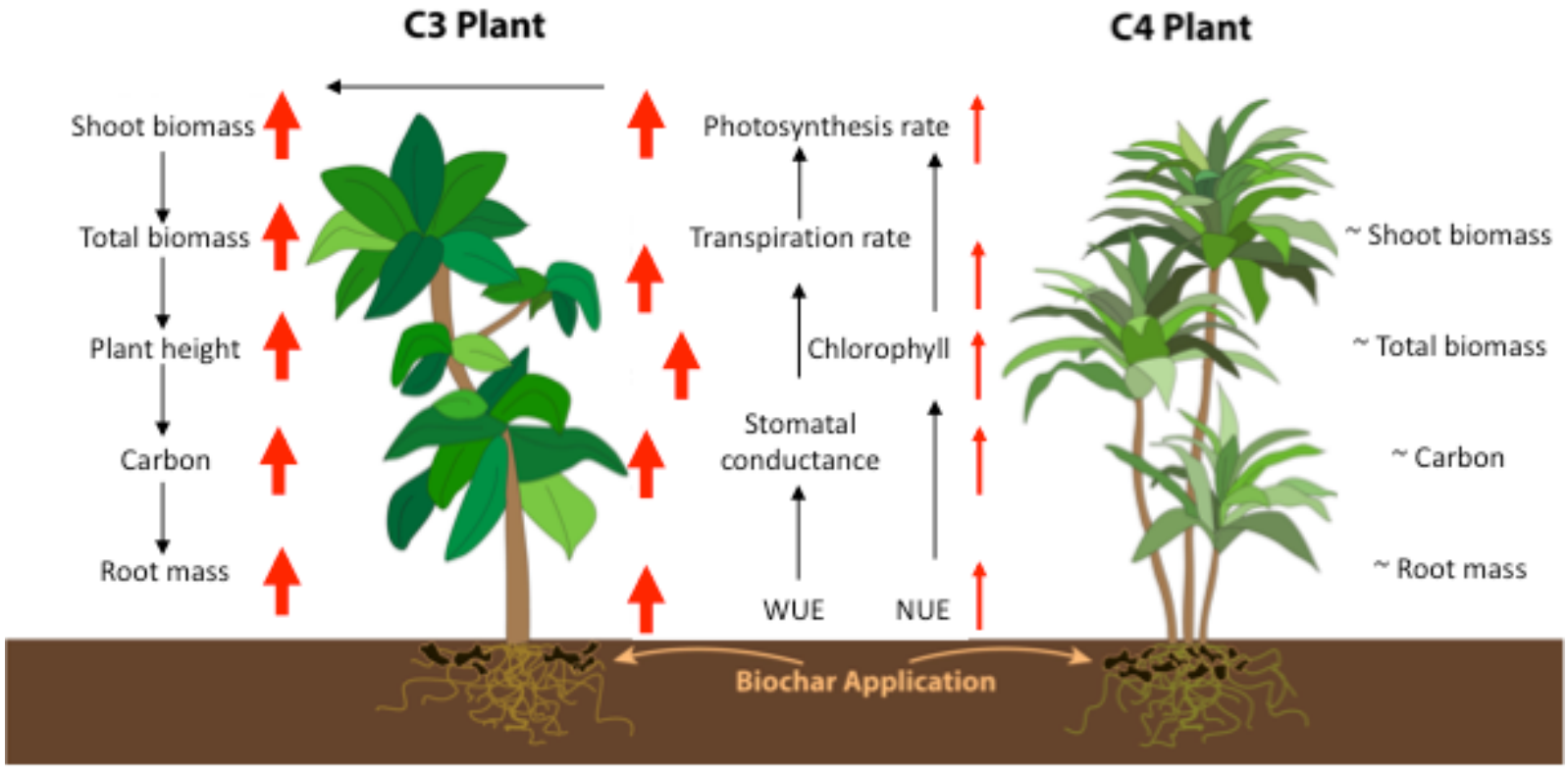
Biochar properties have a complex effect on changing soils water holding capacity



- Straw or grass-derived biochar (at 500–600 °C) increases the WHC of soil if applied at 1 to 3 % in the soil.
- Soil of varying texture requires different particle sizes of biochar to enhance the WHC and reduce hydrophobicity.
- Ageing biochar for at least a year with enhanced oxidation increases the WHC and reduces hydrophobicity

Adhikar et al. 2022 Optimising water holding capacity and hydrophobicity of biochar for soil amendment – A review, STOTEN

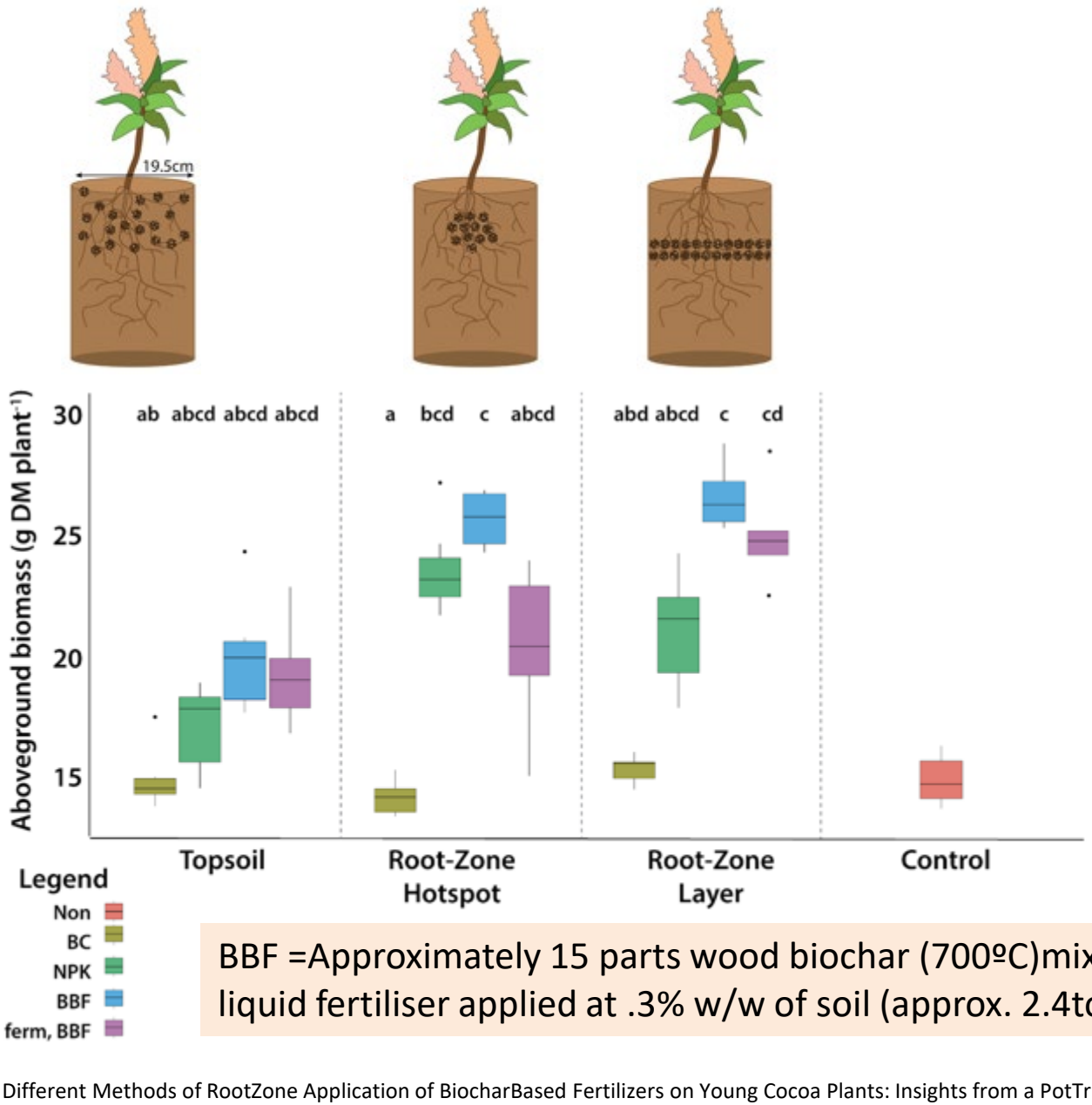
Possible Effects of biochar amendment on plant photosynthesis rate, and thence on biomass and other properties, varied with C3 and C4 plants



Biochar can improve water use efficiency (WUE) and nitrogen use efficiency (NUE), which enhanced plant function along a chain of causation indicated by the black arrows (centre). The boldness of the red upward arrows represents the sizes of the positive responses, which was greater for C3 plants than for C4. This in turn led in C3 plants to increases in biomass and carbon to the roots (arrows on left side), but in C4 plants did not have significant effect on plant biomass (right side, ~ represents non-significant effect

Meyer, J, et al.2022, 'Impact of Different Methods of RootZone Application of BiocharBased Fertilizers on Young Cocoa Plants: Insights from a PotTrial', *Horticulturae*, vol. 8, no. 4

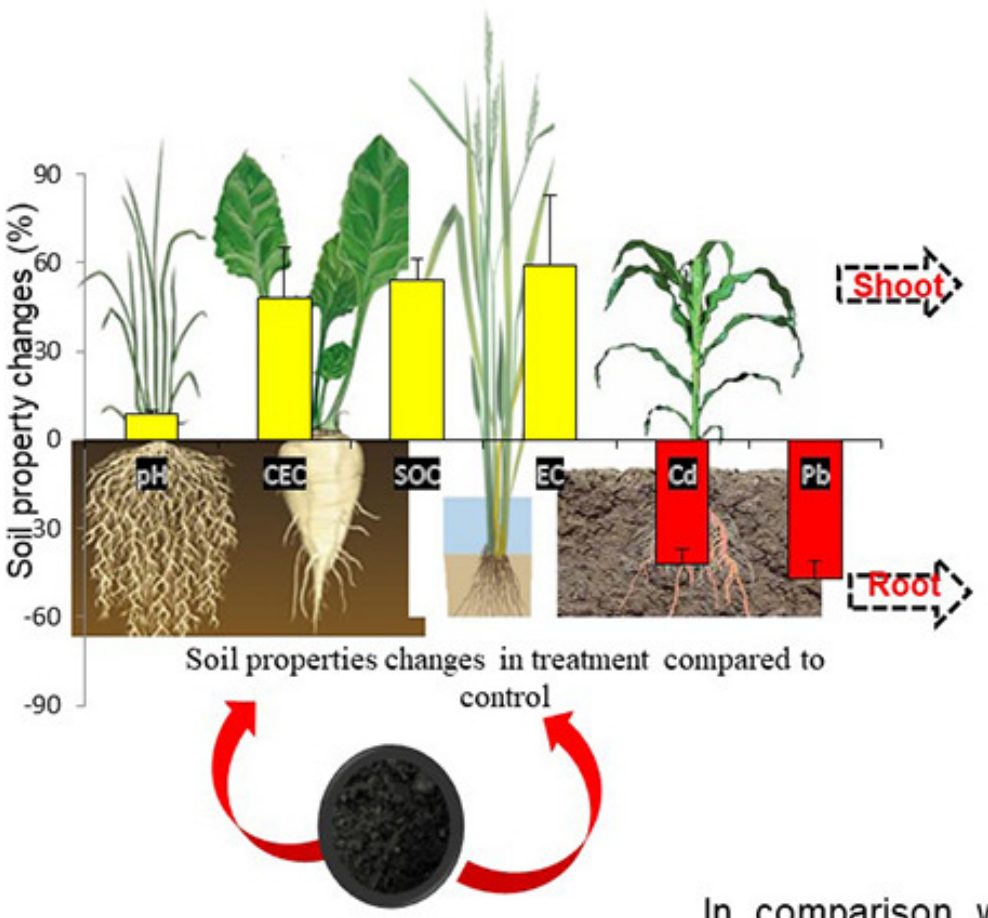
Biochar In Precision Agriculture; Biochar works more effectively if loaded with nutrients and then applied in the rhizosphere;

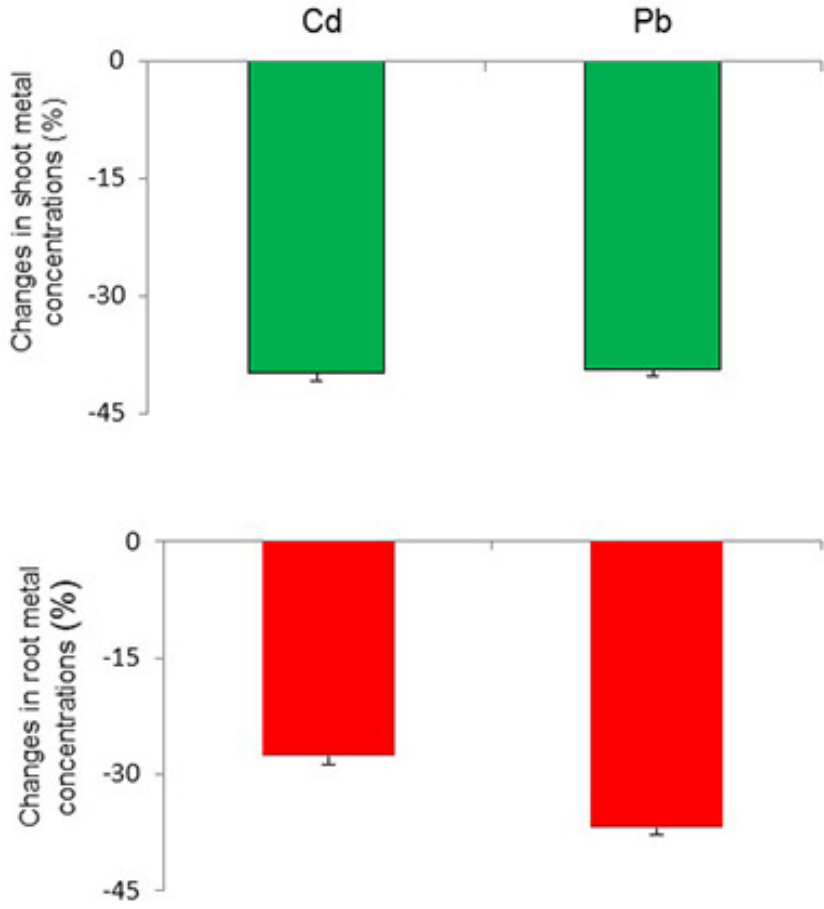


BBF =Approximately 15 parts wood biochar (700ºC)mixed with 1 part liquid fertiliser applied at .3% w/w of soil (approx. 2.4tonne/ha

Meyer, J, et al.2022, 'Impact of Different Methods of RootZone Application of BiocharBased Fertilizers on Young Cocoa Plants: Insights from a PotTrial', *Horticulturae*, vol. 8, no. 4

On Average Biochars Decrease Plant Tissue Concentration Of Heavy Metals By 17-39%

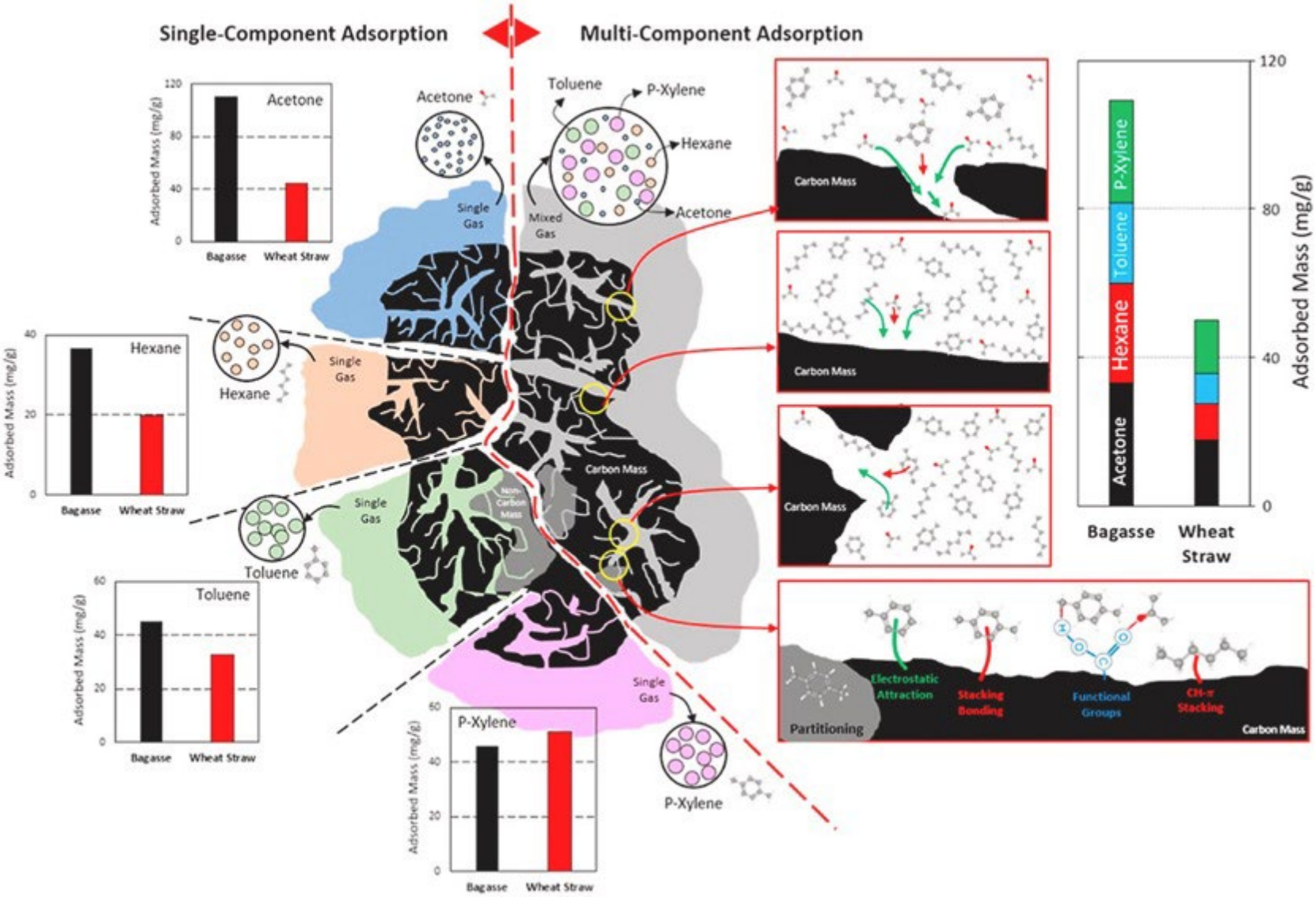




In comparison with the control, biochar treatment greatly improved soil properties, and decreased plant uptake of Cd and Pb.

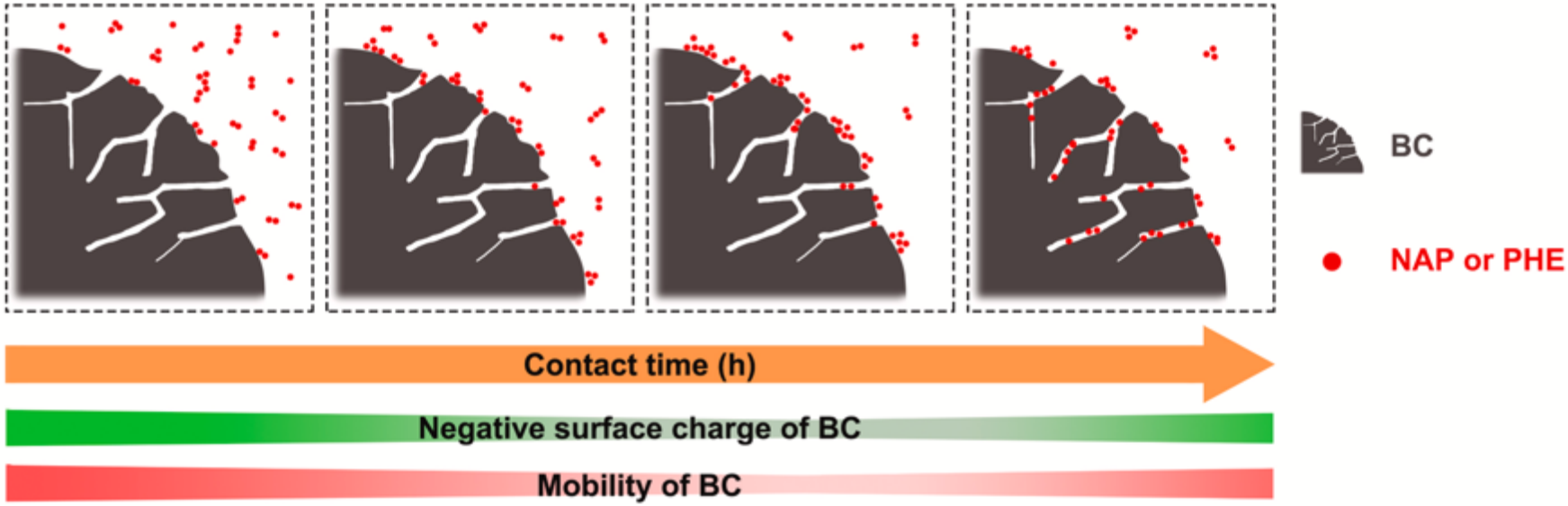
Albert, H.A., et al.2021. Influence of biochar and soil properties on soil and plant tissue concentrations of Cd and Pb: A meta-analysis. *Science of the Total Environment*, *755*, p.142582.

Biochar adsorbs Toxic Organic Compounds Including PAH, and Residual Pharmaceuticals, Pesticides and Herbicide

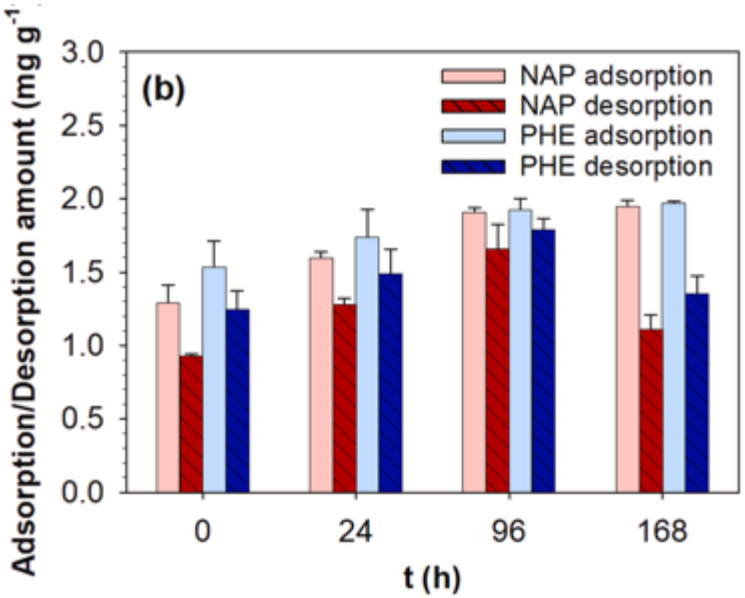


Rajabi, H., Mosleh, M.H., Prakoso, T., Ghaemi, N., Mandal, P., Lea-Langton, A. and Sedighi, M., 2021. Competitive adsorption of multicomponent volatile organic compounds on biochar. *Chemosphere*, *283*, p.131288.

Biochar adsorbs Toxic Organic Compounds (Naphthalene and Phenanthrene .

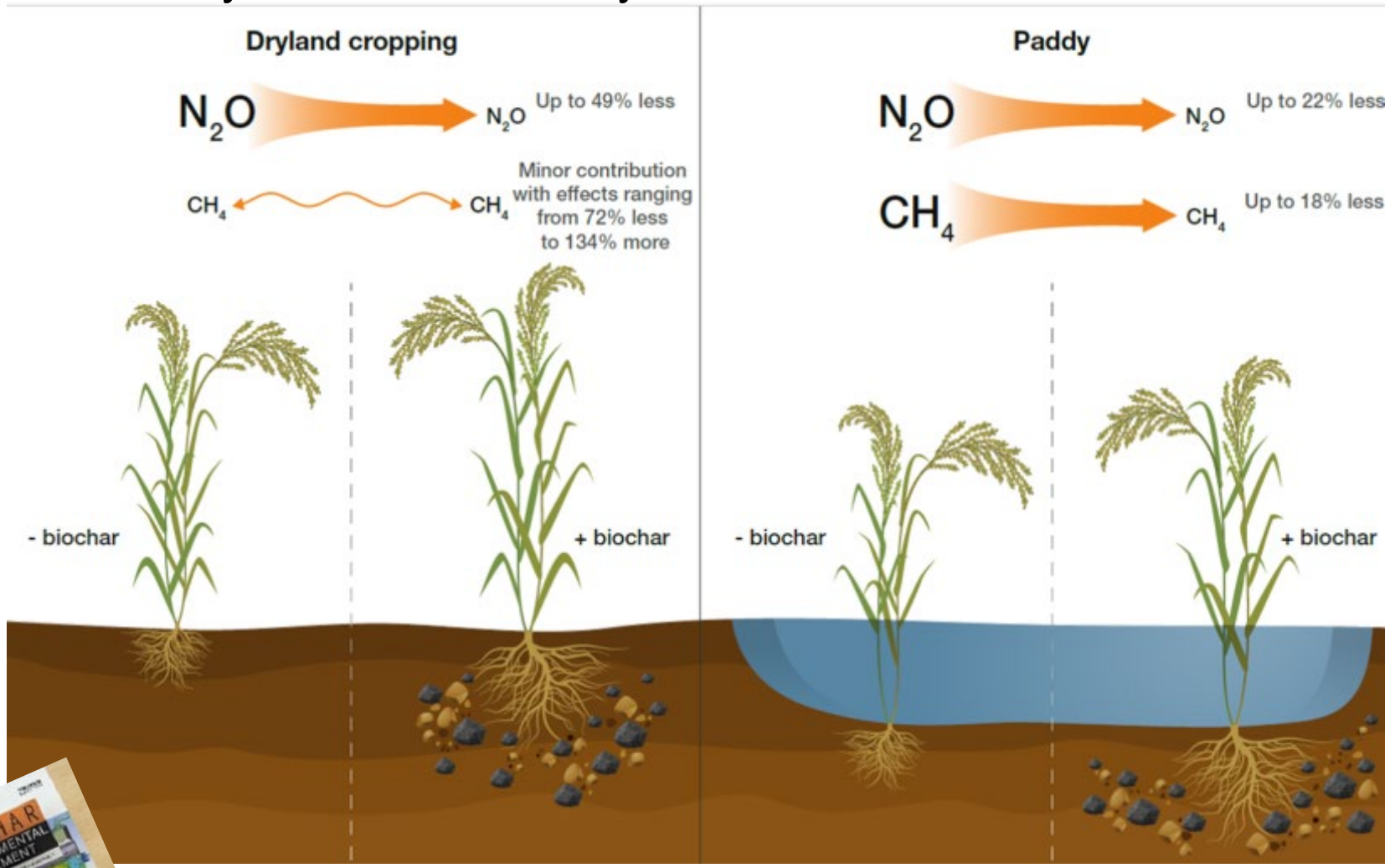


Over time these compounds diffuse into the pores and can be either degraded by microbes or can react with minerals to ensure that they are oxidise and them become non bioavailable.



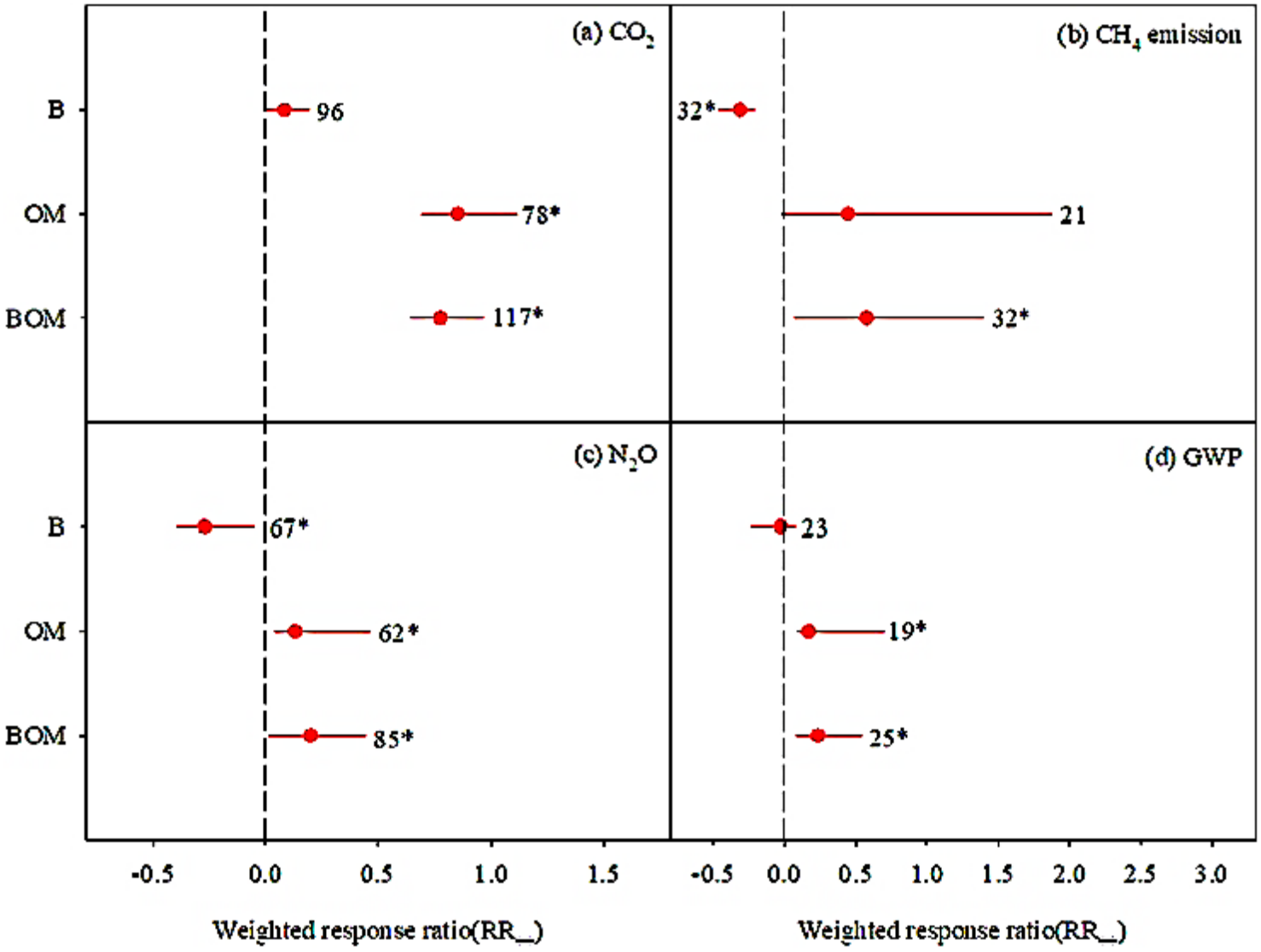
Yang, W.,., Shang, J. and Li, B., 2021. PAHs sorption to biochar colloids changes their mobility over time. *Journal of Hydrology*, *603*, p.126839.
Patel, A.K.,et al.., 2022. Advances on tailored biochar for bioremediation of antibiotics, pesticides and polycyclic aromatic hydrocarbon pollutants from aqueous and solid phases. *Science of the Total Environment*, *817*, p.153054.

Summary of 13 meta-analyses since 2015



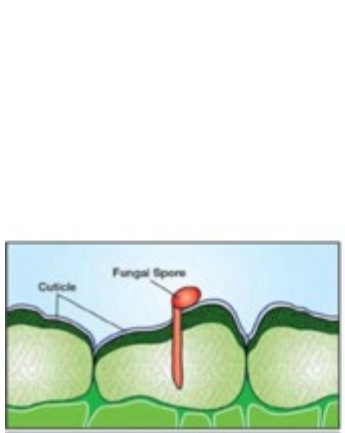
Biochar for Environmental Management- Third Edition (2024) *in press*

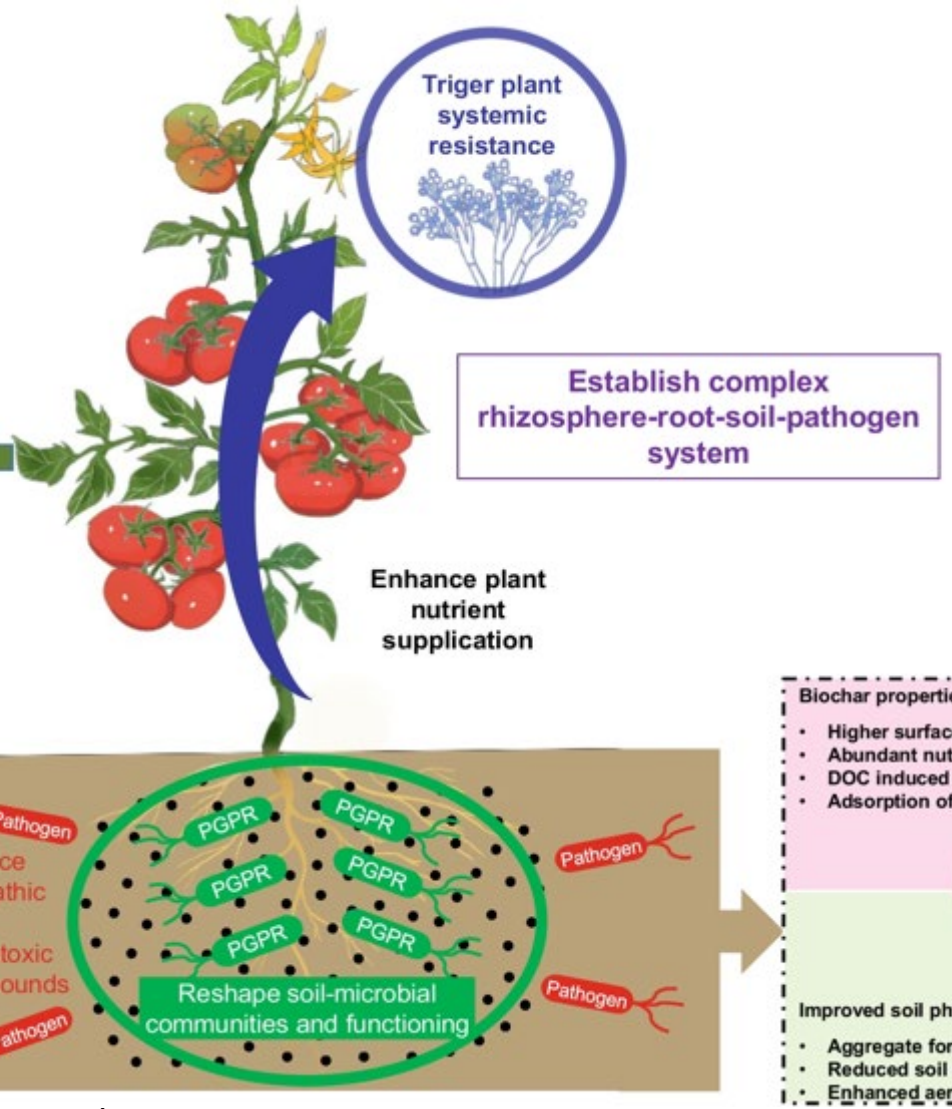
On Average Biochar Decreases N_2O and CH4 especially in paddy soils) and has little effect on CO2



Fu, J., Zhou, X., He, Y., Liu, R., Yao, Y., Zhou, G., Chen, H., Zhou, L., Fu, Y. and Bai, S.H., 2023. Co-application of biochar and organic amendments on soil greenhouse gas emissions: A meta-analysis. *Science of The Total Environment*, *897*, p.166171.

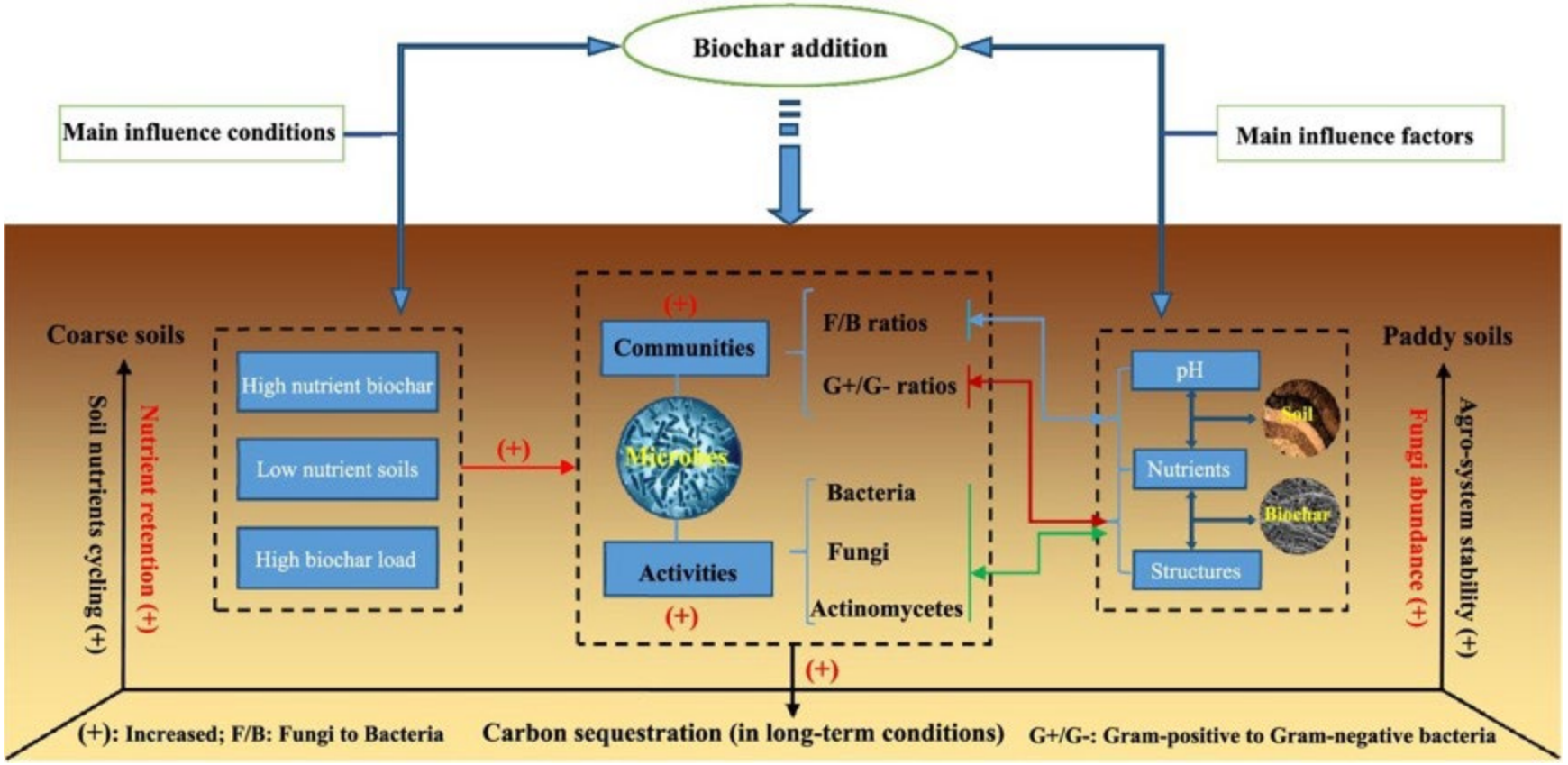
Biochar Assists Plants Resist Disease Through Changes in the Rhizosphere; Low Temperature Straw BC applied at High Application Rates in the Rhizosphere Are, on Average More Effective





Yang *et al. Biochar (2022) 4:43*

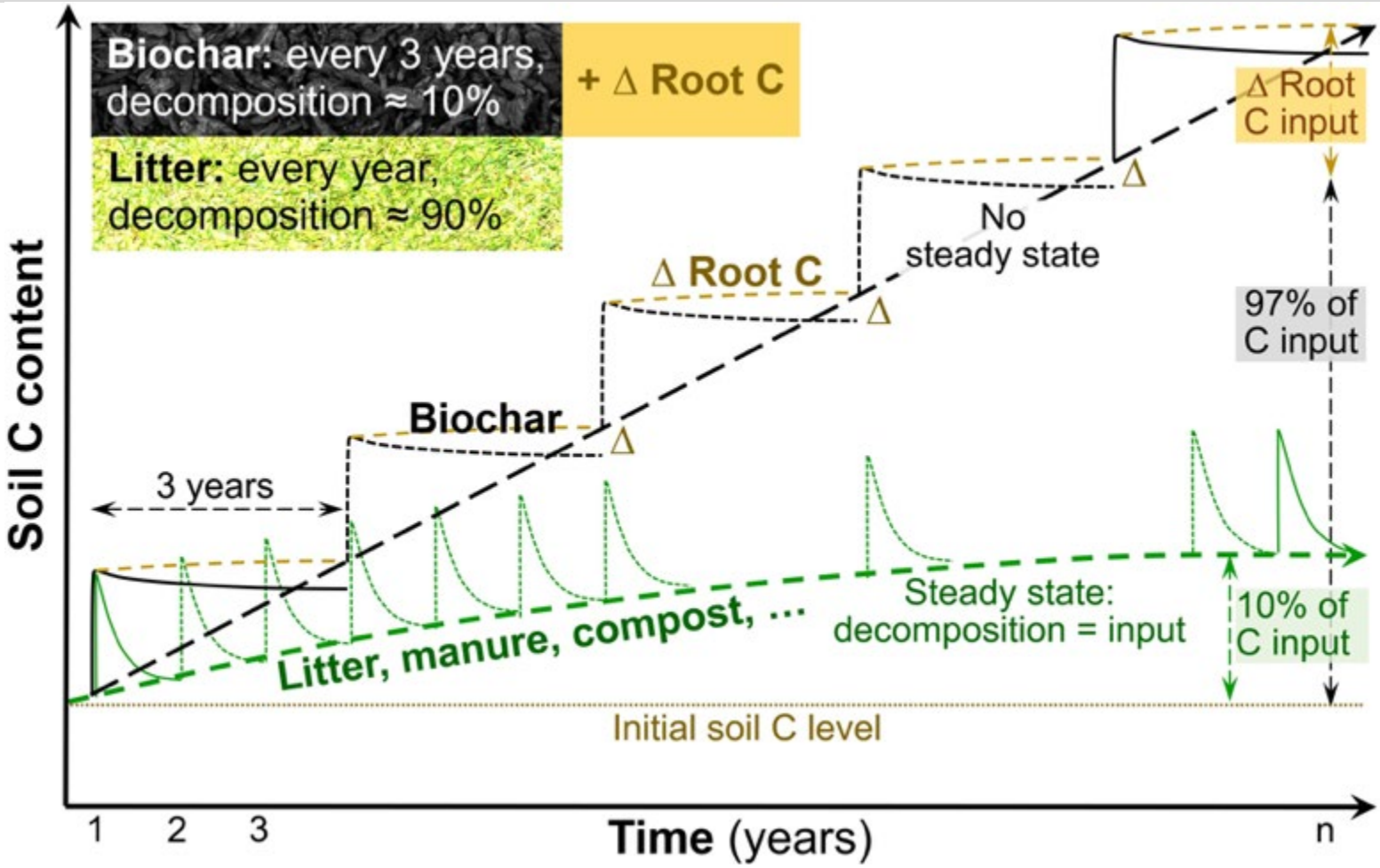
Biochar Effect on Soil Microbial Population



- Low temperature BC addition in low pH soils greatly increased ratios of fungi to bacteria.
- Crop residue BC application in dryland soils increased ratios of Gram-positive bacteria to Gram-negative bacteria the most.
- High load of biochar addition greatly enhanced microbial activities in low nutrients soils.
- BC nutrients and structural properties play the important role in soil microbial community structure changes and activities.

Leiyi Zhang, et al. Responses of soil microbial community structure changes and activities to biochar addition: A meta-analysis, Science of The Total Environment, 643 , 2018,926-935,

Applying Smaller Amounts of Enhanced Biochars in the Root Zone Every Crop Cycle Can Give Greatest Return to the Farmer as well as Enhancing Soil Health and Carbon



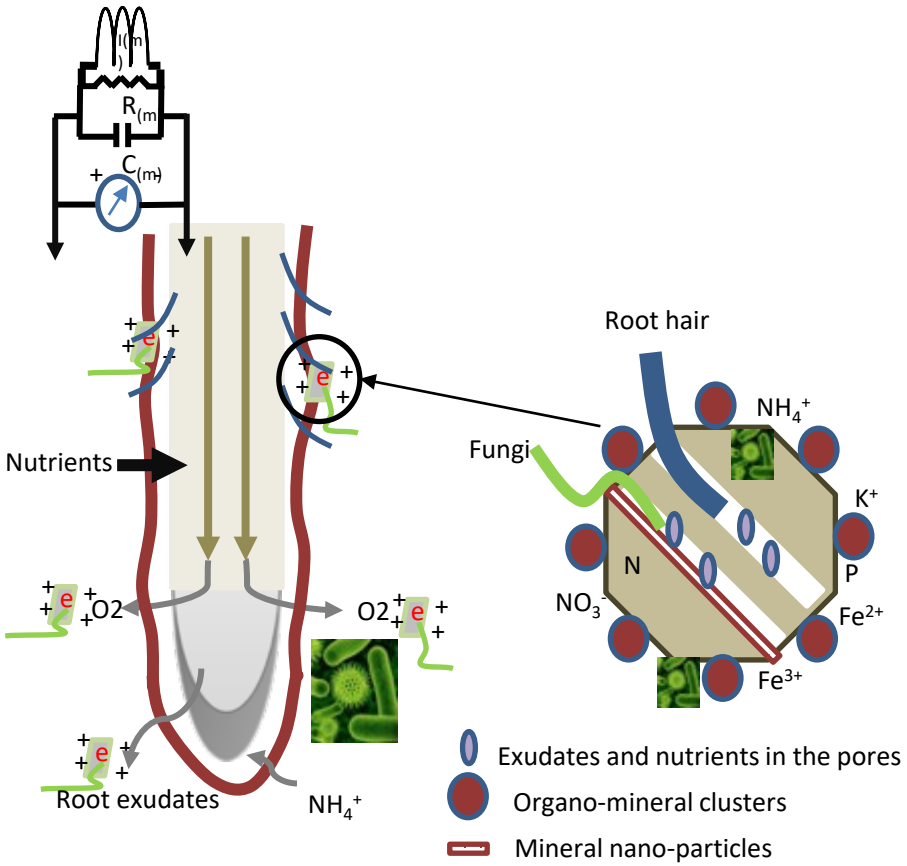
Joseph, S., Cowie, A.L., Van Zwieten, 2021. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy.* 00:1–34

) Ye, L, et al2019, 'Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls', in LM Condron (ed.), *Soil Use and Management*, vol. 36, no. 1, pp. 2–18

Summary of How Biochar Works in the Rhizosphere

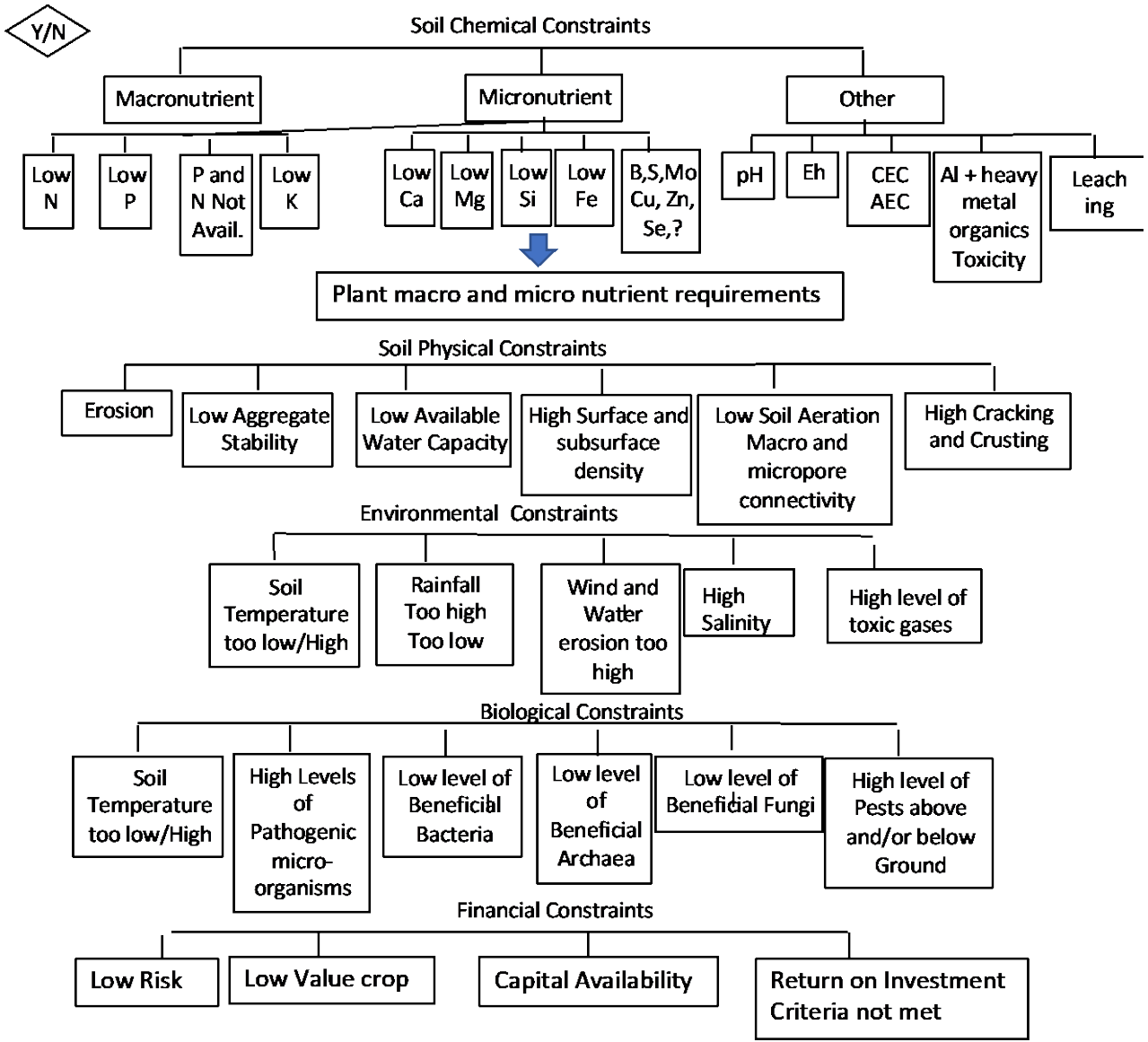
1. Biochar catalyzes microbial and chemical processes in the rhizosphere, decreasing the activation energy for biotic and abiotic reactions, which can increase nutrient mineralization and facilitate nutrient uptake by plants.

2. It can act as a microbial fuel cell where there is growth of beneficial micro-organisms, production and consumption of electrons, fixation of carbon and nitrogen from the soil and the air;



Joseph, S., Cowie, A.L., Van Zwieten, 2021. How biochar works, and when it doesn't: A review of mechanisms controlling soil and plant responses to biochar. *GCB Bioenergy.* 00:1–34

Developing Enhanced Biochars that can be Applied at Low Application Rates That Give a Return to the Users and Meet Specific Constraints; A Decision Matrix

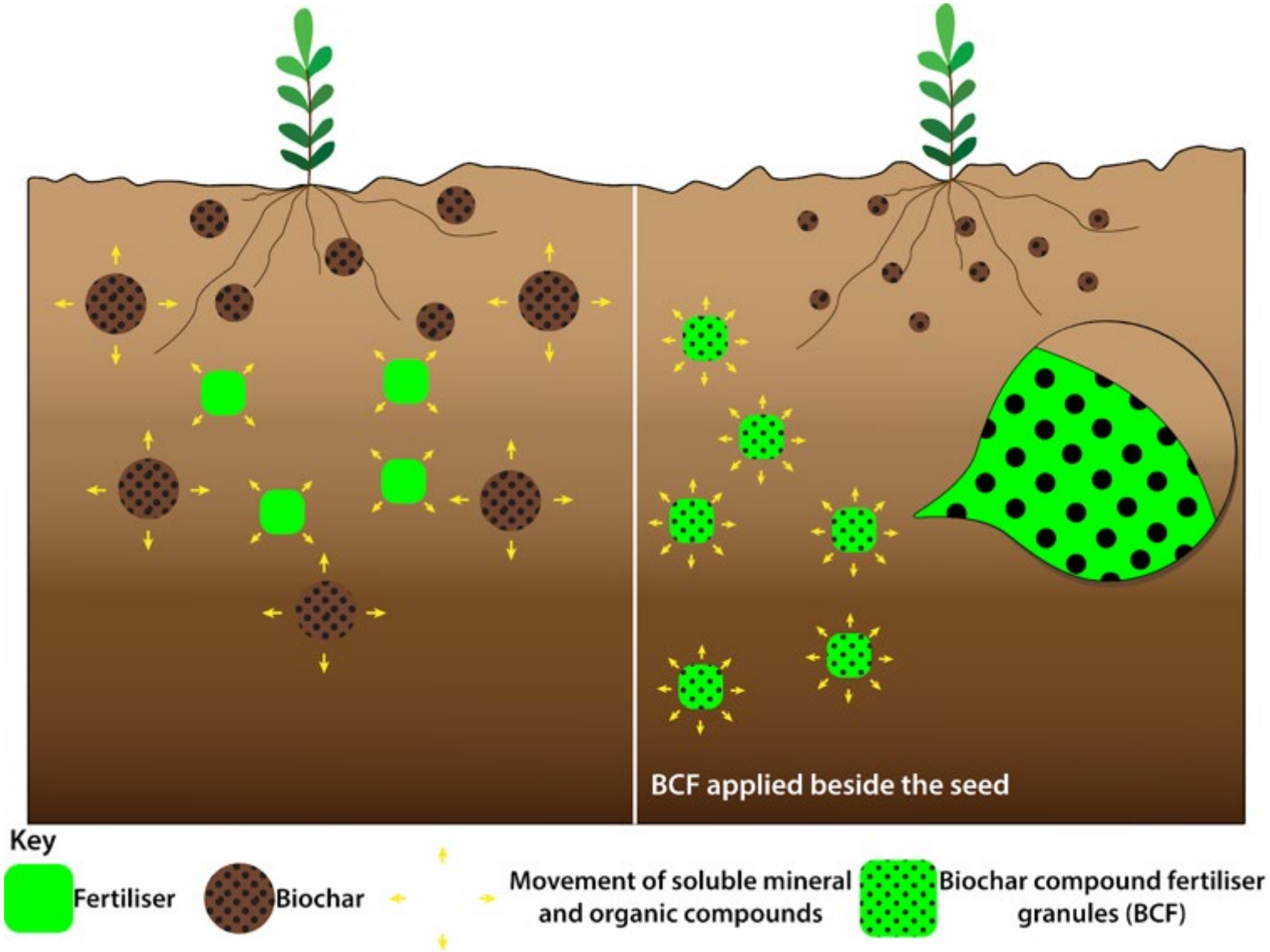


Key Findings to Ensure Effective Plant and Soil Response

1. Use a range of biomass feedstocks to make a composite biochar with a range of properties and if feasible have both high (600C) and low temperature biochar (400ºC) in the product
2. Load the biomass with minerals especially basalt, an amorphous silica, clay, magnetic iron compounds and a high source of P (e.g. rock phosphate bones) and for clayey soils gypsum
3. Quench the hot biochar with macro and micro nutrients (especially N). These can be solids such as manure or compost or liquids (chemical or organic e.g seaweed or fish extract) with high N and P content
4. Size reduce the biochar

Biochar In Precision Agriculture;

Biochar applied at 100-500kg/ha with 200-400kg/ha of Organic or Inorganic fertiliser as Granules, Pellet of Liquids (with <50micron particles) in or near the Rhizosphere



Results of Trials with Wheat in South Australia applying high P biochar mineral fertiliser applied at 500kg/ha to high pH Soils

1.To produce 1.5-tons of straw/basalt/FeSO4 biochar

2. pelletized (Ø4mm) fine biochar powder

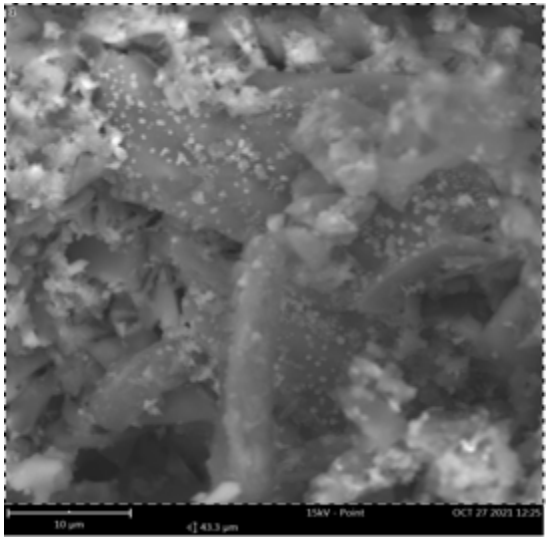
3.The pyrolysis process 450°C

4.Post-pyrolysis treated with Phosphoric Acid (278L per 1.5t biochar.

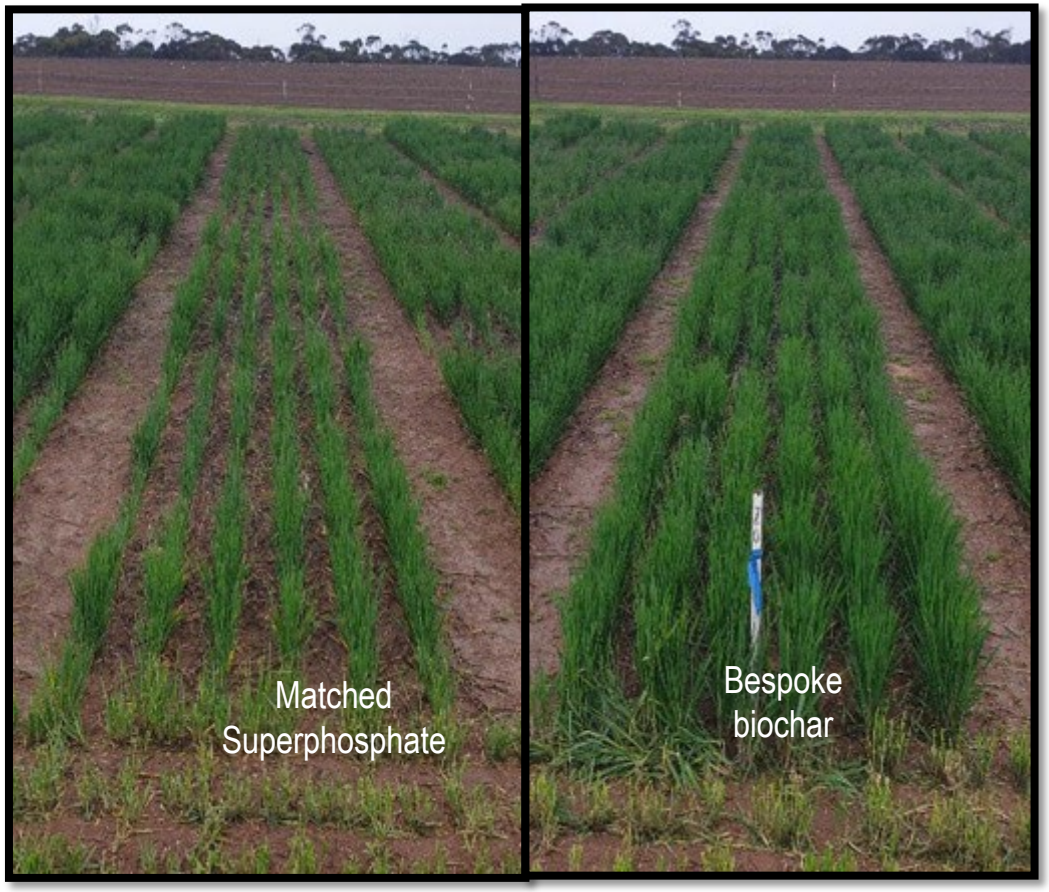
5.The biochar is then ground to fine powder 100 mesh

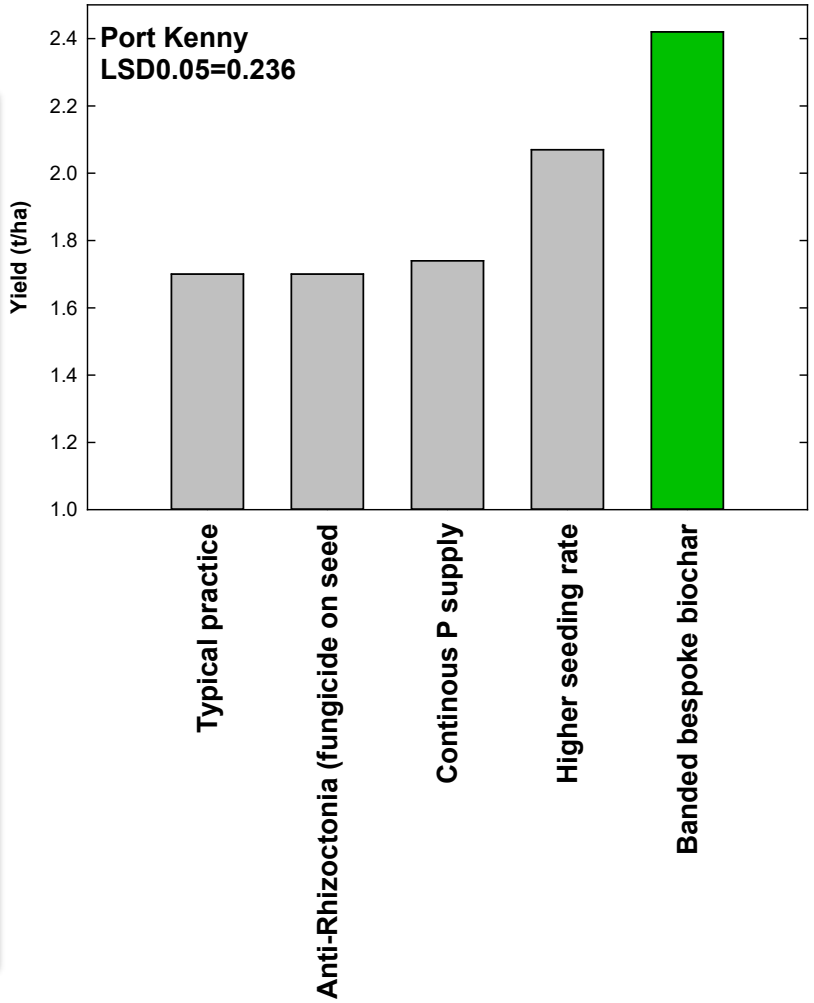
6.1500kg of the biochar powder is to be pelletized (Ø4mm)

7.2% of modified corn starch is used as binder for making soft pellets.



Results of Trials with Wheat in South Australia BMC high P fertiliser applied at 500kg/ha; P same in all treatments





NSW GOVERNMENT Primary Industries

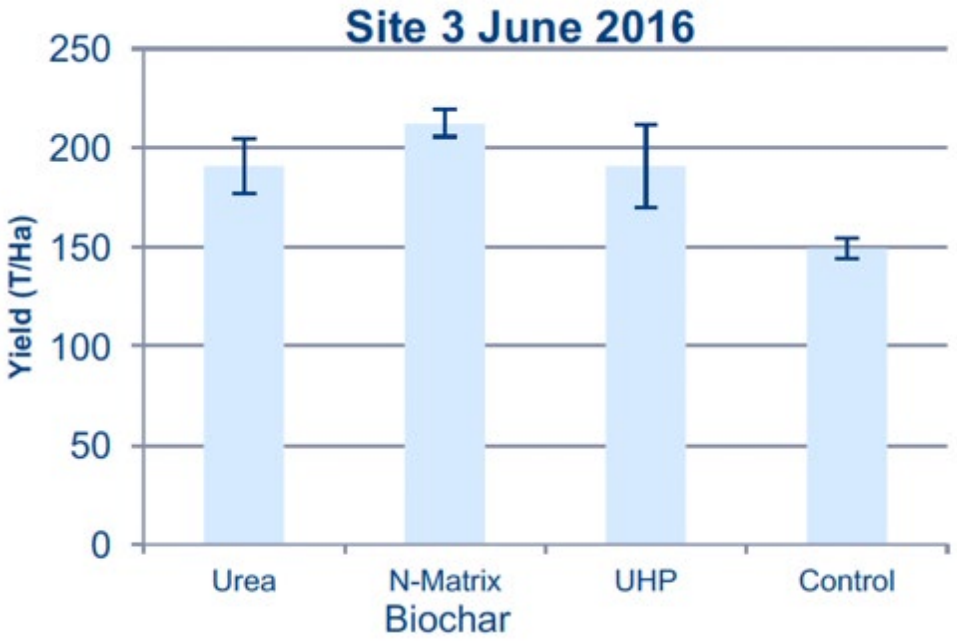
Photo: Brian Dzoma & Nigel Wilhelm SARDI

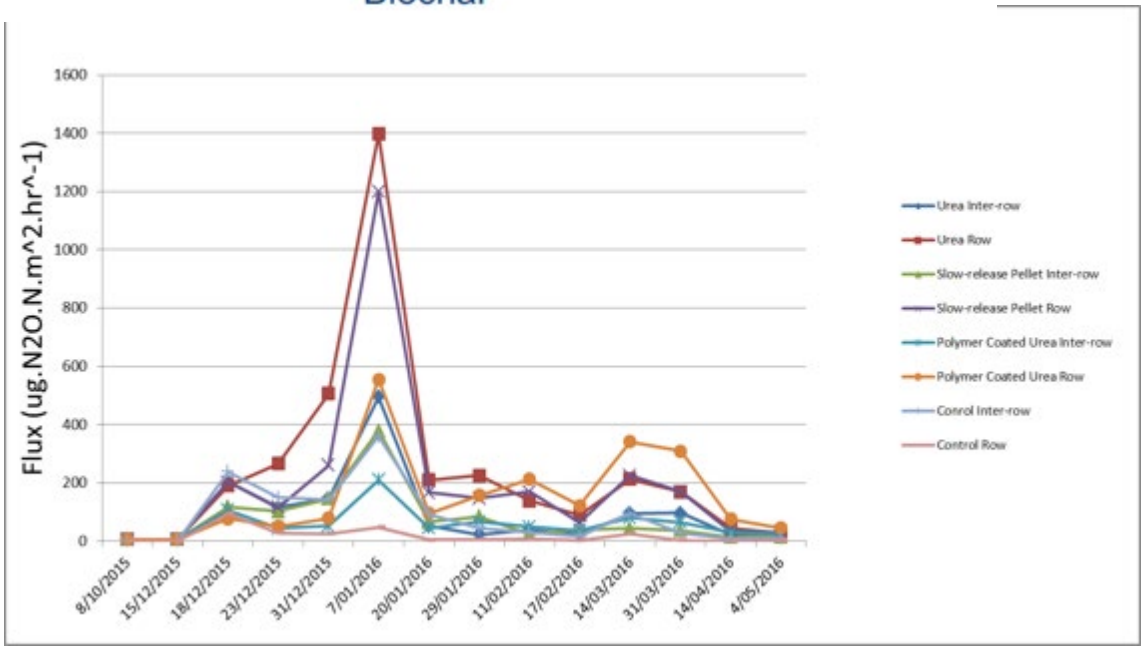
Sugar Cane Field assessment of an ‘early generation of engineered product compared to different urea products’

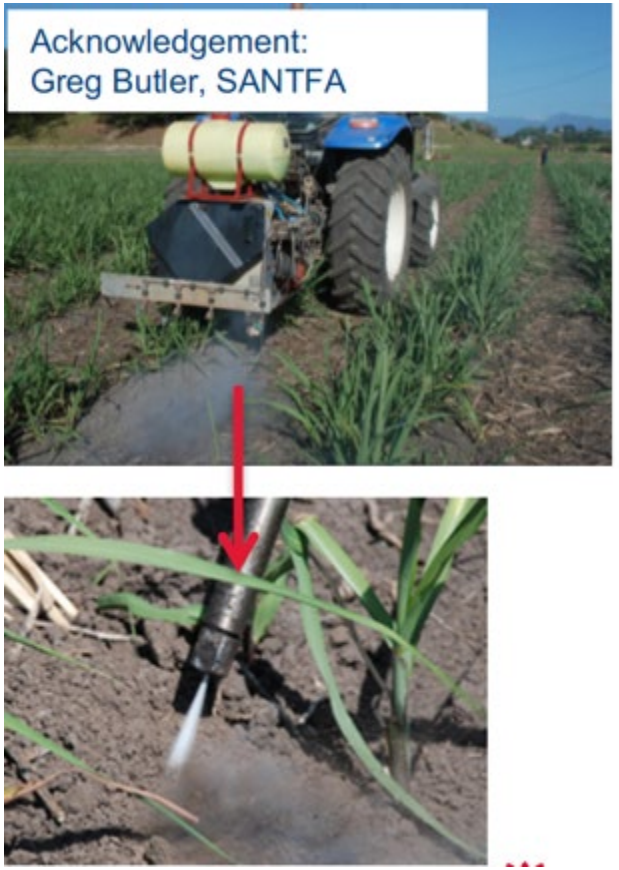
EC	160 dS/m
pH (CaCl2)	7.5
Total Nitrogen	16%
Total Carbon	5.4%

NSW GOVERNMENT Primary Industries

Yield and Nitrous oxide release from BC/Urea and High Pressure Injection



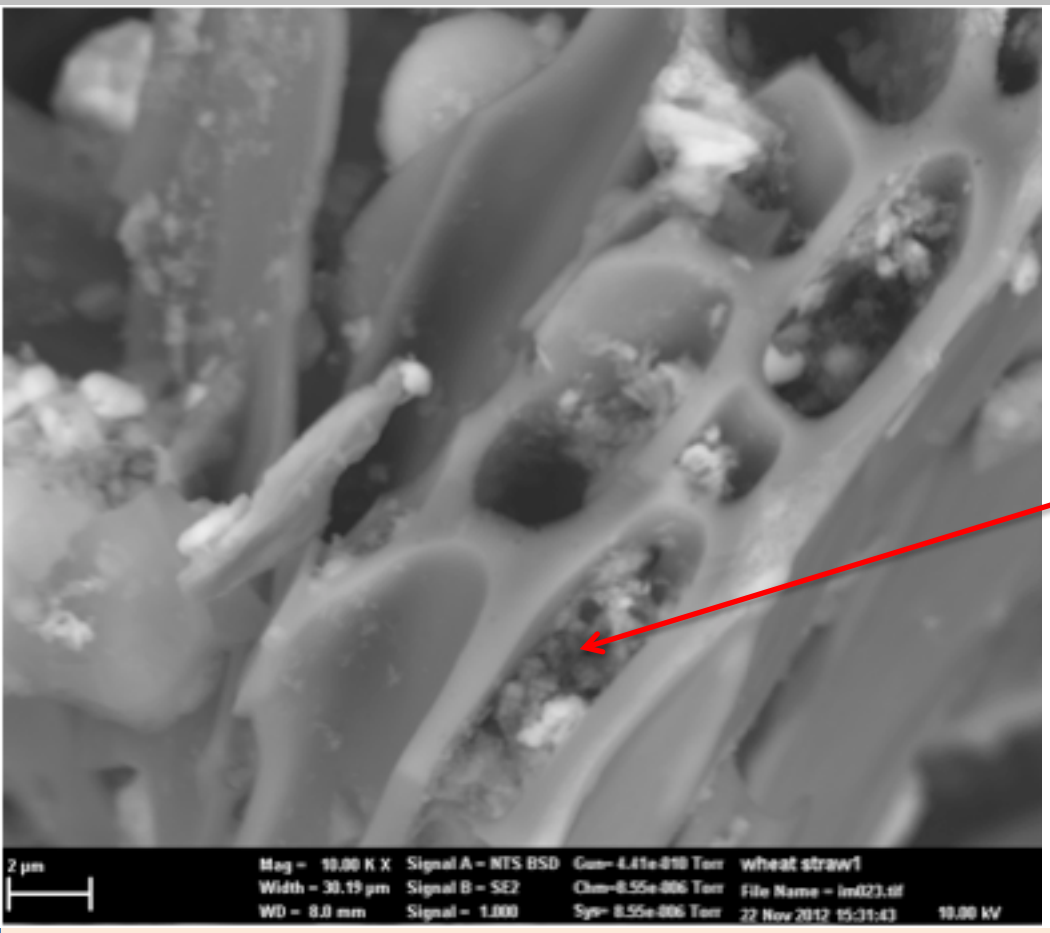


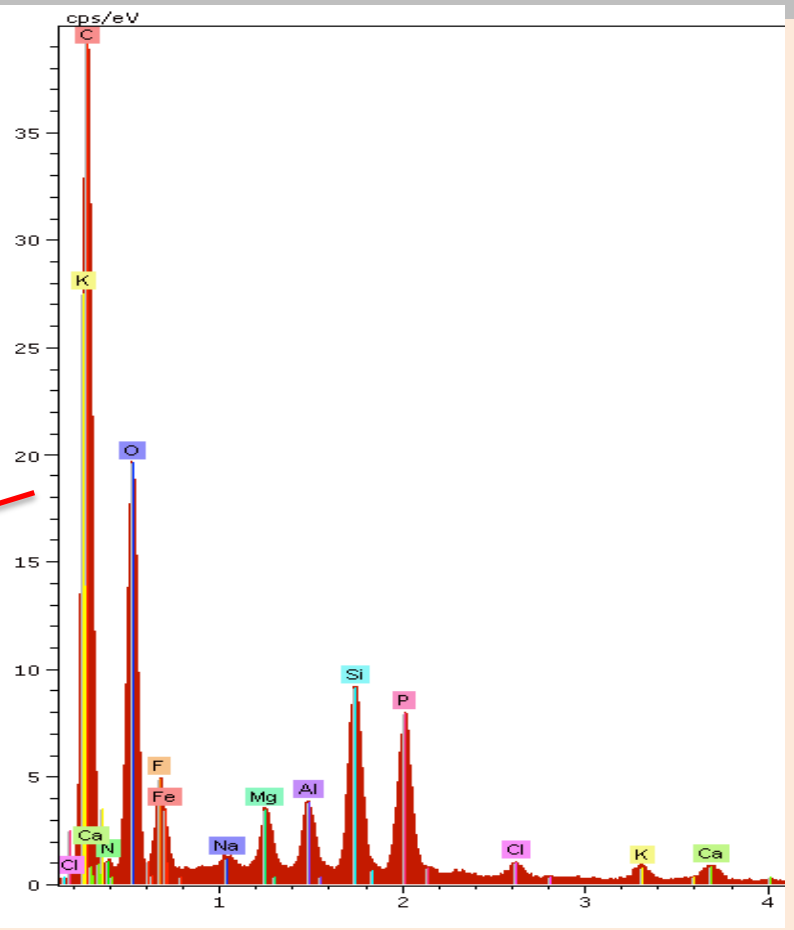


Ultra High Injection liquid Urea

NSW GOVERNMENT Primary Industries

The Structure Of NPK+ Wheat Straw Biochar Both Macro and Micronutrients





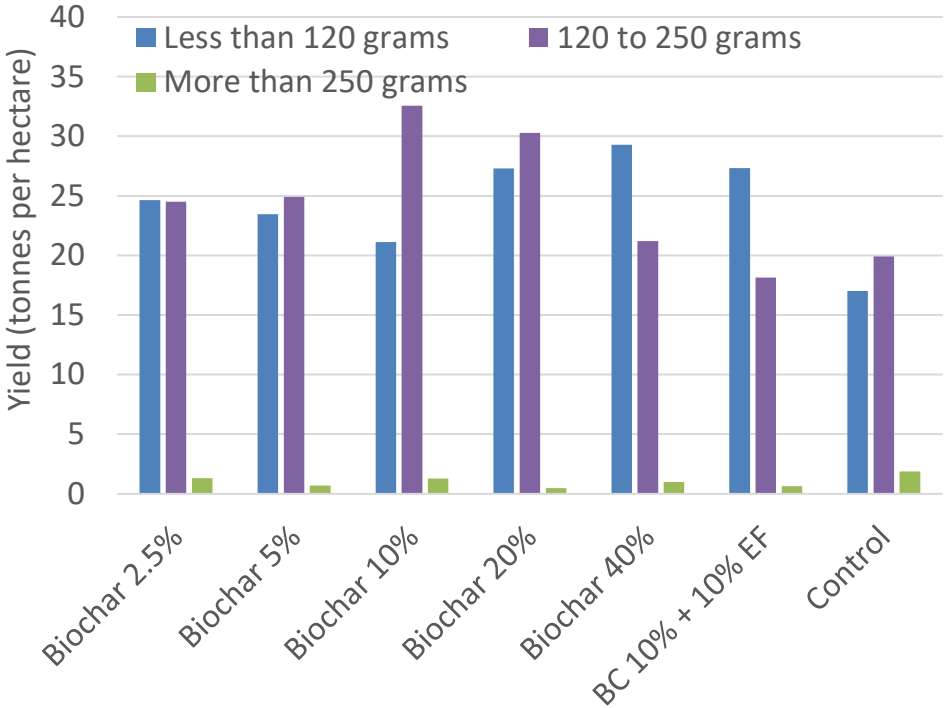
High P, K, Si and clay content in the pores of the biochar. N has reacted with the Carbon Matrix to be released slowly

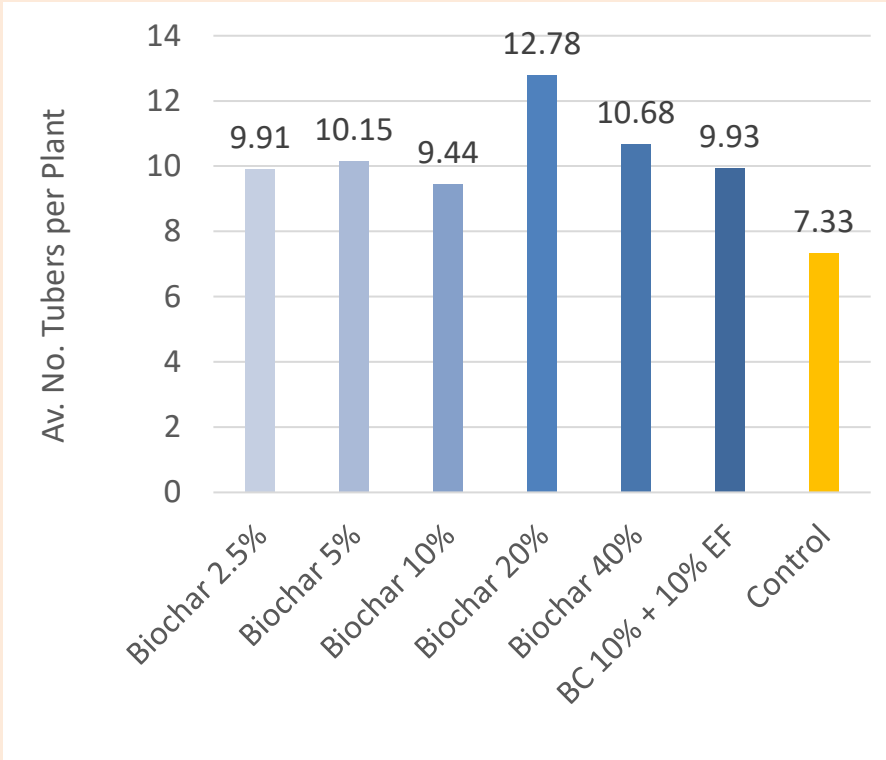
Biochar Mineral Complexes for Potato Production

- Wheat straw poultry litter bentonite and kaolinite with magnetite basalt dust and wheat straw ash pyrolyzed at 450C and pH adjusted with phosphoric acidwas developed to enhance the efficiency of NPK fertiliser for growing seed potatoes
- Standard Fertilisation 7N;14P;14K at 778kg/ha
- Replaced fertiliser with 5%, 10%,20% and 40% enhanced biochar

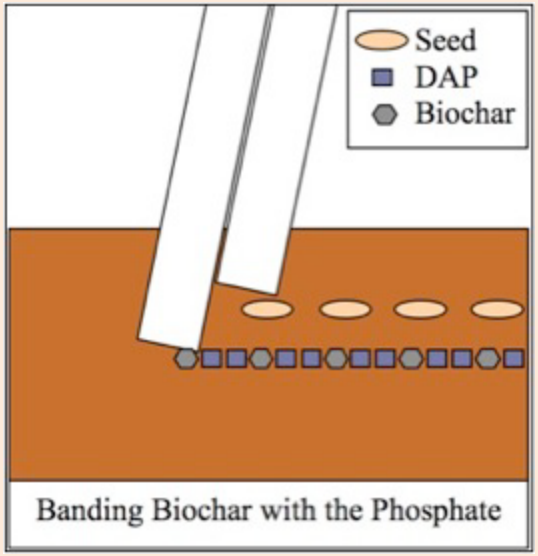
Greatest Yield at 20% replacement but Greatest Yield high Value Seed Potatoes at 10% Replacement of NPK

	User net benefit	User net benefit (NPV) per tonne of biochar	User cost	Payback
Potatoes - Ballarat biochar trial 20% fertiliser substitution	$ 8,000 (Per ha)	$ 53,400	$ 160 (Per ha)	< 1 yr.



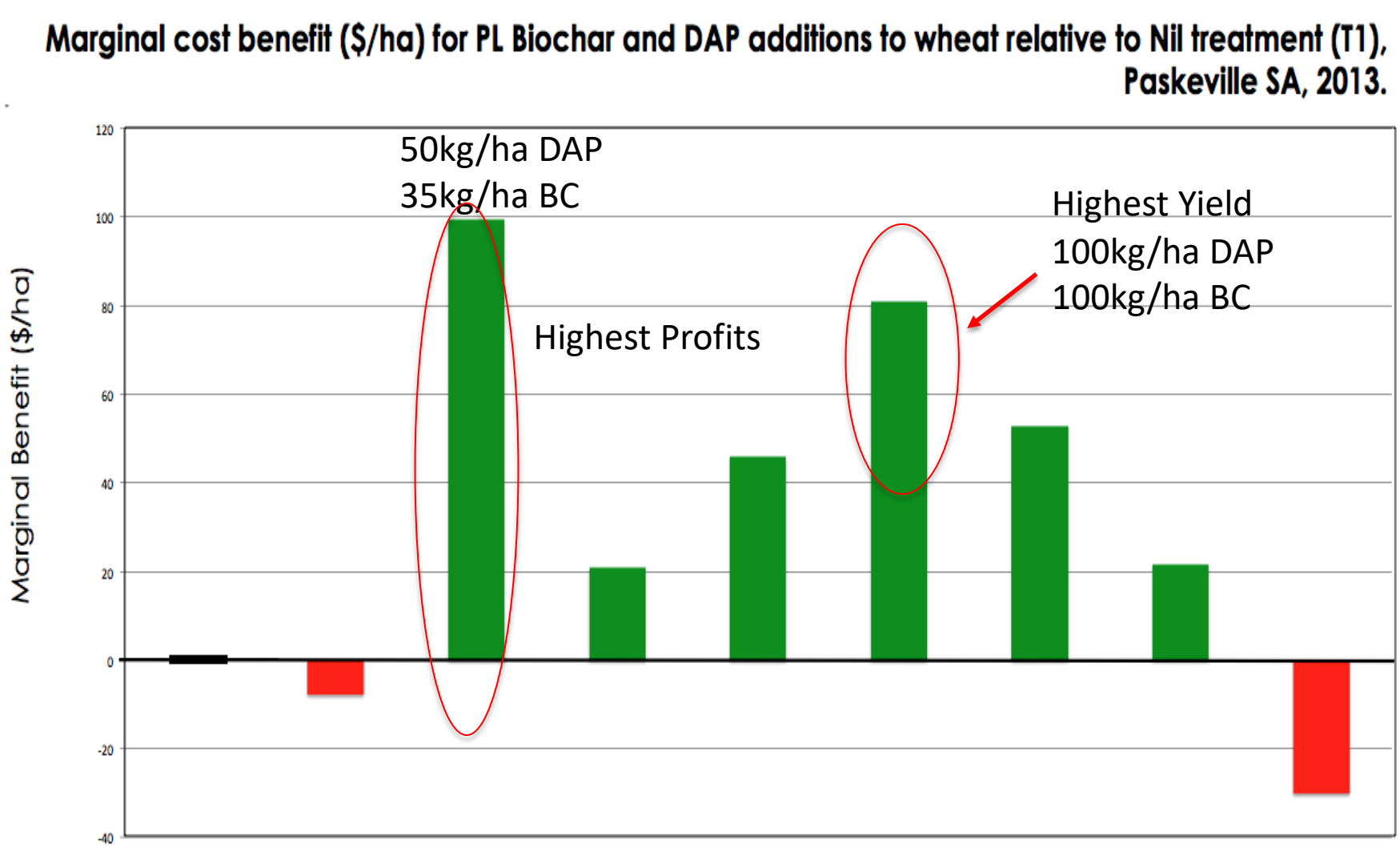


Conservation Farming in Wheat Fields in South Australia



1. Injection of poultry litter biochar with diamonnium phosphate (DAP) underneath seeds in bands using a direct drilling seeder.
2. No Till Farming in calcareous soil with pH approximately 8.
3. Three replicates plots 1.5m by 13.5m
4. Various ratios of poultry litter biochar and DAP
1. Third year of testing on different sites. Same Trend as this test

Conservation Farming in Wheat Fields in South Australia Assuming $500/tonne BC



Treatment	T1	T2	T3	T4	T5	T6	T7	T8	T9
Marginal Cost relative to Nil	0	32.5	46.5	72.5	65	79	105	14	40
Marginal Income relative to Nil	0	24.7	143	93.34	110.76	159.9	157.82	35.62	9.88
Margin Benefit relative to Nil	**0**	**$7.80**	**$96.50**	**$20.84**	**$45.76**	**$80.90**	**$52.82**	**$21.62**	**$30.12**

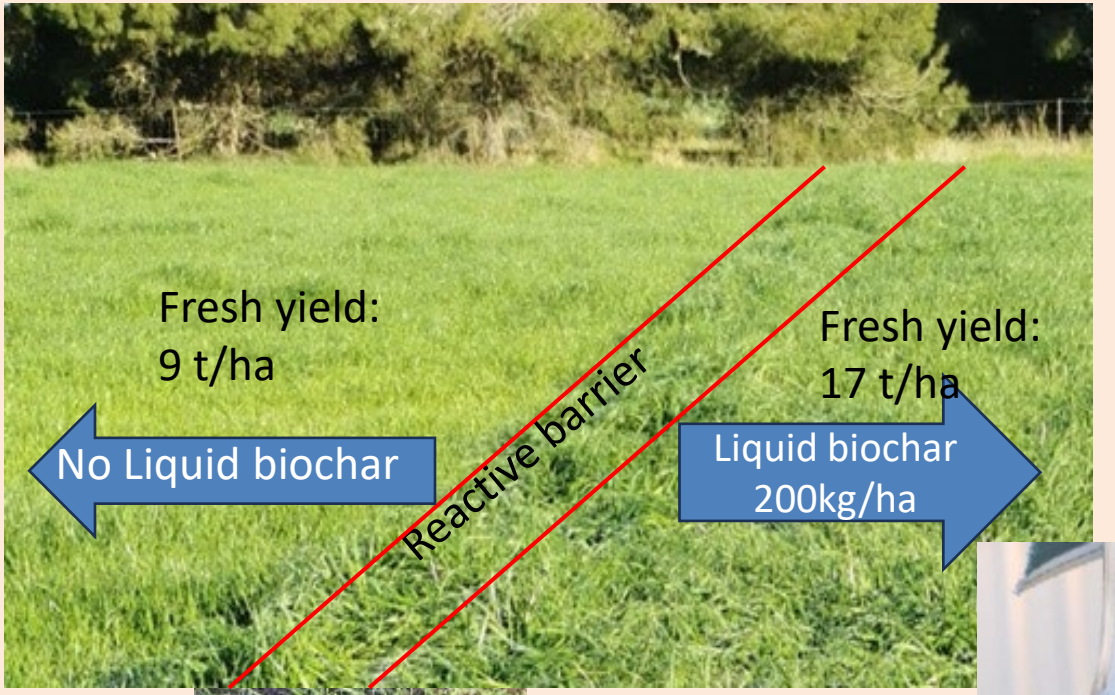
Compound Biochar NPK Clay Fertiliser
20% Wheat Straw Biochar (90kg/ha), 5% Bentonite Clay and 75%NPK Granule Applied at 450kg/ha

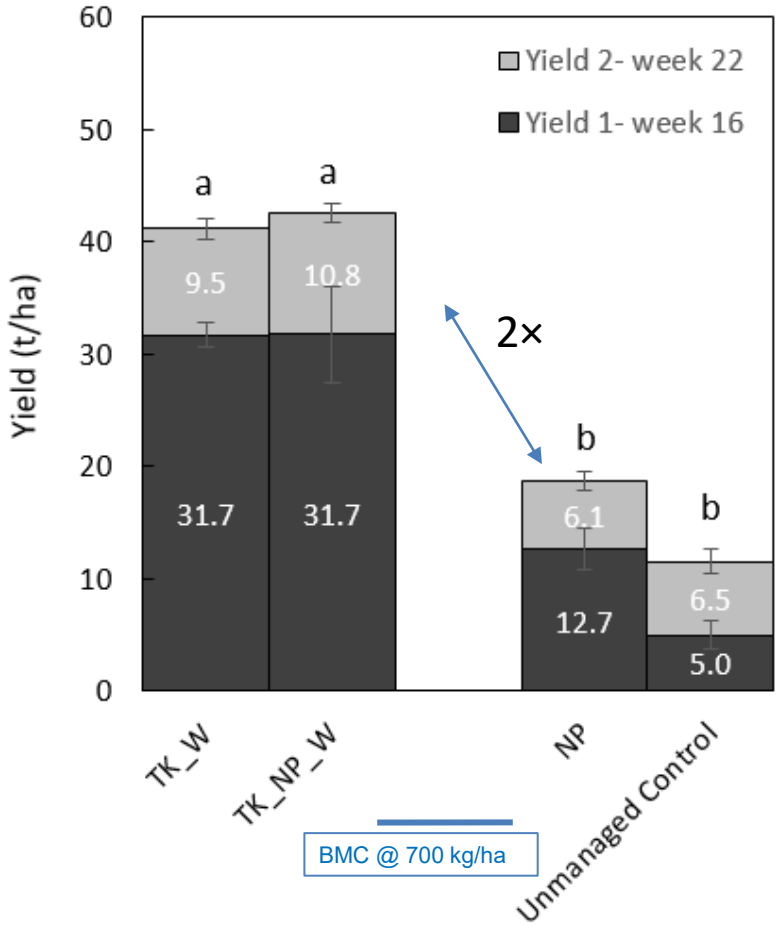
Demonstration Field Plot in Anh Hui. Yield increase 18-30% increase in yield and a reduction in disease

Financial Analysis for Farmer with .45ha Land Based on Field Trial for One Season With Rice Assuming 1/5 Lower Pesticide Use and Reduction of Urea from 126kg/ha to 111kg/ha. Rice Yield Increased from 8.2t/h to 11.4t/ha

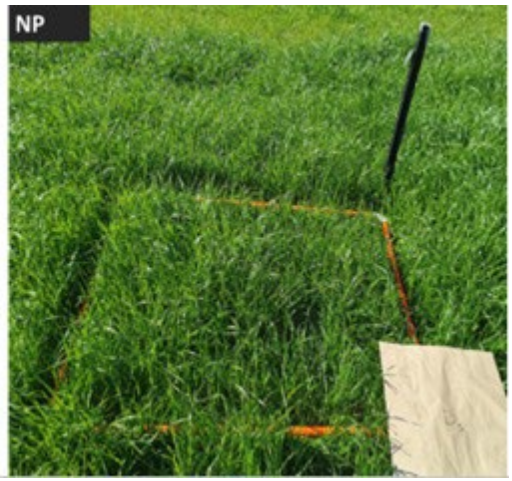
Costs for Farmer			
Fertiliser NPK + urea	$	$131.1	
Biochar NPK +urea	$		$128.4
Seed	$	$45.0	$45.0
Pesticide	$	$121.5	$97.2
Mechanical Harvesting	$	$100	$100
Total Cost		$397.6	$370.6
Revenue			
Sale of Rice	$	$1,365.3	$1,898.1
Income-Costs	$	$967.7	$1,527.5
% Increase in income	%		**58%**

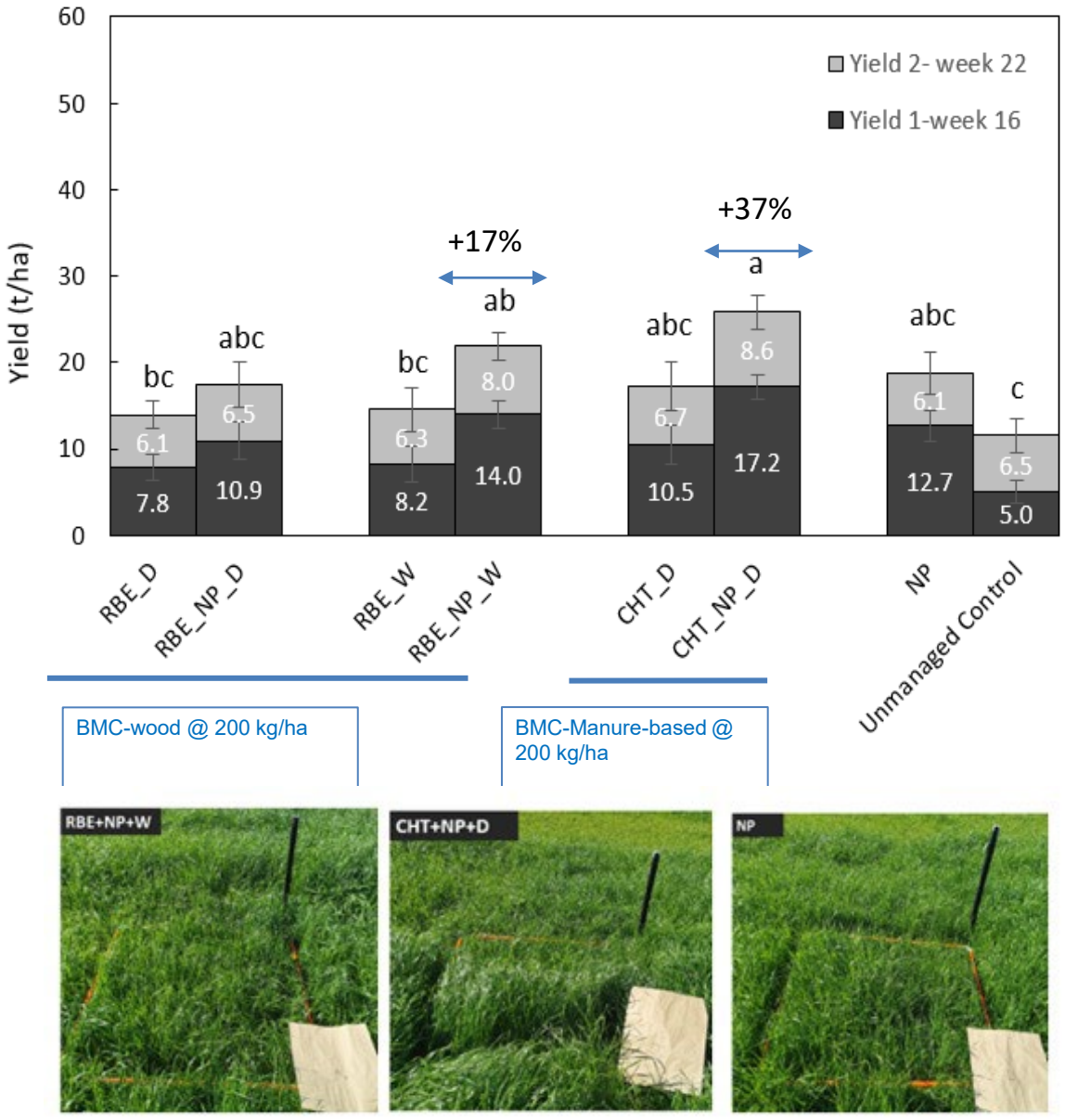
Biochar Based Liquid Fertilisers and Foliar Sprays Applied in The Rhizosphere Applied at 10-200kg/ha; A Game Changer





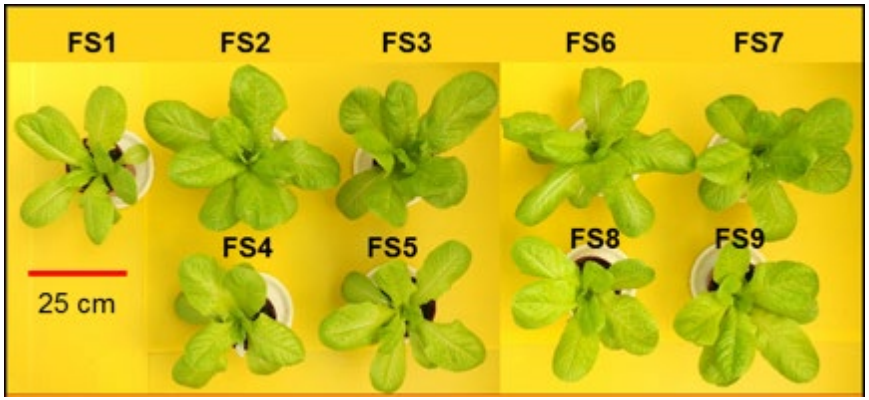
Liquid biochar mineral complex applied at 700kg/ha with high P low N doubled yields compared with a DAP Urea solid fertilizer applied at 400kg/ha





Liquid manure straw biochar mineral complex and wood biochar with added N and P complex with dispersant applied at 200kg/ha increased pasture yield by 37% and compared with a DAP Urea solid fertilizer applied at 200kg/ha

Extracts from biochar from mixed feedstock high in NPK and Si gave greatest yield and quality increase; Lettuce Experiment

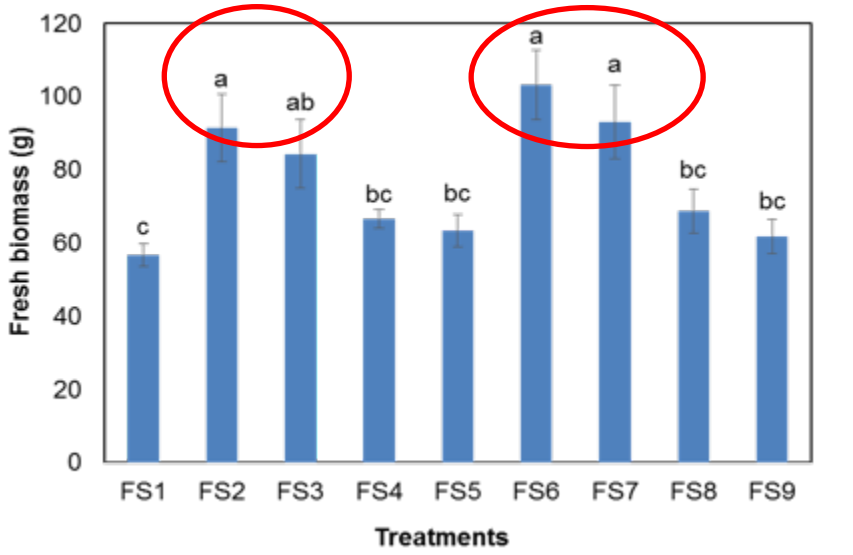


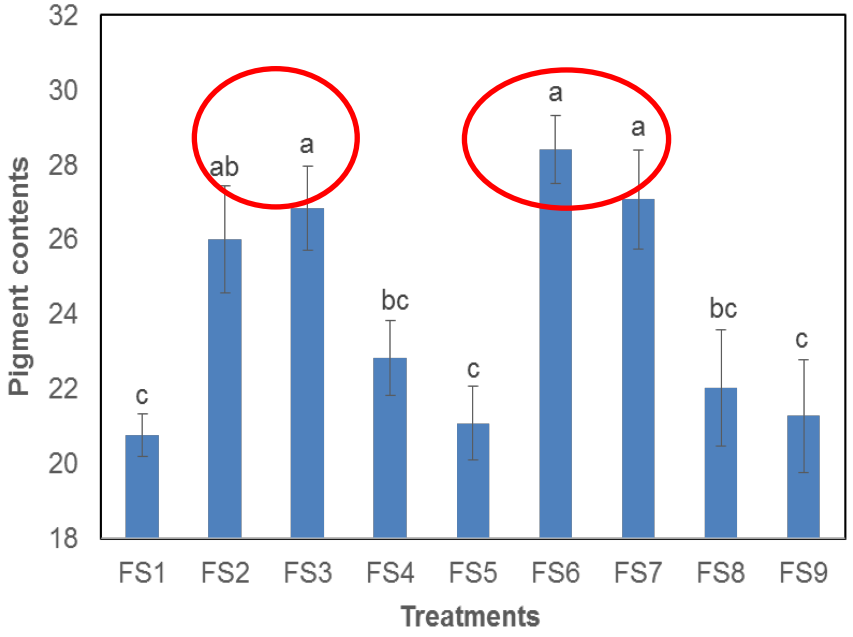
FS= foliar spray every 4 days

SB 1: Pine impregnated with SiO2 and Clay nanoparticles 600C . 25 (FD2) and 50 (FD3) times dilution for foliar spray

SB2 50% Wheat straw + 50% Bird manure- 50 (FD6) and 100 (FD7) times dilution for foliar spray

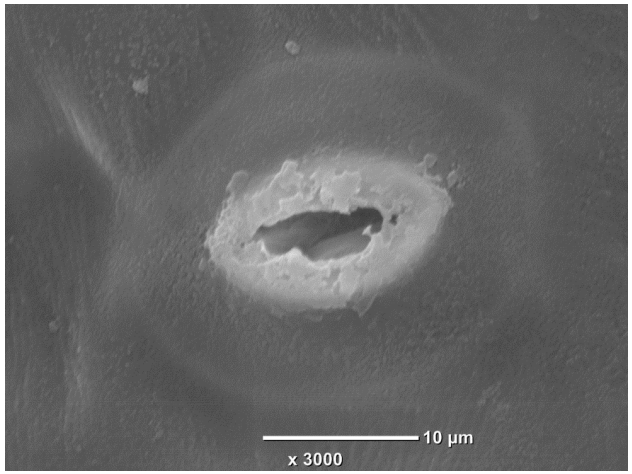
F1: No Chemical Fertilizer (control;
F2: SB-1 Dilution 50 times
F3: SB-1 Dilution 100 times;
F4: Chemical Fertilizer 1 Dilution 1
F5: Chemical Fertilizer 1 Dilution 2 ;
F6: SB-3 Dilution 1
F7: SB-3 Dilution 2;
F8: Chemical Fertilizer 2 Dilution 1
F9: Chemical Fertilizer 2 Dilution 2;

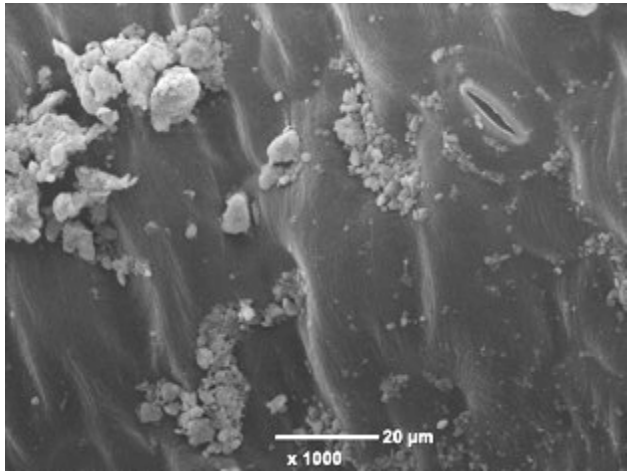


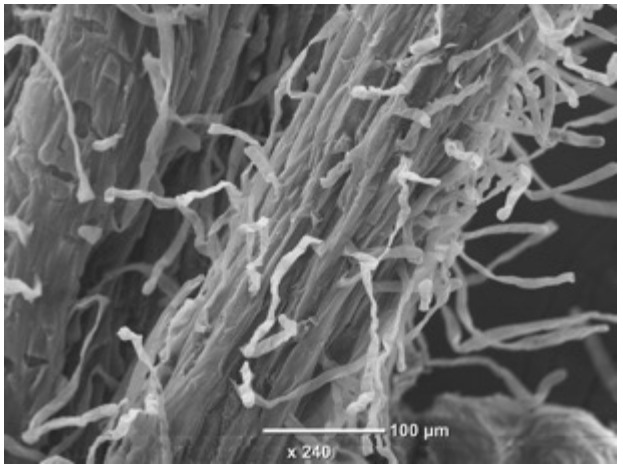


Extracts from biochar either as foliar spray or as part of fertigation results in yield increased; SEM

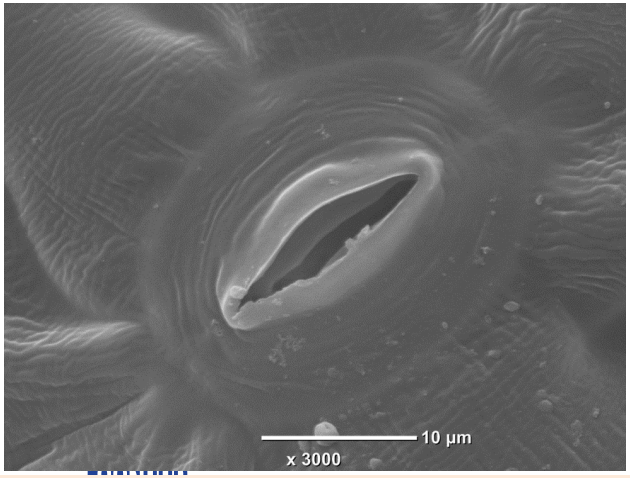
Image of Stomata and Root of Mixed Feedstock Biochar Foliar Spray

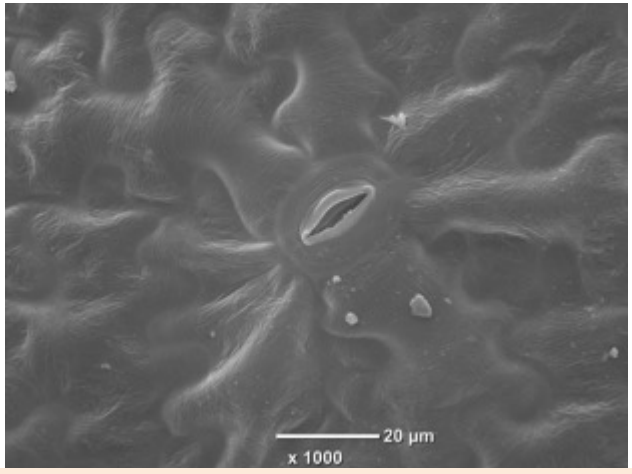


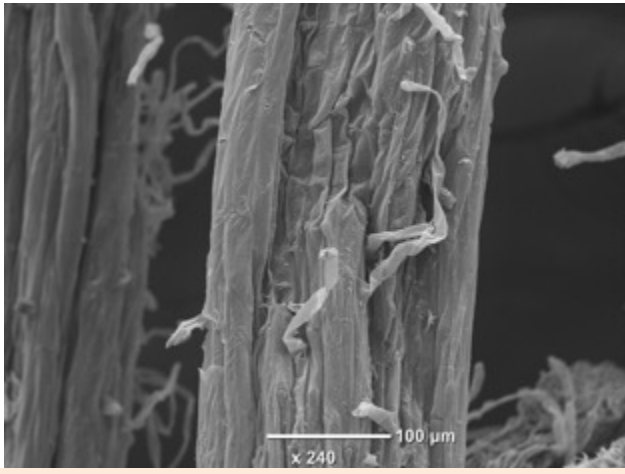




Control

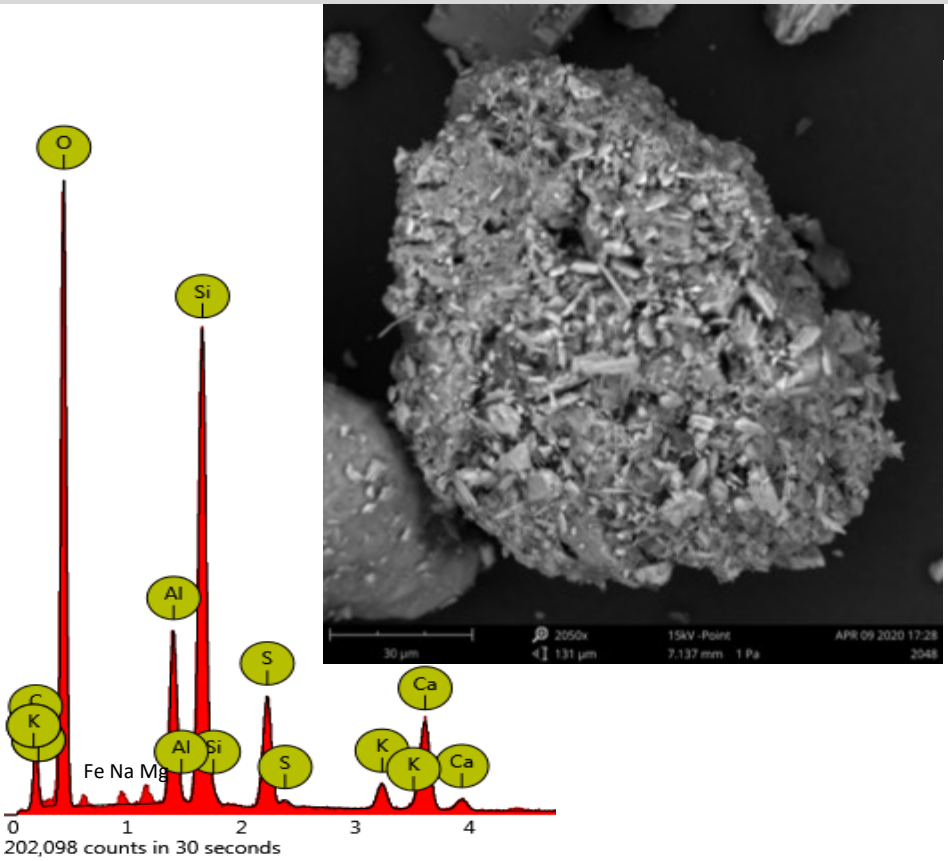


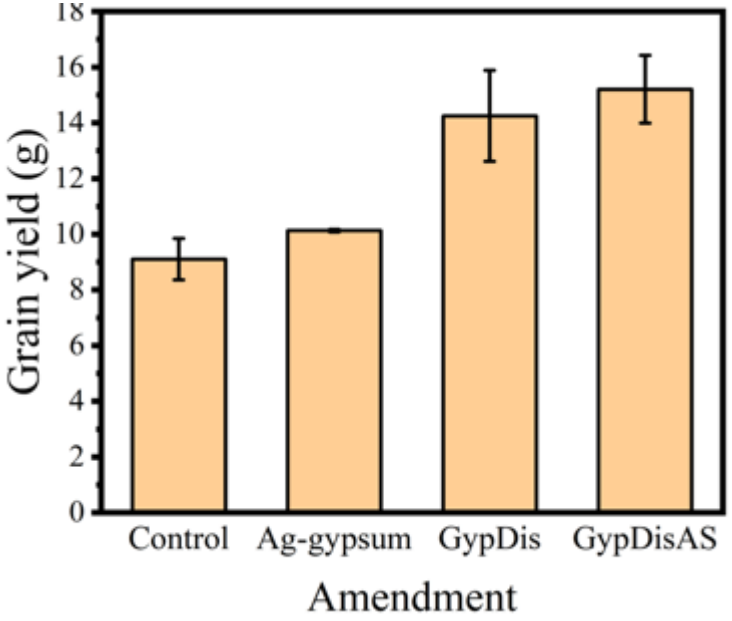


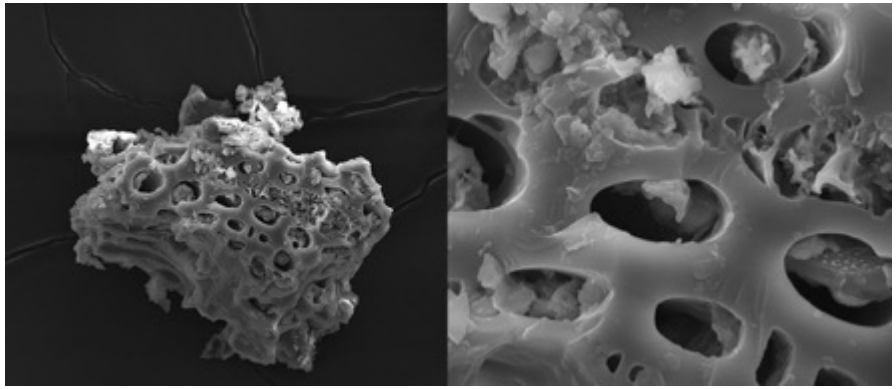


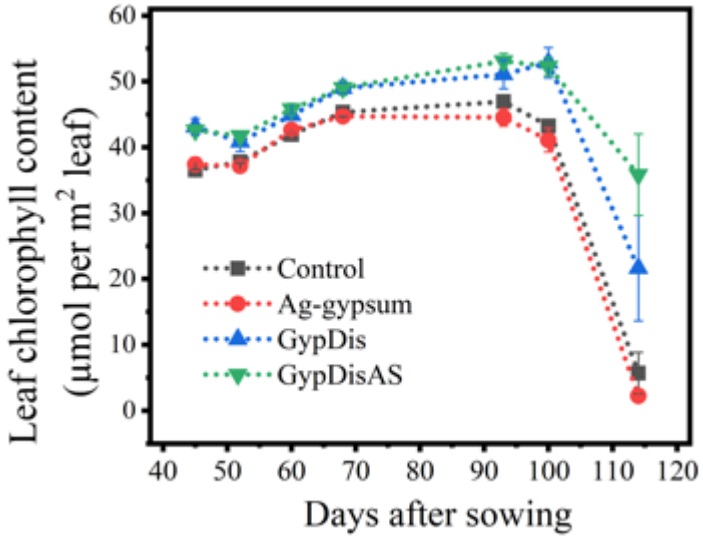
Kumar, A., Joseph, S., Graber, E.R., Taherysoosavi, S., Mitchell, D.R., Munroe, P., Tsechansky, L., Lerdahl, O., Aker, W. and Sæbø, M., 2021. Fertilizing behaviour of extract of organomineral-activated biochar: low-dose foliar application for promoting lettuce growth. *Chemical and Biological Technologies in Agriculture*, *8*(1), pp.1-15

Carbon Coated Gypsum With or Without CHT Dispersants



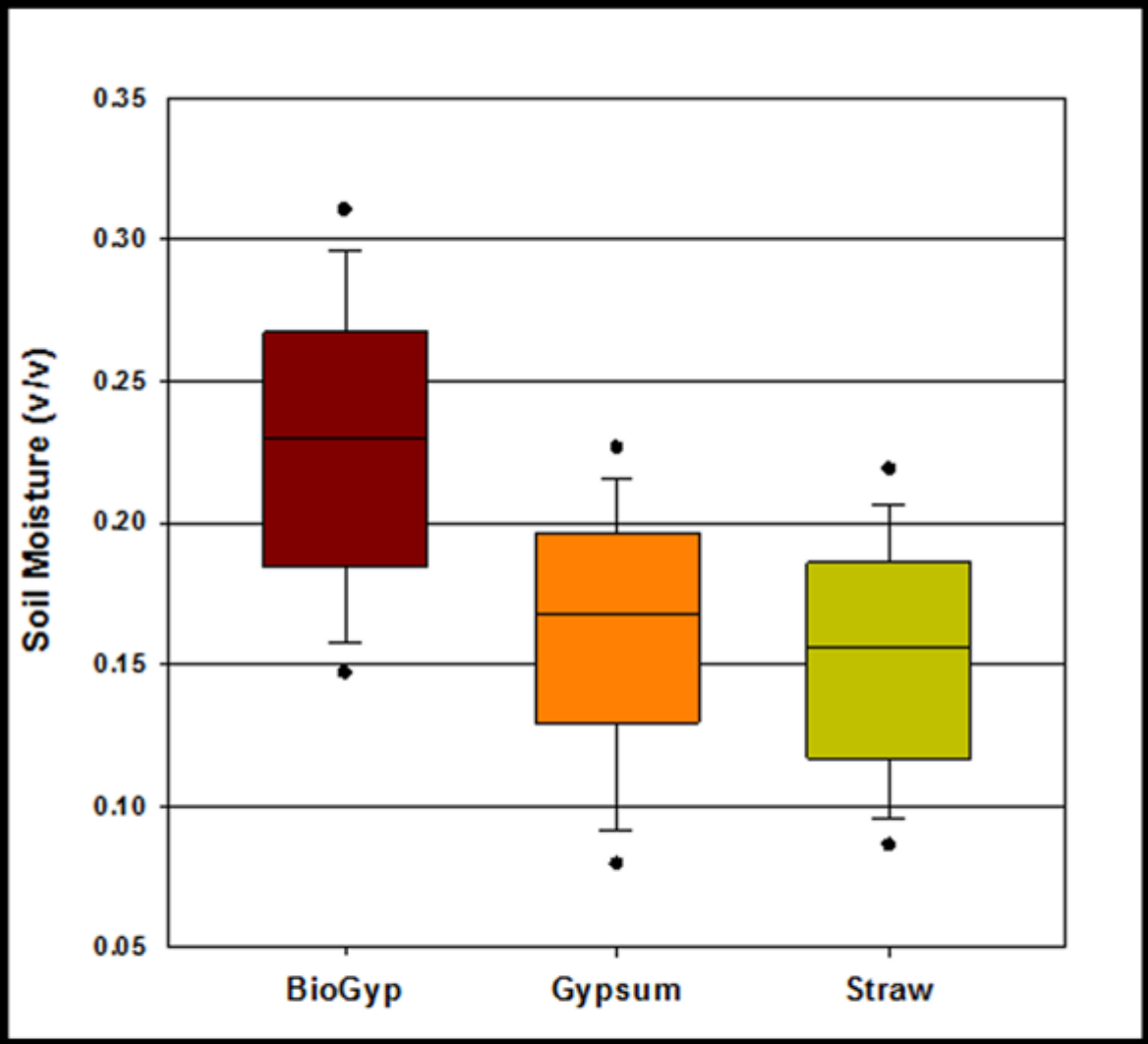






Courtesy Dr Ehsan Tavakkoli NSW DPI

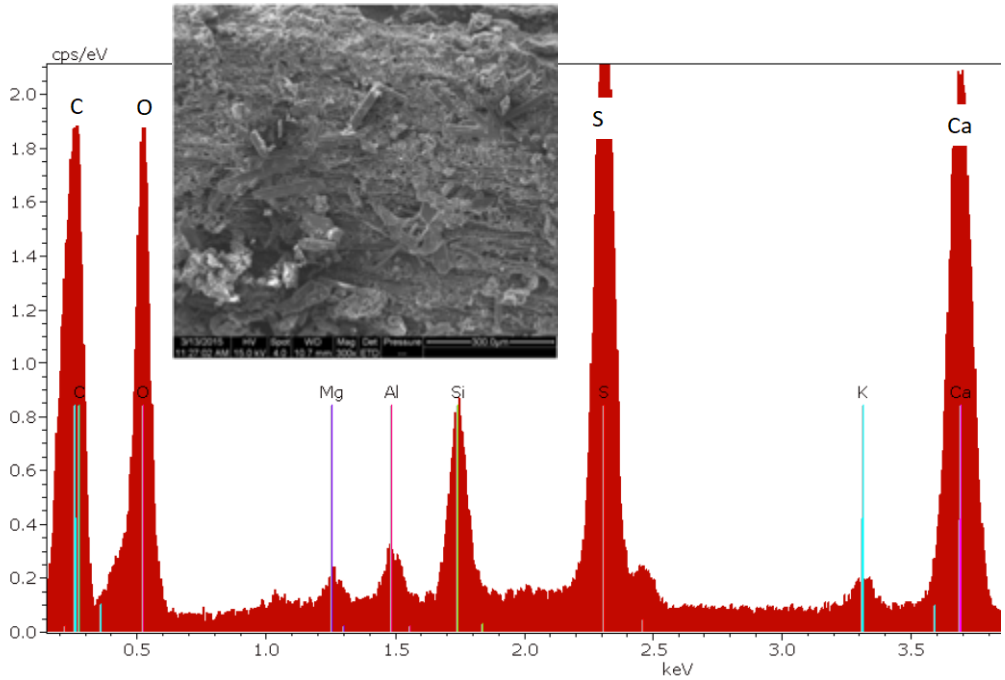
Adding Gypsum to Wood and Pyrolysing at 600C; Increasing Soil Water



Group	Median	25%	75%	Comparison	P<0.05
BioGyp	0.230	0.184	0.267	BioGyp vs Straw	Yes
Gypsum	0.168	0.130	0.197	BioGyp vs Gypsum	Yes
Straw	0.156	0.117	0.186	Gypsum vs Straw	Yes

Adding Gypsum to Wood and Pyrolysing at 600C

- Farmer practice adding gypsum at 5 tonnes per hectare plus NPK.
- Biochar treatment was 2.5 tonnes/ha biochar/gypsum along with NPK fertiliser.
- Normal yield is 6 to 8 stems in summer which is the best time to pick.
- The pickers were averaging 15 stems per plant which they had never experienced for a winter first pick.
- The biochar stems were healthier, more dense and survived a record 6 frost events



Biochar Increased Pasture Productivity by 25%; Biochar was taken through the soil to 40cm depth. C pH, and N content increased . Sequestered Carbon Approx. 75 t CO_2-e.

Depth	Soil Properties No BC	Soil Properties With BC
0-5cm	C= 5.7 N=.48 pH= 5.4	C= 6.0 N=.47 pH= 6.2
25cm	C= 2.1 N=.13 pH= 5.0	C= 3.6 N=.24 pH= 6.1
40cm	C= .67 N=.03 pH= 5.3	C= 2.0 N=.11 pH= 5.8

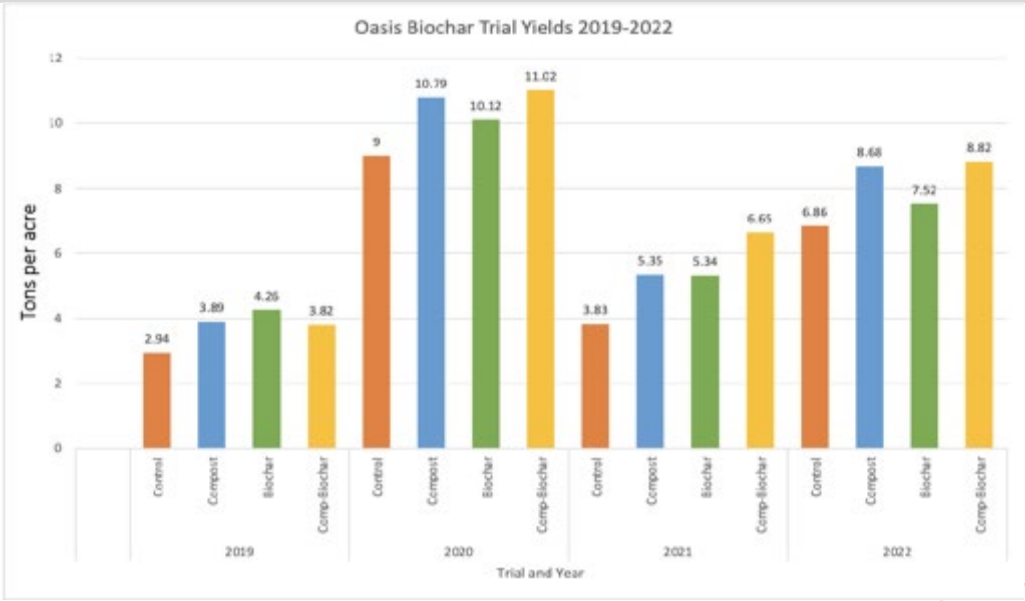
Biochar and Compost Field Trials in A Vineyard

Sub-Soil Injection

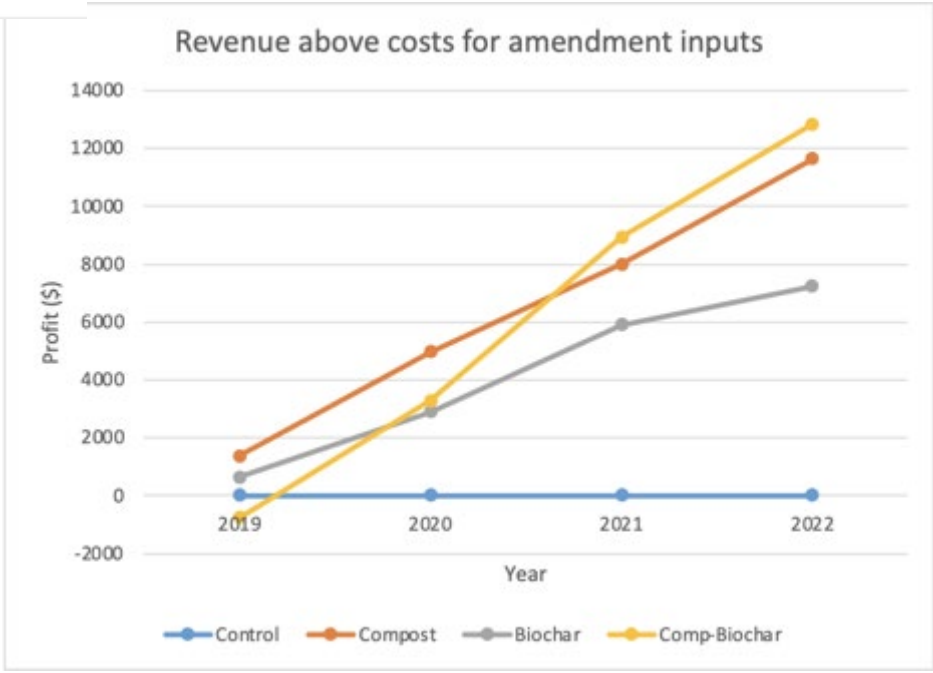
The application of each treatment involved deep ripping using GPS-guided winged tine down the vine row, leaving a delve in the soil where the amendments were applied and then mixed with the soil to 3 feet depth via a second ripper pass. The amendments included:

- Control: no compost or biochar was added but the soil was still mixed
- Compost: 15 tonnes/ acre
- Wood biochar: 10 tonnes/ acre
- Compost and wood biochar: 15 tonnes of compost + 10 tonnes of biochar/acre

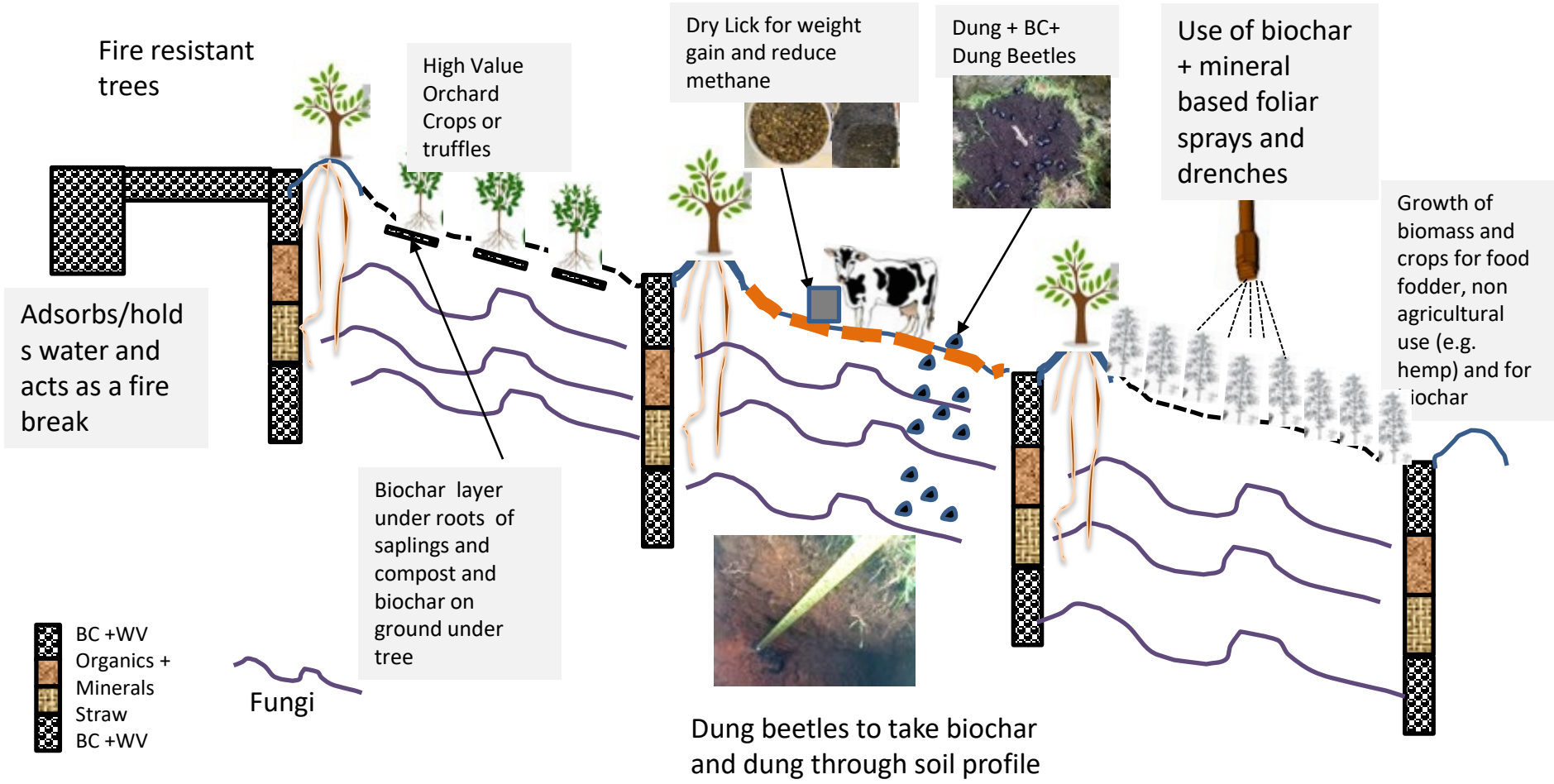
Biochar and Compost Field Trials in A Vineyard; Highest Profits at end Year 2 from Biochar and Compost



The net increase in yield for the different treatments. In 2021, environmental factors during flowering and fruitset decreased yields considerably. The compost-biochar treatment, however, showed the most resilience and produced profitable yields.



A Model System to Build Soil Carbon Produce Fuel Feed Fodder and Non Agricultural Biomass



Integrating Regenerative Agriculture, Carbon and Water Drawdown with Solar Energy Production; A conceptual model

- Solar Panel
- Biochar Hydrogel panel for water capture
- Crops mulched with biochar and compost
- Biochar based foundations
- Biochar based fertilisers
- Biochar based trenches for holding soil moisture; subsoil carbon drawdown and growth of fungal networks

A Biochar Primer for Farmers; Looking for Reviewers and Sponsors to Publish

A Practical Guide to the Production, Use and Application of Biochar

Stephen Joseph and Paul Taylor

Biochar organomineral complex compost with deep burial increases corn biomass in well watered and water stressed conditions

	Biomass		Leaf N con.		Total	Total	Transpiration
	Shoot	Root	Day 38	Day 52	N uptake	water use	efficiency
	(g column^{-1})		(mg g^{-1})		(g column^{-1})	(l column^{-1})	(g l^{-1})
Well-watered							
Control	151.6 c	20.7 ab	24.8	14.6 a	1.66 a	15.7 cd	9.64 a
Surface compost	173.8 d	23.1 bc	26.0	13.3 a	1.62 a	15.9 d	10.69 b
Deep compost	170.0 d	23.0 bc	25.5	14.6 a	1.79 b	15.7 cd	10.57 b
Deep compost/biochar	173.0 d	26.8 c	24.5	13.8 a	1.91 bc	16.5 d	10.47 b
Water-stressed							
Control	127.1 a	16.8 a	23.7	17.1 b	1.62 a	13.7 b	9.28 a
Surface compost	142.4 b	17.4 a	24.6	15.6 b	1.74 ab	12.8 a	11.12 b
Deep compost	149.4 bc	20.9 ab	24.6	17.1 b	2.02 c	13.9 b	10.72 b
Deep compost/biochar	155.0 c	22.9 bc	23.9	15.8 b	2.00 c	14.4 bc	10.76 b

Biochar organomineral complex compost with deep burial

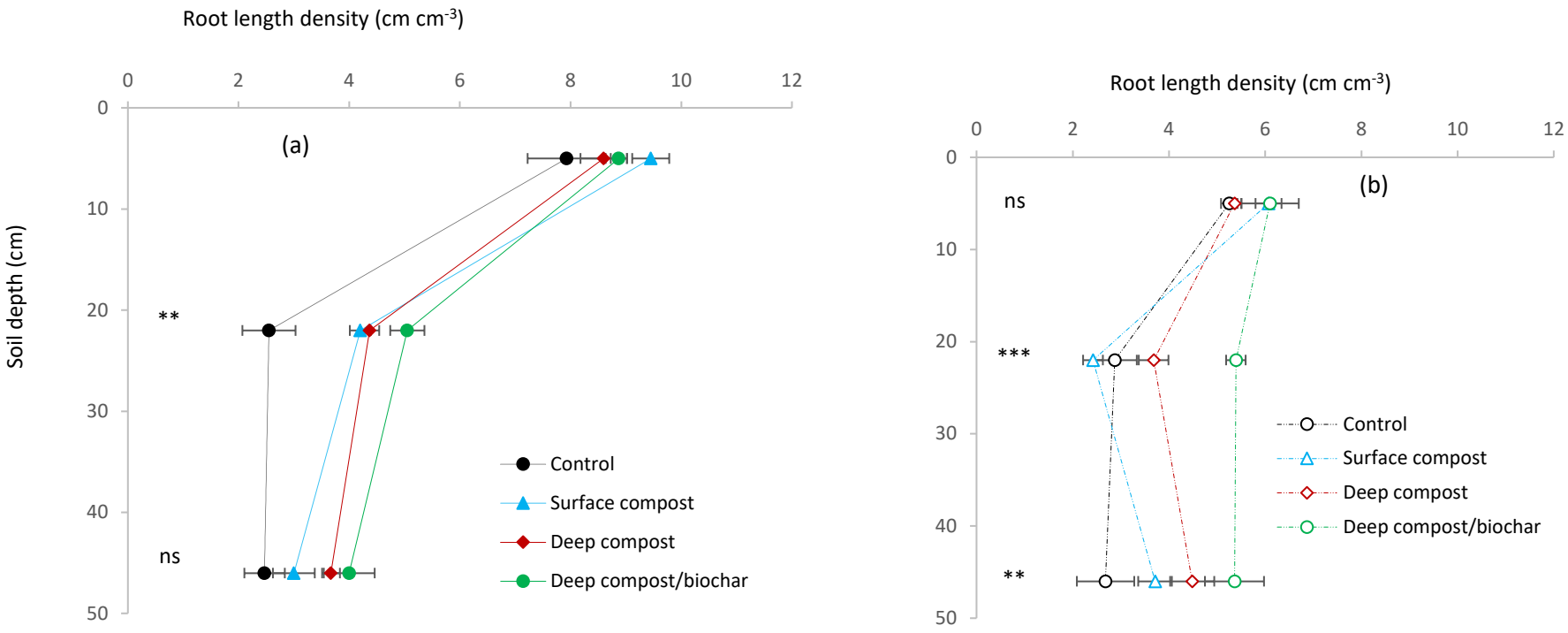


Fig 3. Root length density of corn plants at depth of 0-20, 20-32 and 32-50 cm in soils amended with surface, deep compost and deep compost/biochar under well-watered (a) and water-stressed condition (b), relative to surface inorganic fertilizer control. Error bars represent means ± the standard error of three replicates.

Cow Farmer Applied BC to Grow Avocados Using Mechanised Equipment; Super P and Mg, Cu, Zn, Mg Sulphate; Biochar 5%,10%,20%, Control. BC at 5% Double Leaf Area and 20% increase in Stem Diam and Height.; Less H2O, 23% less NaCl in Soil and More Flowers

Control

Biochar

Biochar with NPK Fertigation Can Increase Harvest after 4 Years with Application of 20 tonnes/ha underneath the saplings

	User net benefit (NPV)	User net benefit (NPV) per tonne of biochar	User cost	Payback
Avocados - Doug Pow **7 years of effects, 1 hectare (400 trees)**	$20,000 (per hectare)	$400	$5,040 (per hectare)	4 years (first fruiting)