The Use of Biochar in Agroforestry to Promote Soil Health, Tree Productivity, and Carbon Sequestration

Research Report

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NORTHEAST SARE
Sustainable Agriculture Research & Education

ARTHUR'S POINT FARM

Will Brinton Foundation
A 501-C3 Organization

Objective & Hypotheses

Objective - focus on statistically significant findings about biochar and compost treatments in newly planted Chestnut orchard over several years

Hypotheses

H1 - Biochar/compost/amendment = ⇡ soil microorganism abundance, ⇡ nutrient bioavailability, ⇡ tree health/vigor, ⇡ carbon sequestration

H2 - Native soil = ⇣ vs. compost and biochar treatments across assessment metrics

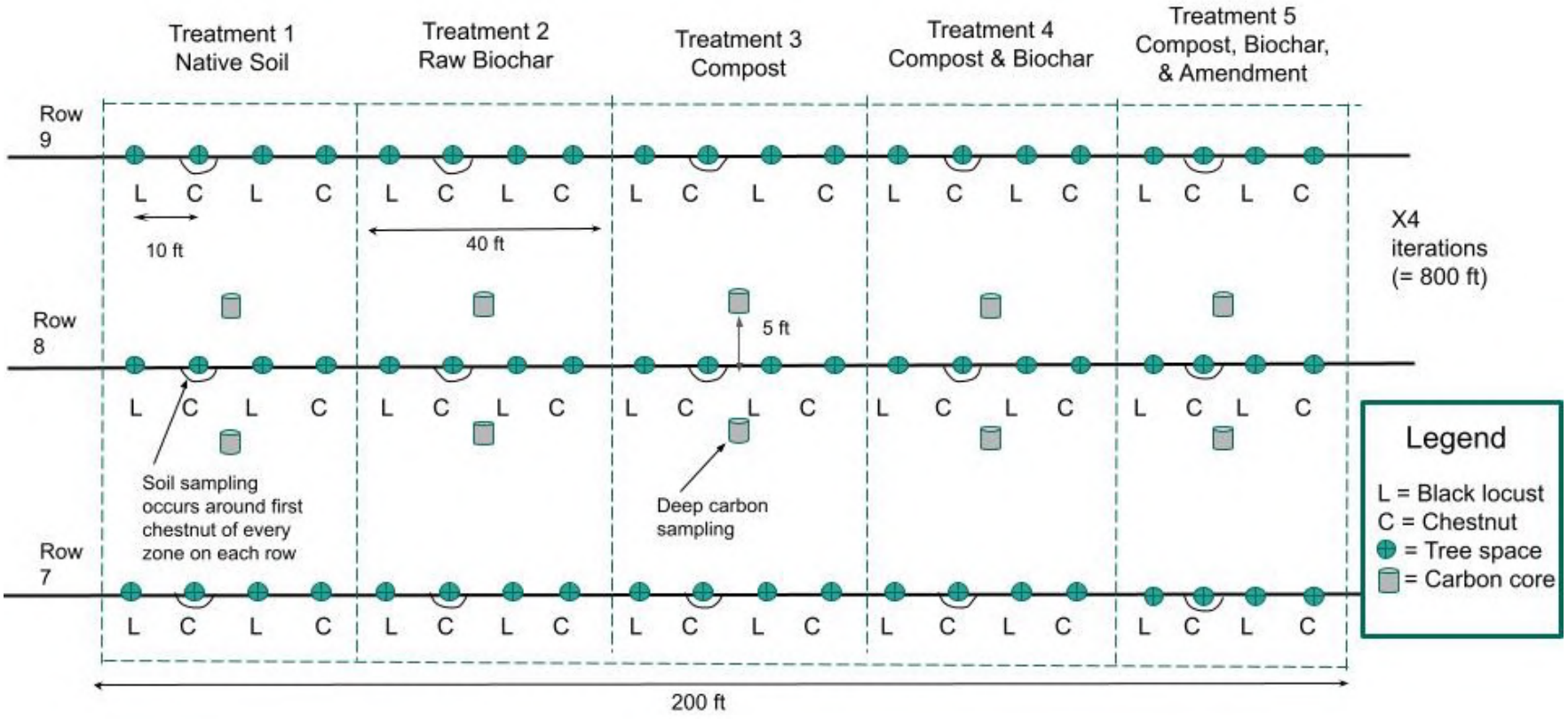
H3 - Biochar w/o compost or amendment = ⇣ nutrient bioavailability, ⇣ inhibit tree health/vigor vs. compost and biochar treatments across assessment metric

Research Trial Location – Ghent, New York (2020)

Research Rows (2024)

ARTHUR'S POINT FARM

Experimental Design



Research Treatments

T1 – Planted in native soil. No treatment (“Control”)

T2 – Raw biochar in planting hole (4 cups)

T3 – Compost (1 gal) in planting hole, top-dressed annually with compost (2 gal)

T4 – Biochar (4 cups) + compost (1 gal) in planting hole, top-dressed annually w/ 10:90 biochar-compost (2 gal)

T5 – Biochar (4 cups) + compost (1 gal) + microbial amendment* (4 cups) in planting hole, top-dressed annually w/ 10:90 biochar-compost (2 gal)

All treatments – top-dressed annually w/ wood mulch (10 gal)

* **Microbial Amendment** – 41.5% Alfalfa Meal, 32.05% Kelp, 16.2% Azomite; 10.12% Oat Flour, 0.15% Bacterial & Fungal Spores

Treatment Characteristics

Material	Rate of Appl	BD lbs/ft^3	WHC %	TC %	TN %	Mineral Ash** %
Compost	1 gal	50	111	15	0.6	68
Biochar	4 cups	11	190	87	< 0.3	< 5
Probiotic	4 cups	50	110	16	1.5	67

BD= bulk density (dry); **WHC** water holding capacity on dry-basis by capillary cylinder; **TC/TN** total carbon total nitrogen by total combustion; **Ash**=residue after oven-ashing @ 550C; wood mulch not included as tested amendment

** **Mineral Ash residue shown since this is where all minerals are found.**

Fig. 1 Fresh biochar; **Fig. 2** Biochar up close showing mixed particle-size distribution; **Fig. 3** Wood mulch layer covers ~30” circle; **Fig. 4** cattle grazing on farm – manure compost

Amendment Rate Characteristics

Material	Rate of Application/Tree	Area applied (estimate)*	Rate per area (estimate)*	Carbon Added	Annual Repeat
Compost (Comp)	1 gal @ 0.8 g/cc= 3 kg	 ~32”W *x* 12”D = 0.16 m^3 or 175 kg soil	1.7% @1ft = **26 tons /acre**	3,360 lb/a	Top-dressing only†
Biochar (BC) unsieved	4 cups @ 0.17 g/cc = .17 kg		0.09% @1ft = **1.4 tons/acre**	2,210 lb/a	Top-dressing only
Comp + BC	1 gal + 4 cups = 3.17 kg		1.8% @ 1ft = **27 tons/acre**	5,570 lb/a	Top-dressing only
Comp + BC + Probiotic Amend.	1 gal + 4 cups + 4 cups = 4 kg		2.3% @1 ft = **35 tons/acre**	6,410 lb/a	Top-dressing only

Notes: Weigt of soil area assumes tested soil BD of 1.1 g/cc from BD core samples. 1 acre @ 6” = 1,525,000 lbs
† annual surface applications are not considered a soil treatment
** due to uncertainty of exact depth and width of treated soil this is considered an estimate.*

Material Sourcing

Biochar – Produced on farm in Exeter Retort Kiln from mix hardwood/softwood

Compost – Made from manure and bedding from cattle grazed on farm

Chestnut Seedlings – Complex hybrids of select Chinese chestnuts (*Castanea mollissima)* Rt. 9 Coop, grown from seed

Wood Mulch – Annual cover from local mill; neutral amendment across all treatments

Testing Framework

Tree Health (Tested Years 1*, 3, 4)

- Most immediate, observable responses to treatments
- *Plant Leaf Tissue* analyzed for minerals and trace elements
- *Visual Observation Survey* (Forest Ecosystem Monitoring Cooperative)

Soil Health (Tested Years 1, 3, 4)

- Secondary rooting responses that develop over time
- *Soil Health Tests* for minerals, soil structure and biology
- 6” deep samples outside treatment zone

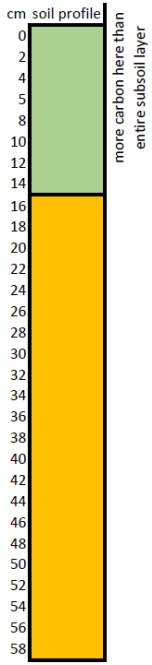
Deep-Core Carbon Soil Tests (Tested Years 1, 4)

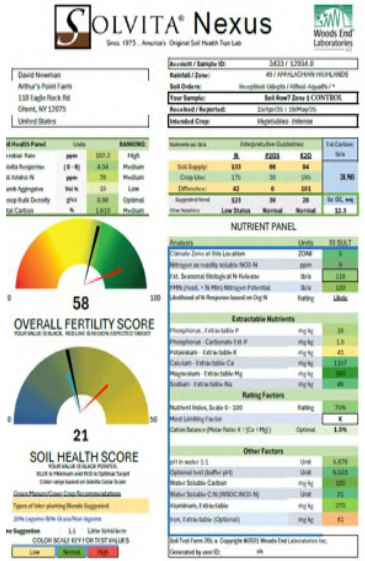
- Long-term changes at depth and helps reveal underlying site character
- Meter deep cores for total carbon[+] and bulk density

* Only total-N was performed in first year due to limited quantity of leaves

[+] Total-carbon is total organic carbon since no HCl-reactive carbonates found

Testing Procedures





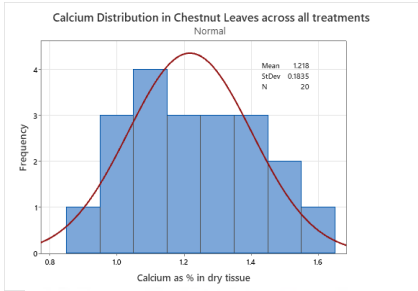
Statistical Handling

Normality
Data not normally distributed was normalized before statistical analysis

ANOVA (*Analysis of Variance)*
Identifies differences among treatments *that are real and not due to random variation*

Correlation Coefficients
Used to reveal significant relationships among variables regardless of treatments (e.g., leaf mineral levels vs. tree growth)

1



2

Treat	N	Mean	Grouping	
Compost	12	53.25	A	
ComBcAd	12	43.83	A	B
ComBC	12	43.33	A	B
Control	12	37.25		B
Biochar	12	36.42		B

3

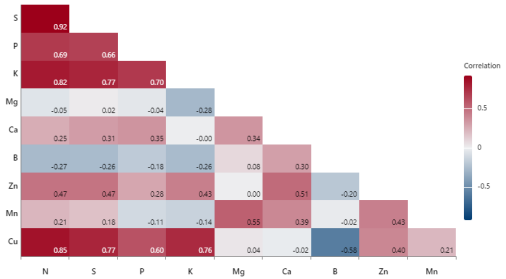


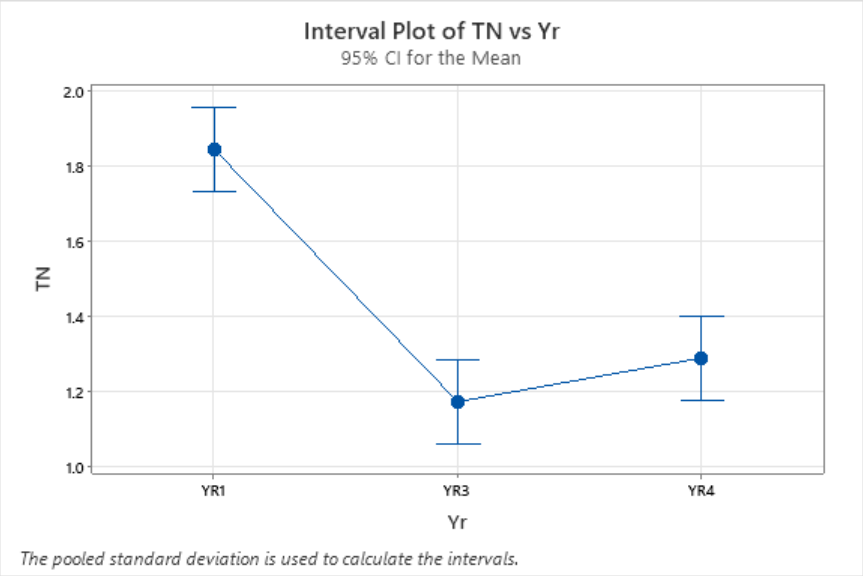
Fig 1. Calcium in plant tissue was normally distributed
Fig 2. ANOVA shows separations and significance
Fig 3. Correlations are strongest in darker colored cells

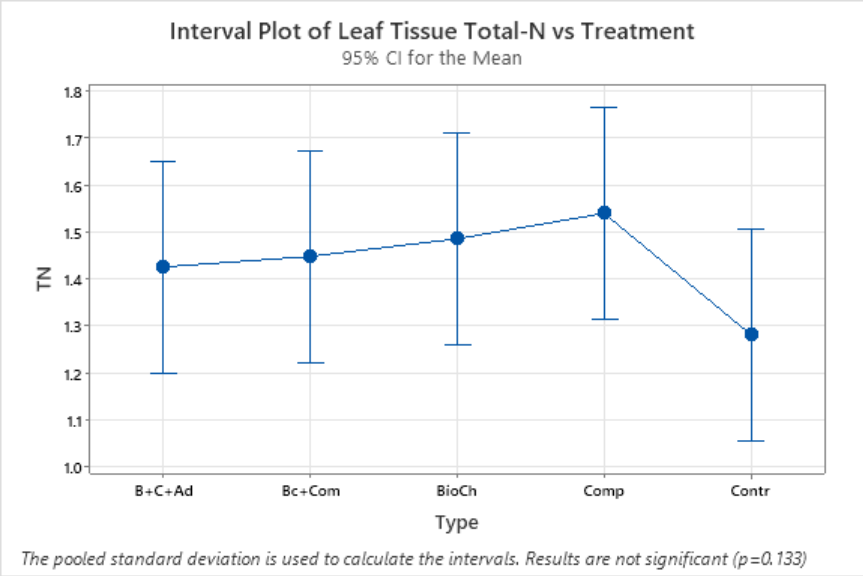
Data Analyses

- Data Analysis focused on *Treatments x Years* (e.g., 5 tr x 3 yrs x 4 reps)
- Normality tests used Anderson-Darling assessment for $p \geq 0.05$
- Select non-standard data normalized to optimal using Box-Cox transformation
- ANOVA: General Linear Model and One-Way model with Tukey/Fisher Mean-Separation to test individual-paired differences
- Correlations between plant productivity and soil variables
  - ✓ Plant Tissue
  - ✓ Soil Health
  - ✓ Deep carbon
- Examination of the literature for corroborative data

Tree Health – Leaf Tissue Nitrogen (Years 1, 3, 4)

- N-levels (protein) highest in Year 1, typical of early growth
- Compost consistently higher N but not significantly different from other treatments
- Native Soil with no amendments (Control) lowest N





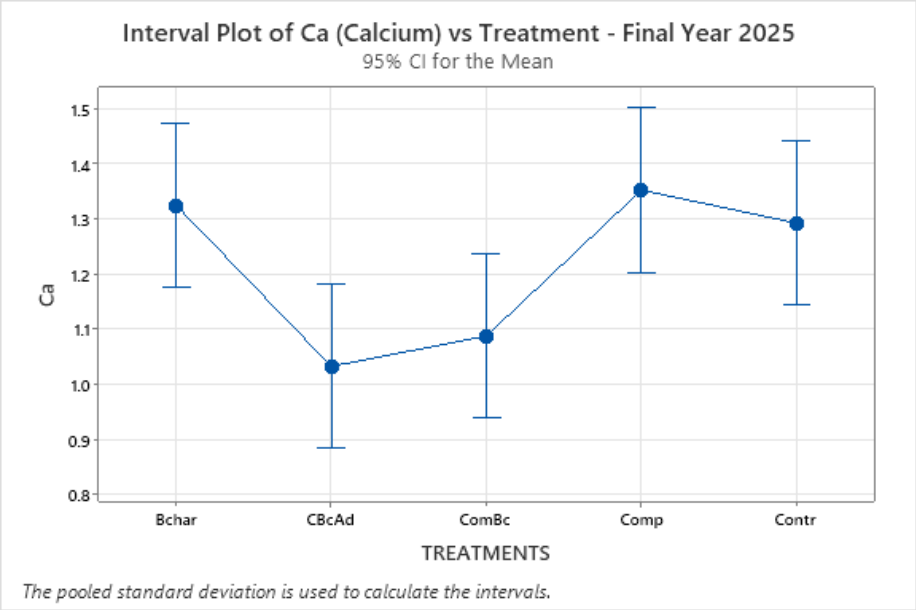
Tree Health – Leaf Tissue Calcium (Year 4)

- Calcium significantly higher in Compost treatment than Comp+Bc+Ad
- All other effects non-significant

Grouping via Fisher LSD Method (95% Confidence)

DESC	N	Mean	Grouping		
Comp	4	1.353	A		
Bchar	4	1.3250	A	B	
Contr	4	1.2925	A	B	
ComBc	4	1.0875	A	B	
CBcAd	4	1.0325		B	

Means that do not share a letter are significantly different.



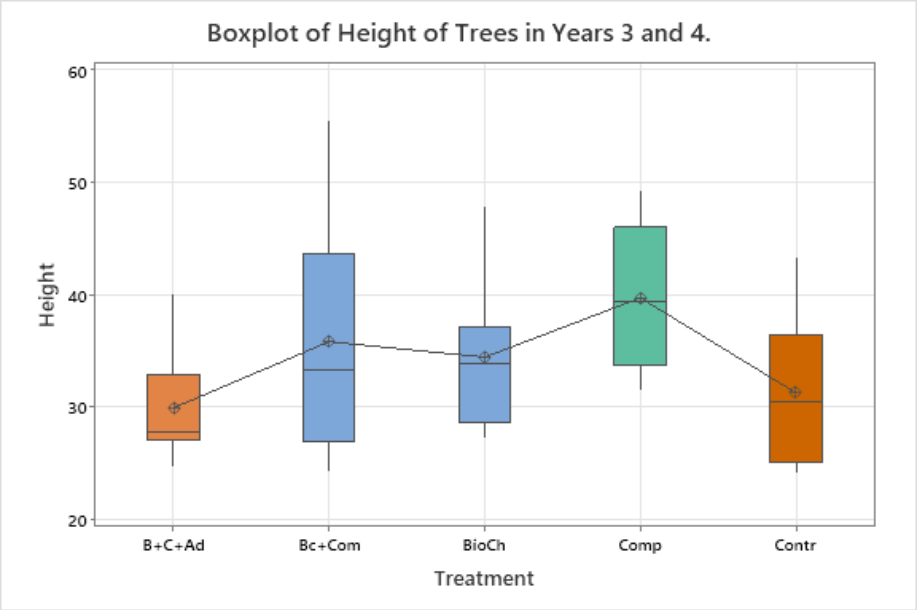
Tree Health – Plant Height (Years 3 and 4)

- Tree height significantly greater with Compost than Control and Comp+Bc+Ad
- Tree mortality did not influence data
- No other effects significant

Grouping via Fisher LSD Method (95% Confidence)

Type	N	Mean	Grouping	
Comp	8	39.69	A	
Bc+Com	8	35.80	A	B
BioCh	8	34.42	A	B
Contr	8	31.24		B
B+C+Ad	8	29.92		B

Means that do not share a letter are significantly different.



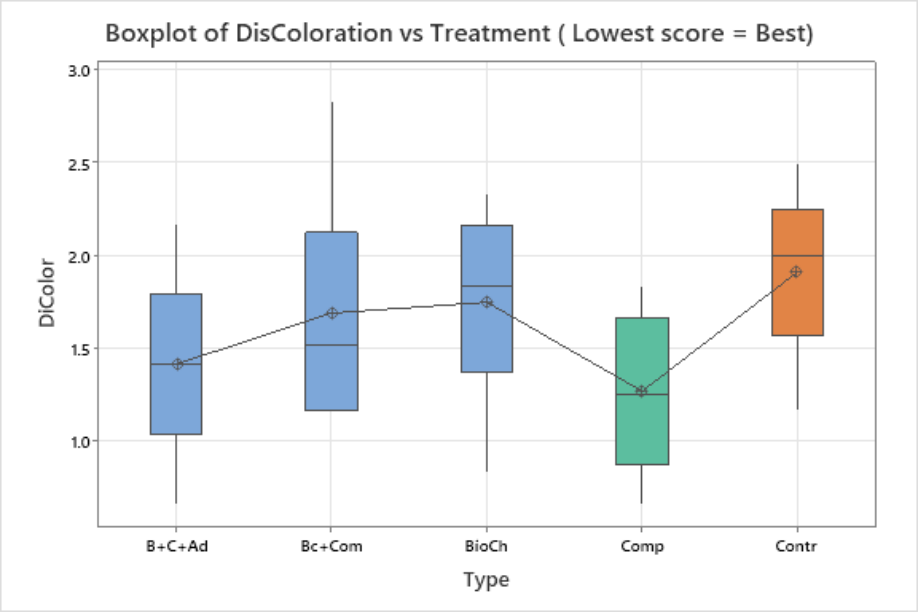
Tree Health – Leaf Discoloration (Overall Effects)

- Discoloration (Years 3 and 4) shows significant nutritional effect of compost vs control
- No other treatment had a significant influence overall on coloration

Grouping via Fisher LSD Method (95% Confidence)

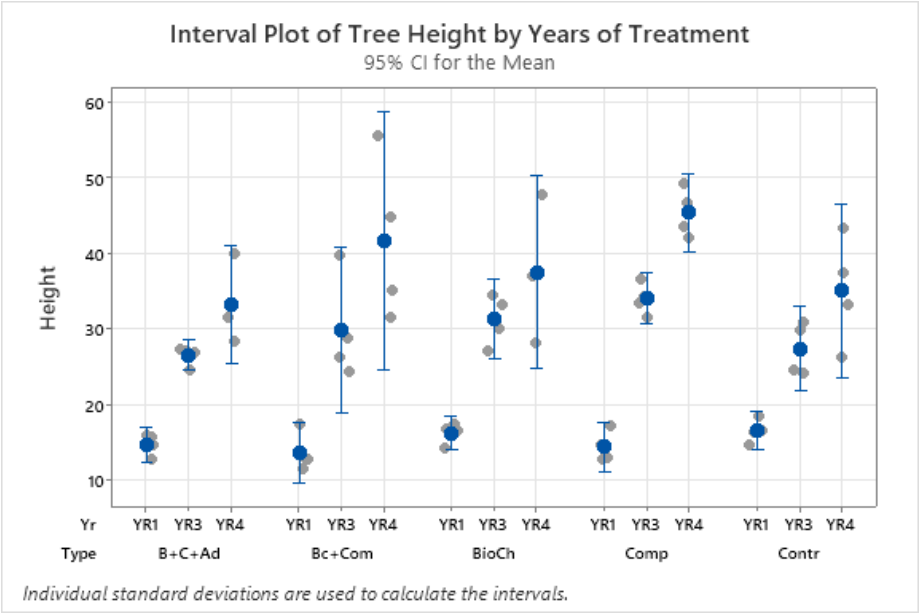
Type	N	Mean	Grouping	
Contr	8	1.913	A	
BioCh	8	1.750	A	B
Bc+Com	8	1.692	A	B
B+C+Ad	8	1.417	A	B
Comp	8	1.271		B

Means that do not share a letter are significantly different.



Tree Health – Tree Height (All Years)

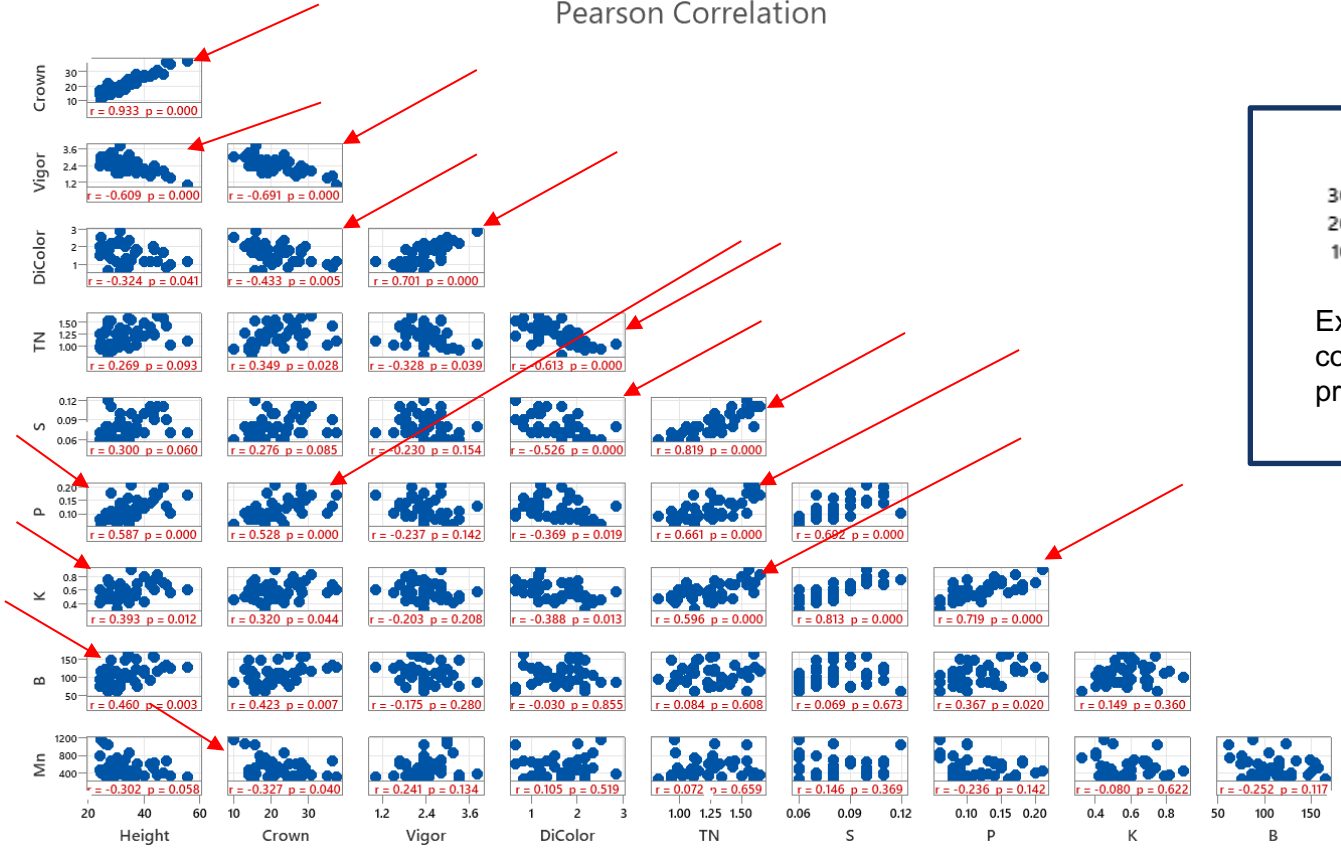
- Growth shows *gains across all treatments*
- Most consistent (and least variable) gain with compost
- Biochar has least gain, nearly identical to control

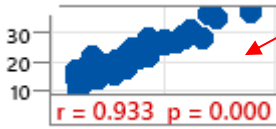


Tree Health – Leaf Tissue/Visual Survey Correlation

Final 2 Years: Tree Height, Crown, Vigor, DiColor, TN, S, P, K, B, Mn

Pearson Correlation

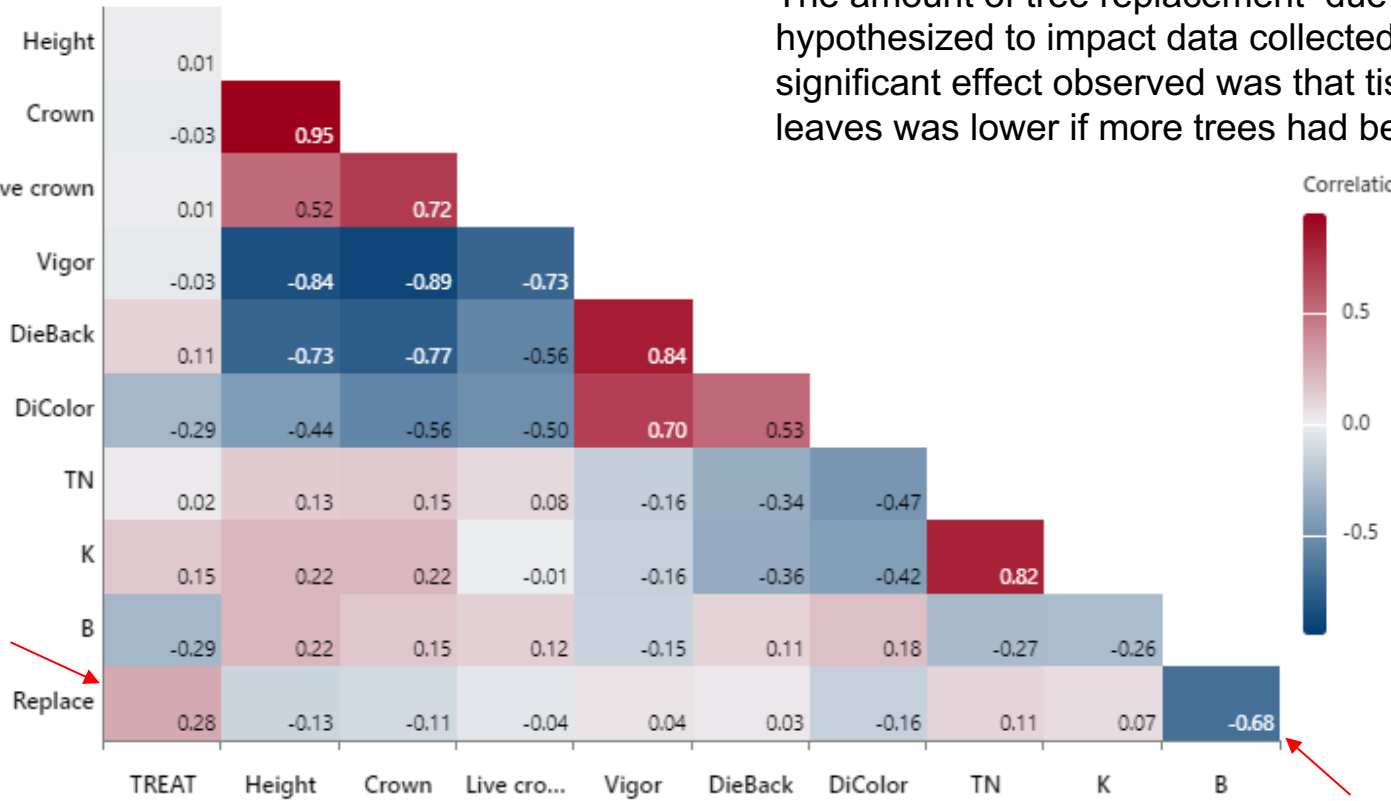




Example: Look for high correlation (r) and very low p= probability of error

Tree Health – Influence of Tree Mortality

The amount of tree replacement due to mortality was hypothesized to impact data collected. However, the only significant effect observed was that tissue Boron (B) in plant leaves was lower if more trees had been replaced.

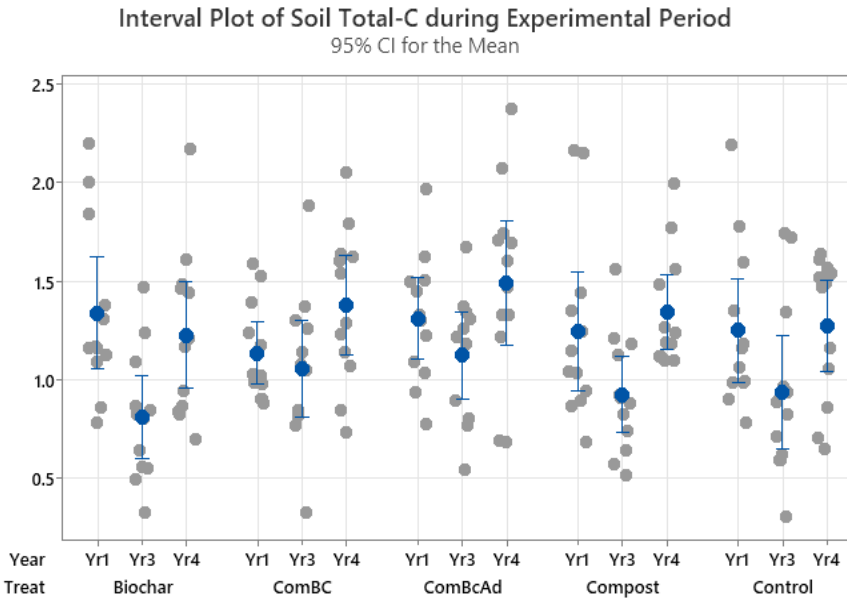


Key: Look for high correlation (r) and very low p= probability of error

Soil Health* – Total Organic Carbon (TC) Over time

Carbon varied significantly between annual samplings.

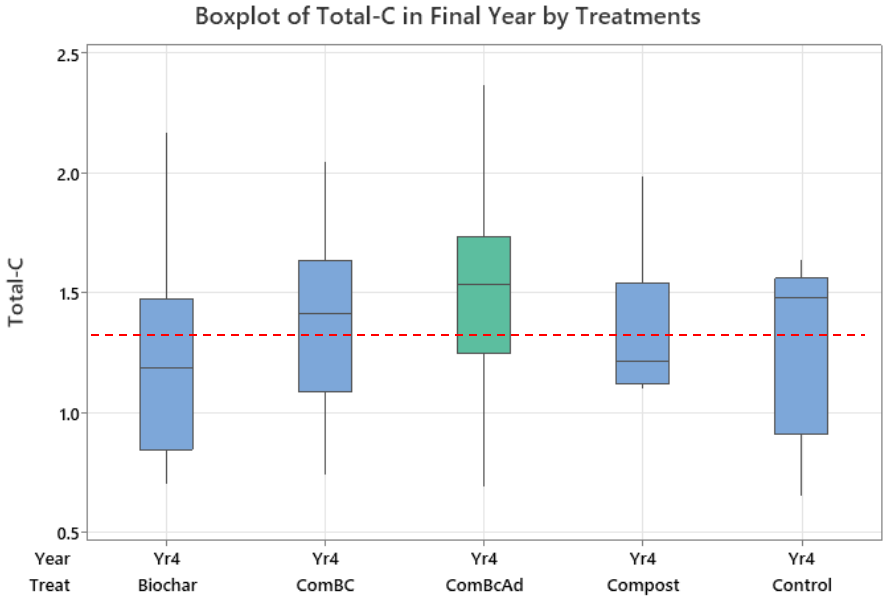
- TC data very variable
- TC difference by Years very significant with a dip in Yr 3
- Treatments *did not* differ significantly, but Full Rate Treatment had highest TC



* Soil Health refers to soil samples taken separately in the 0 – 6” layer in Yr 1, 3 and Yr 4.

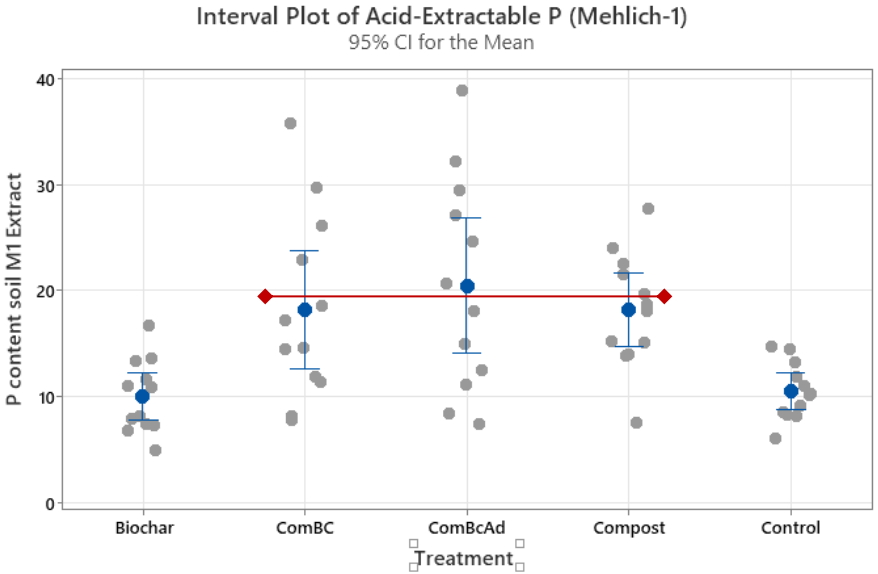
Soil Health – Total Organic Carbon (Final Year)

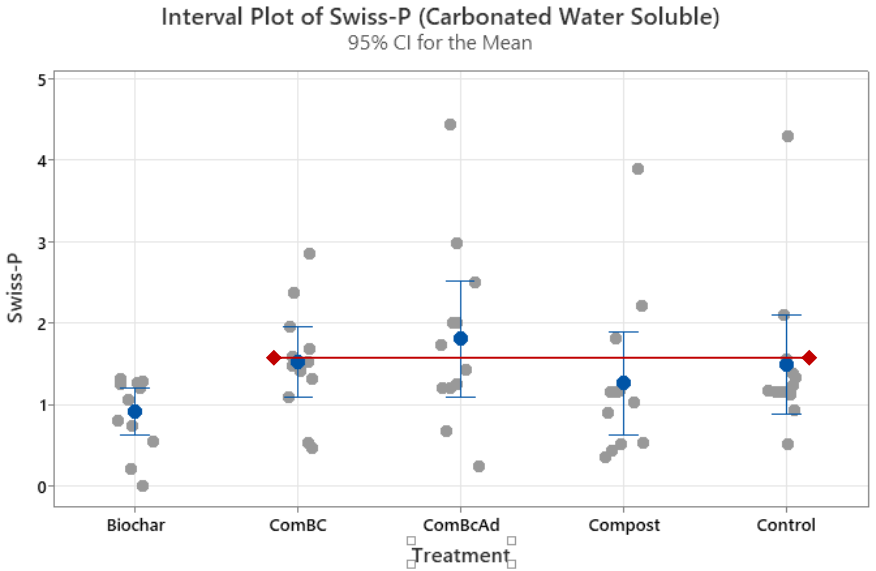
- Grand mean TC is 1.34% ± 0.40 (overall 30% variability) (red dashed line)
- Com+Bc+Ad slightly but no significantly higher (had most TC added at start)
- Original (2022) Control Plots were 1.34% ± 0.26 = no change during study



Soil Health – Phosphorous extractable, water soluble Final Year

- P significantly affected by soil treatments ($p < 0.0001$ and $p < 0.1$) resp
- Compost+Biochar+Amend treatment highest; control and biochar lowest





Range bar covers high treatments that are not significantly different from each other

Soil Health – Potassium (Final Year)

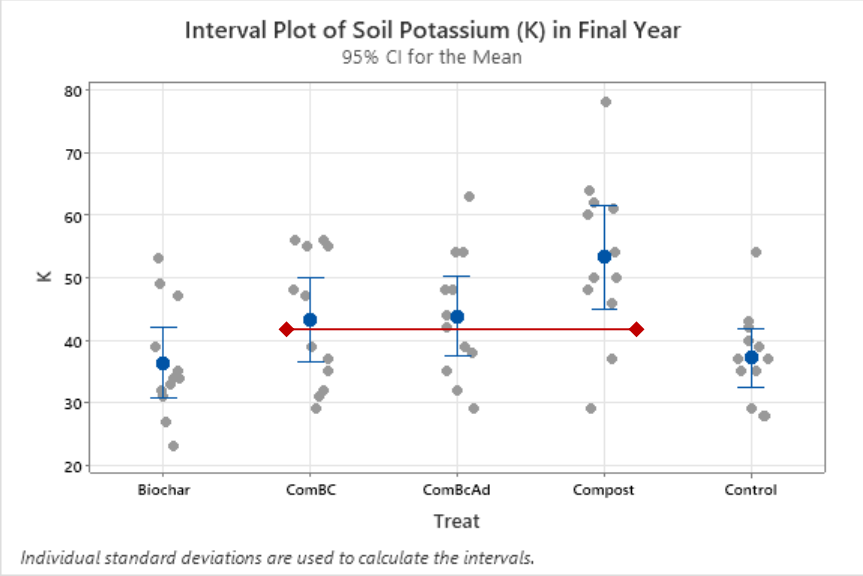
- K significantly influenced by soil treatment by final year
- Compost significantly raised K levels over biochar and control ($p < 0.01 = 99.99\%$)

Grouping via Fisher LSD Method (95% Confidence)

Treat	N	Mean	Grouping
Compost	12	53.25	A
ComBcAd	12	43.83	A B
ComBC	12	43.33	A B
Control	12	37.25	B
Biochar	12	36.42	B

Means that do not share a letter are significantly different.

In this example, compost is significantly higher than Control and Biochar treatment. “Mean” = ppm of potassium in soil



This graph shows visually what is shown in the Table at left indicating the scatter of points which are all samples

Soil Health – Cation Balance (Final Year)

- We expected a cation influence from biochar, but found no evidence
- Compost statistically higher than other treatments

Grouping via Fisher LSD Method (95% Confidence)

Treat	N	Mean	Grouping	
Compost	12	53.25	A	
ComBcAd	12	43.83	A	B
ComBC	12	43.33	A	B
Control	12	37.25		B
Biochar	12	36.42		B

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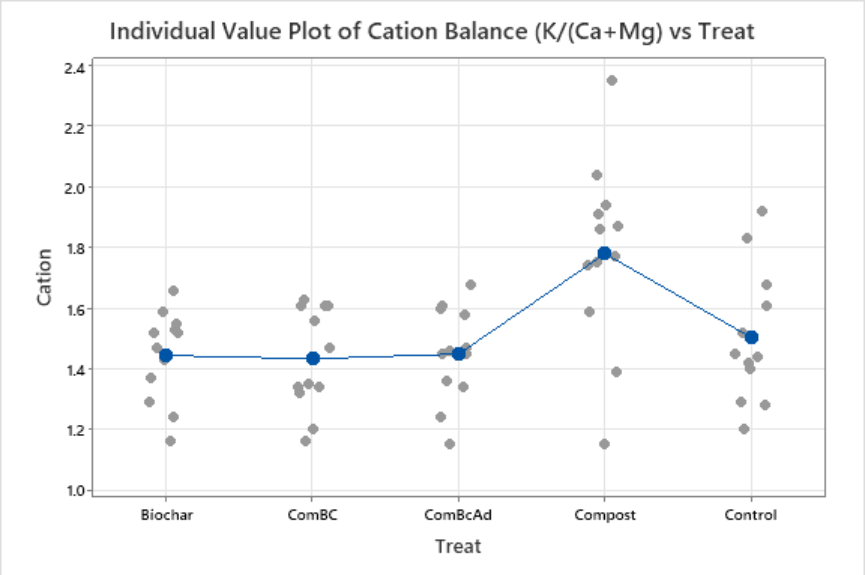
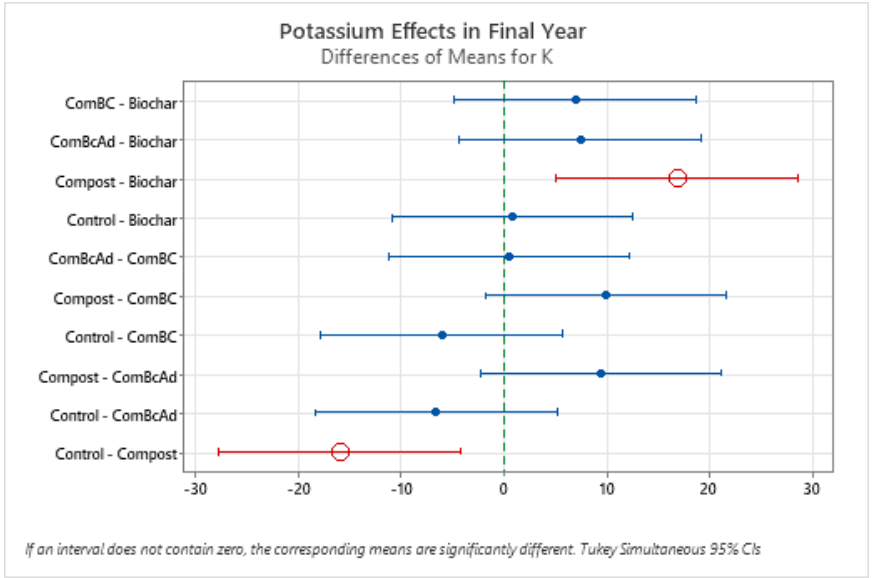
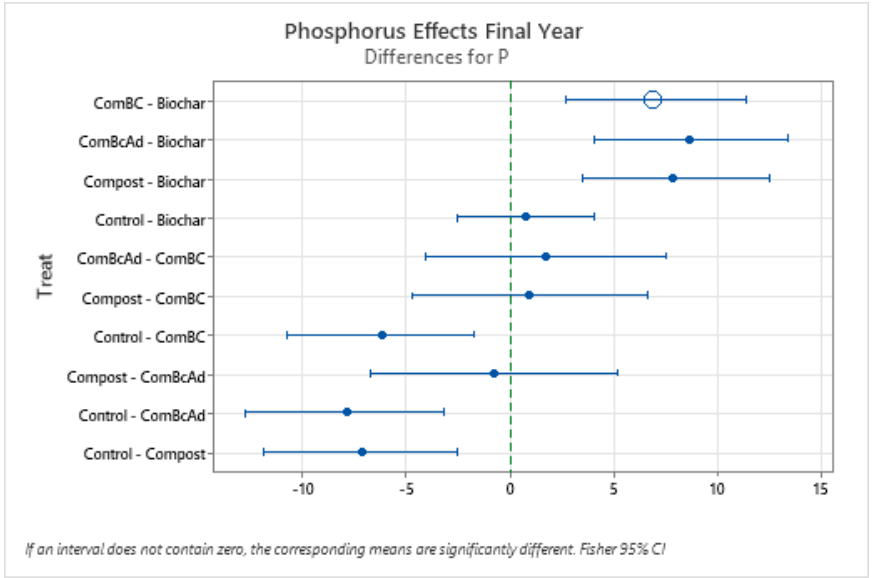


Soil Health – Potassium & Phosphorous

- Adding Probiotic to BC and/or Compost made no difference over compost alone
- Strong evidence that K pathway is mediated entirely by compost
- For P all compost treatments behaved similarly
- Biochar had no influence





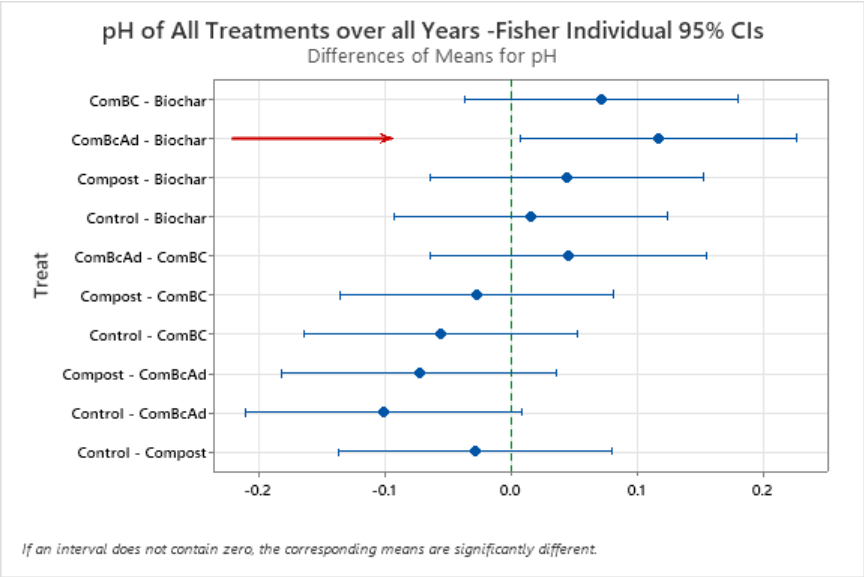
Soil Health – pH effects

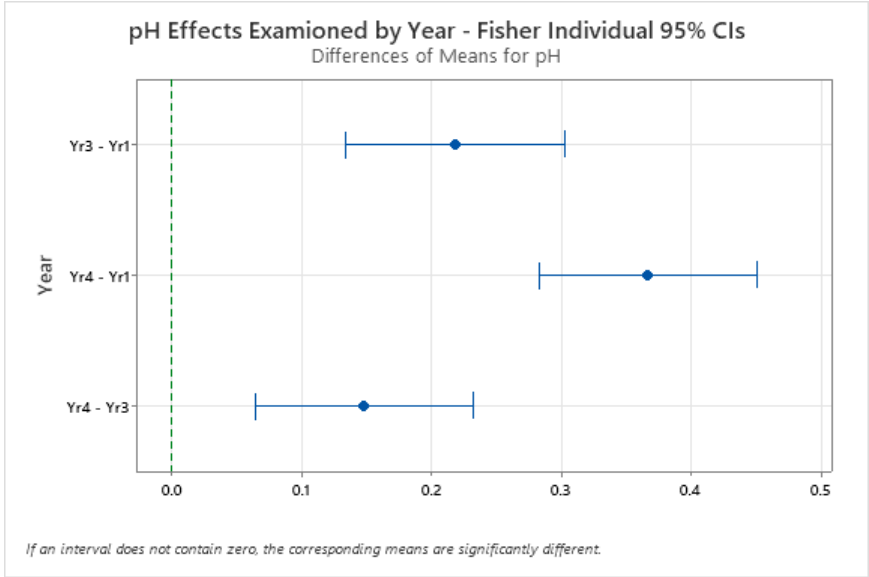
- Significant pH effect from Comp+BC+Amend
- Biochar *significantly lowest*
- Significantly increases of pH over time

Year	N	Mean	Grouping
Yr4	60	6.53993	A
Yr3	59	6.39150	B
Yr1	60	6.17310	C

Means that do not share a letter are significantly different.

pH over time





Soil Health – Overall Soil Health

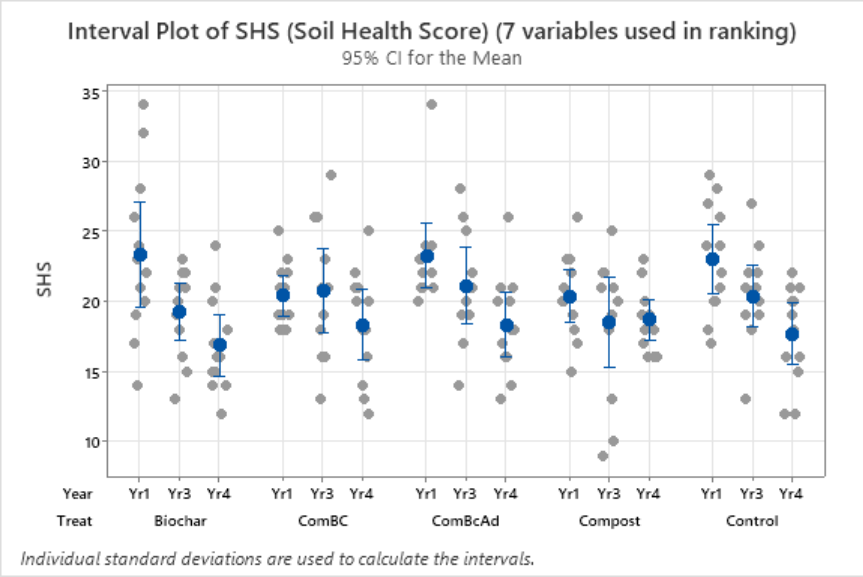
- Soil health declined steadily each year ($p < 0.001$; highly significant)
- Least decline in compost and greatest decline in biochar and control (not significantly)
- Decline could be explained since sampled area was not directly treated.

Grouping via Fisher LSD Method (95% Confidence)

Year	N	Mean	Grouping
Yr1	60	22.067	A
Yr3	59	19.966	B
Yr4	60	17.967	C

Each year significantly lower than previous Mean

Means that do not share a letter are significantly different.



Soil Health – Overall Fertility Score (Final Year)

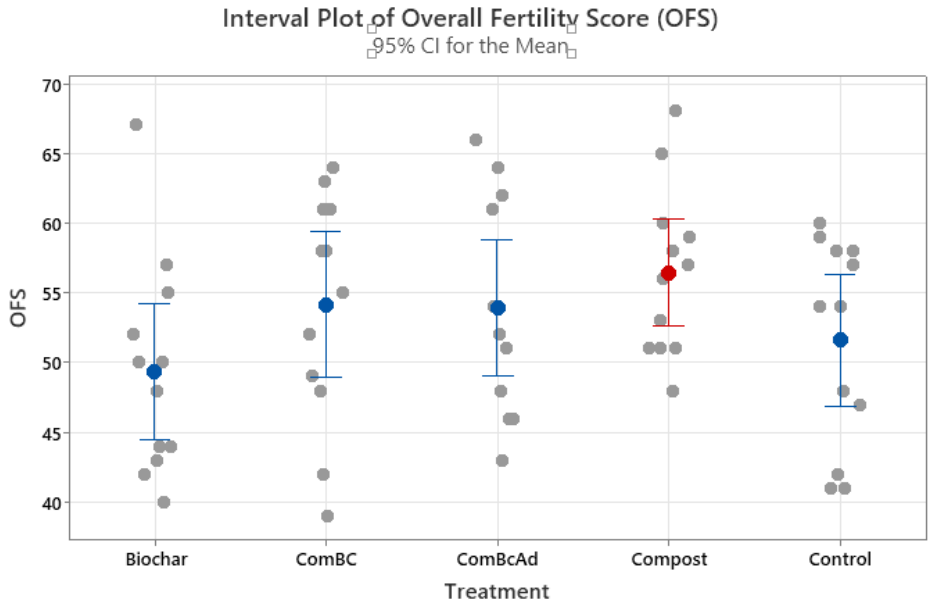
- Ranking 50% Soil Health / 50% Nutrients - Compost had greatest influence
- Biochar *scored lower than Control*
- Supports hypothesis that raw biochar may reduce soil health factors

Grouping Information Using Fisher LSD Method

Treat	N	Mean	Grouping	
Compost	12	56.4167	A	
ComBC	12	54.1667	A	B
ComBcAd	12	53.9167	A	B
Control	12	51.5833	A	B
Biochar	12	49.3333		B

Means that do not share a letter are significantly different.

Compost score is significantly higher than biochar

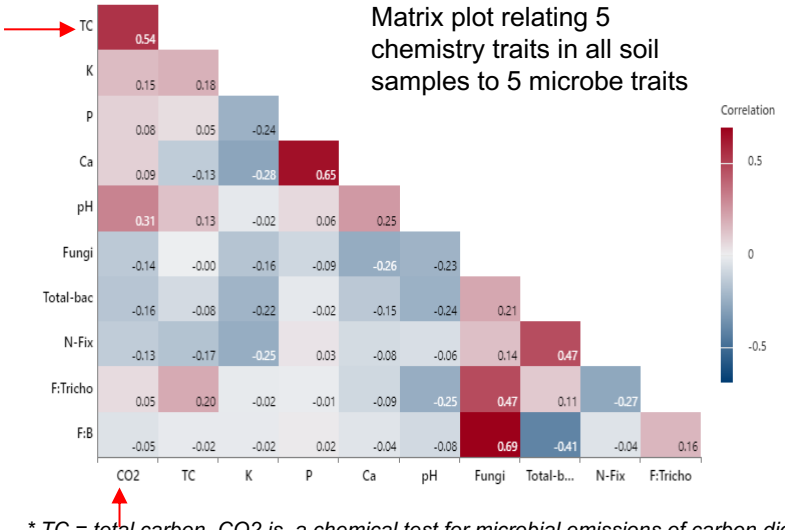


Soil Biology – Measurable Biological Synergy Effects

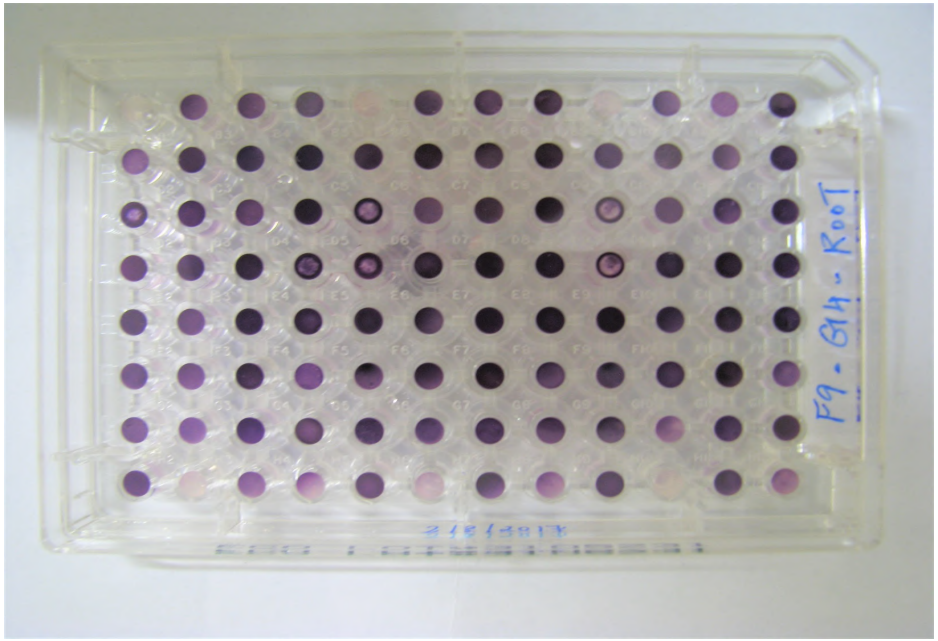
tested by *modified substrate utilization assay,* 12 properties

-TC* and CO_2-microbial respiration are well correlated

-No definitive relation of SU‡ microbiology to other traits



Matrix plot relating 5 chemistry traits in all soil samples to 5 microbe traits



* *TC = total carbon, CO2 is a chemical test for microbial emissions of carbon dioxide*

‡ *SU - Substrate utilization test, a 12 x 8 array of modified protocol for semi-quantitative estimates "Vitellus" test by A&L Canada. This protocol has not been validated in peer-review journals.*

Soil Biology – Fungi:Bacteria Ratios (Years 1 and 3)

Substrate utilization (SU) test showed strong year effects and no treatment effects for 10 of 12 indicators. **Fungi-Bacteria Ratio** was improved by adding biochar to compost, but inoculated treatment had no effect.

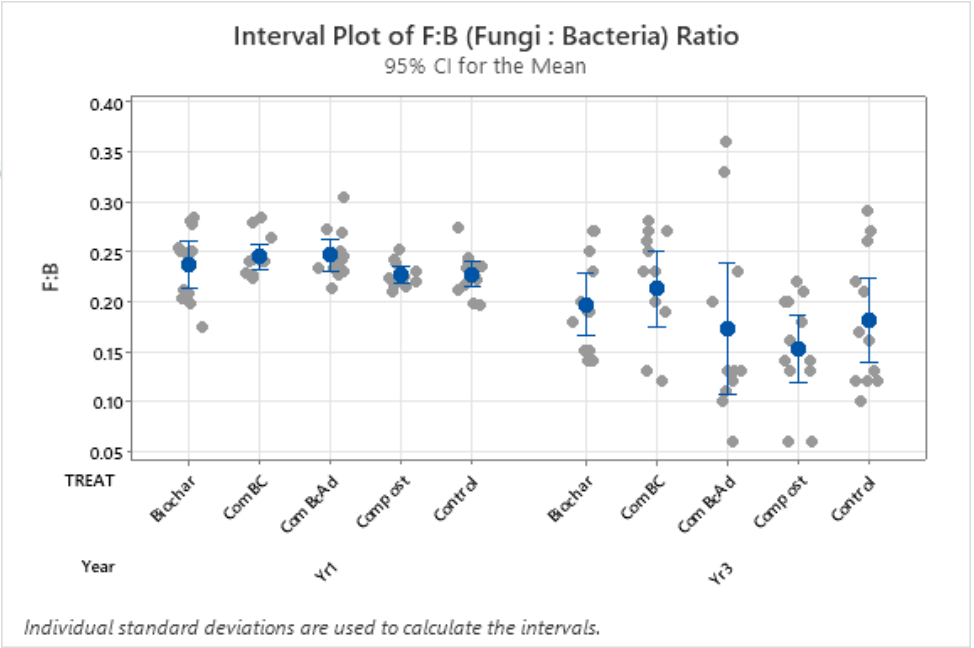
After baseline year, variability huge

Grouping Information Using Fisher LSD Method

TREAT	N	Mean	Grouping
ComBC	24	0.228556	A
Biochar	24	0.216574	A B
ComBcAd	23	0.209512	A B
Control	24	0.204096	A B
Compost	24	0.189389	B

Means that do not share a letter are significantly different.

Com+Biochar is significantly higher in fungi and lower in bacteria vs compost alone



Soil Health – N-Fixer Effects (Years 1 and 3)

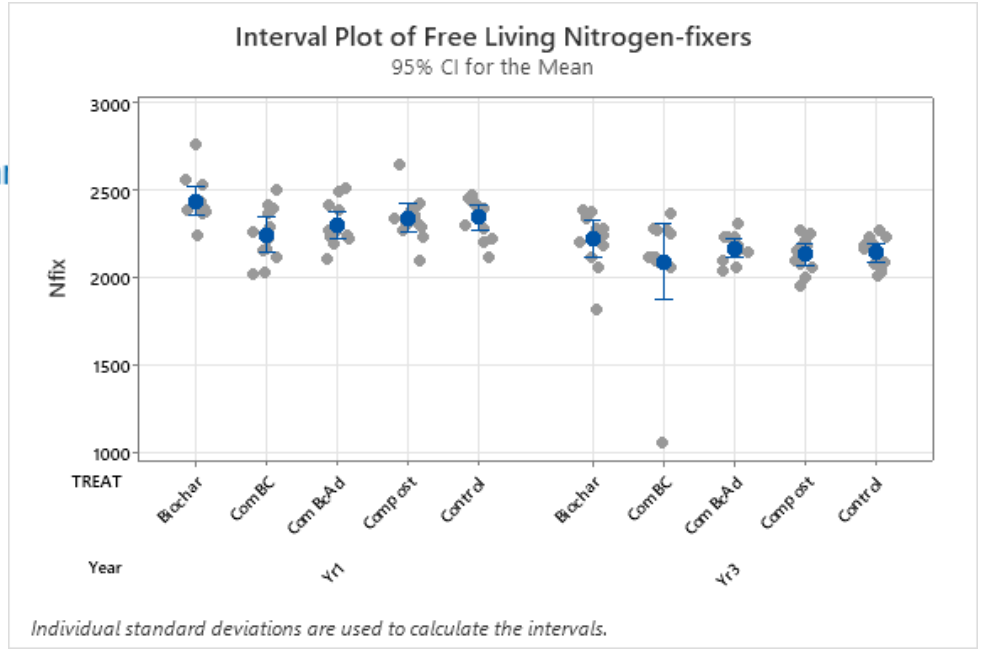
- Free living N-fixers results indicate Biochar alone increased generalized N-fixers but specific N-bacterial groups (Rhizobium, Pseudomonas) showed no effects.
- Suspicious baseline year (elevated)
- Outlier Yr 3 may invalidate conclusion

Grouping Information Using Fisher LSD Method a

TREAT	N	Mean	Grouping
Biochar	24	2347.69	A
Control	24	2254.87	B
Compost	24	2251.04	B
ComBcAd	23	2243.22	B
ComBC	24	2203.12	B

Means that do not share a letter are significantly different.

Biochar higher in general N-fixers compared only to compost mixed with BC



Deep-Core Carbon Soil Tests

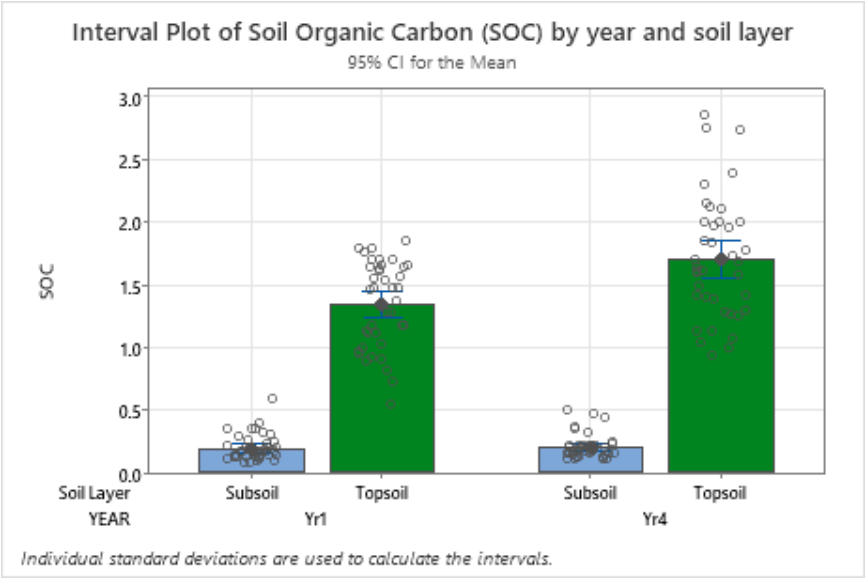
- Geoprobe hydraulic sampler
- Target 100 cm depth; Avg. recovered 77 cm
- Stones/rocks produced highly variable interference
- Data correction applied but potentially erroneous conversion in Yr4 due to lab method difference.

Deep-Core Soil Tests – Soil Organic Carbon

- Soil carbon in cores appeared to increase (but not significantly) in year-4 topsoil
- The % gain appears large, but the margin of error is also large
- A higher error in Yr4 likely resulted from change in lab methodology in handling stones

Year	# of tests	Topsoil SOC %	Stat. Group
2022	80	1.303	**A***
2025	80	1.646	**A**

* Statistical group: same letters denote no difference between sampling. In this case, 1.65% C was not significantly more than 1.30% C.



Deep-Core Soil Tests – Soil Density

- Initial soil density varied little (1.07 to 1.13); No difference by treatment, depth or years
- Expected result (e.g., Bulk Density of 1.0 g/cc = 62 lbs/ft^3 of soil)

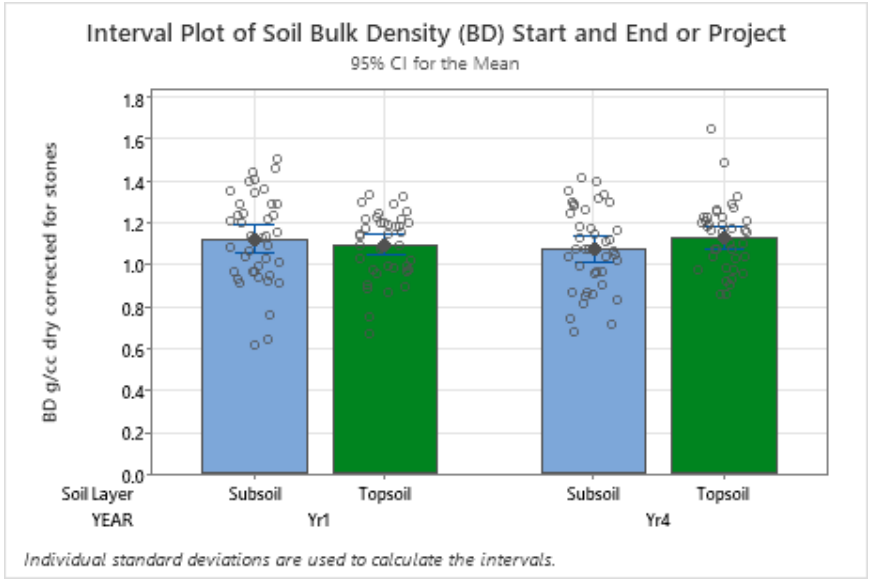
Grouping via Fisher LSD Method (95% Confidence)

YEAR*Layer	N	Mean	Grouping
Yr4 Top	40	1.13128	A
Yr1 Bottom	40	1.12124	A
Yr1 Top	40	1.09502	A
Yr4 Bottom	40	1.07416	A

Means that do not share a letter are significantly different.

No difference or change between years and depth (Top=topsoil; Bottom = subsoil

Year	# of tests	Mean BD g/cc	Group
2022	80	1.108	**A**
2025	80	1.103	**A**



Deep-Core Soil Tests – Impact of Lab SOP Changes

Change in Lab SOP between Yr 1 and Yr 4

A Corrected Bulk Density = stones removed

B Raw Bulk Density= entire sample used

Grouping via Fisher LSD Method (95% Confidence)

A.

YEAR*Layer	N	Mean	Grouping
Yr4 Top	40	1.13128	A
Yr1 Bottom	40	1.12124	A
Yr1 Top	40	1.09502	A
Yr4 Bottom	40	1.07416	A

No difference between depths
(Top=topsoil; Bottom = subsoil

Means that do not share a letter are significantly different.

B.

Yr1 Bottom	40	1.87068	A		
Yr1 Top	40	1.44054		B	
Yr4 Bottom	40	1.21329			C
Yr4 Top	40	1.13187			D

All samples significantly different

Means that do not share a letter are significantly different.

Year 1 = all stones were collected and quantified before analyzing

Year 4 = large stones were discarded and all else ground and sieved before analyzing

Study Conclusions

- **Biochar treatment did not measurably influence** any single or combined plant or soil trait over four years. We conclude that biochar had no detectable effect within this agroforestry system.
- **Compost emerged as primary driver** of plant and soil responses. Compost+ Biochar+Probiotic effects were not statistically distinguishable from Compost alone, proving that inoculation had no additional synergistic effect.
- **Field-level variability was high** and reduced power to resolve treatment effects. However, even with lower variability, the direction and magnitude of the responses suggest the overall conclusion would likely remain unchanged.

Study Critique & Recommendations

- **Undulating Landscape** imposed a challenge to achieving field uniformity and reduced ability to accurately distinguish non-random effects
- **Confinement of Treatments** (biochar, compost etc.) to small area under trees limited holistic and interactive observations which might have emerged
- **Decline in Soil Health** during project relates to large untreated areas suggesting growers should not confine amendments to desired spots
- **Balanced Soil Testing** should have included tree center and aisles; better control of lab SOPs advisable
- **Reduced Treatments** would have improved efficiency, since literature does not support distinguishing highly “nuanced” effects
- **Deep Carbon Reliability** challenged by interference from stones and how labs handle this. USDA-Kellog method 3B6* should be used for deep cores.

Scientific Literature Review - Main Findings

- **Terra Preta** – “Ancient” dark earths: we found competing geomorphic origin theory.
- **Agronomic Response** – We found very variable reports for: positive, neutral, or negative effects, depending on soils, fertility, crops, and biochar used.
- **Short-Term/High Applications**: We found few long-term science studies exist; many reported trials rely on pots or unusually high application rates.
- **Biochar Variability**– Strong evidence shows feedstock and process affect chemistry and structure, but practical guidance for tailoring materials to field conditions remains limited.
- **Inoculation** – Co-composting or post-mixing can create surface coatings, yet evidence for consistent biological or agronomic synergy is limited.
- **Expensive ($200-300/yd)** – High cost necessitates clearly diagnosed soil limitations, defined objectives, and field-verified responses.
- **Climate Benefits Depend** – Life-cycle outcomes vary widely with assumptions and model boundaries, limiting transparent attribution and field-scale verification; who gets paid?

Recommendations

- **Initiate Biochar Projects Only With** a clear economic frame, including defined soil limitations, measurable endpoints, and the expectation that benefits should reasonably exceed costs.
- **Use Biochar Strategically -** where specific, diagnosed soil constraints justify intervention, with greatest likelihood of benefit in depleted or structurally impaired soils rather than well-functioning systems**.**
- **Integrate with Existing Fertility Practices,** not as substitute, and only where integration demonstrably improves efficiency or reduces net costs.
- **Prioritize Long-Term Trials in Real Farm Systems -** use realistic application rates; document performance, variability and opportunity costs over time.

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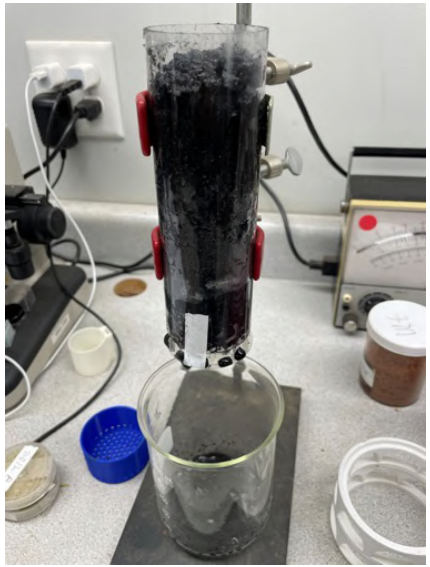
ENDNOTE: Water Holding Capacity (WHC) Test:

Biochar not significantly different than compost given typical application rates

Capillary Column



Buchner Funnel

Sample saturated slowly over several hours then drained for 12 hours covered, re-weighed

WHC – ability to hold and retain water under gravity force

Measured – as grams water retained per gram dry material ($g \cdot g^{-1}$)

Our Biochar = 1.9 $g \cdot g^{-1}$ (=190%)

Our Compost = 1.1 $g \cdot g^{-1}$ (=110%)

Soil (for reference) = 0.2 $g \cdot g^{-1}$ (~20%)

Notes on how to read data

Data plots: Grey dots are measured replicates;
Blue dots are means and handlebars are the “95% confidence” range.

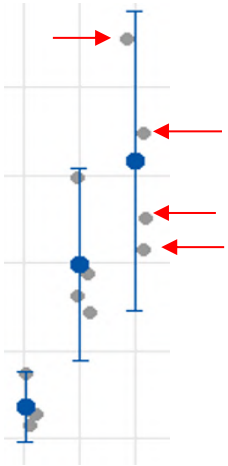


Fig 1. Height gain over time; arrows show replicates

Variability: In this example the measurements (dots) are widely scattered around the average indicating large variability. In a dataset like this results are best sub-categorized to reduce variation; otherwise, this would suggest non-significant results.

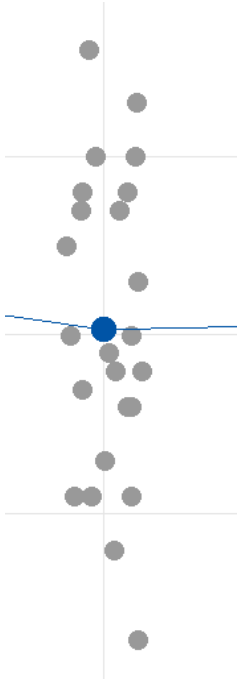


Fig 2. Soil Fertility-Health score over all years