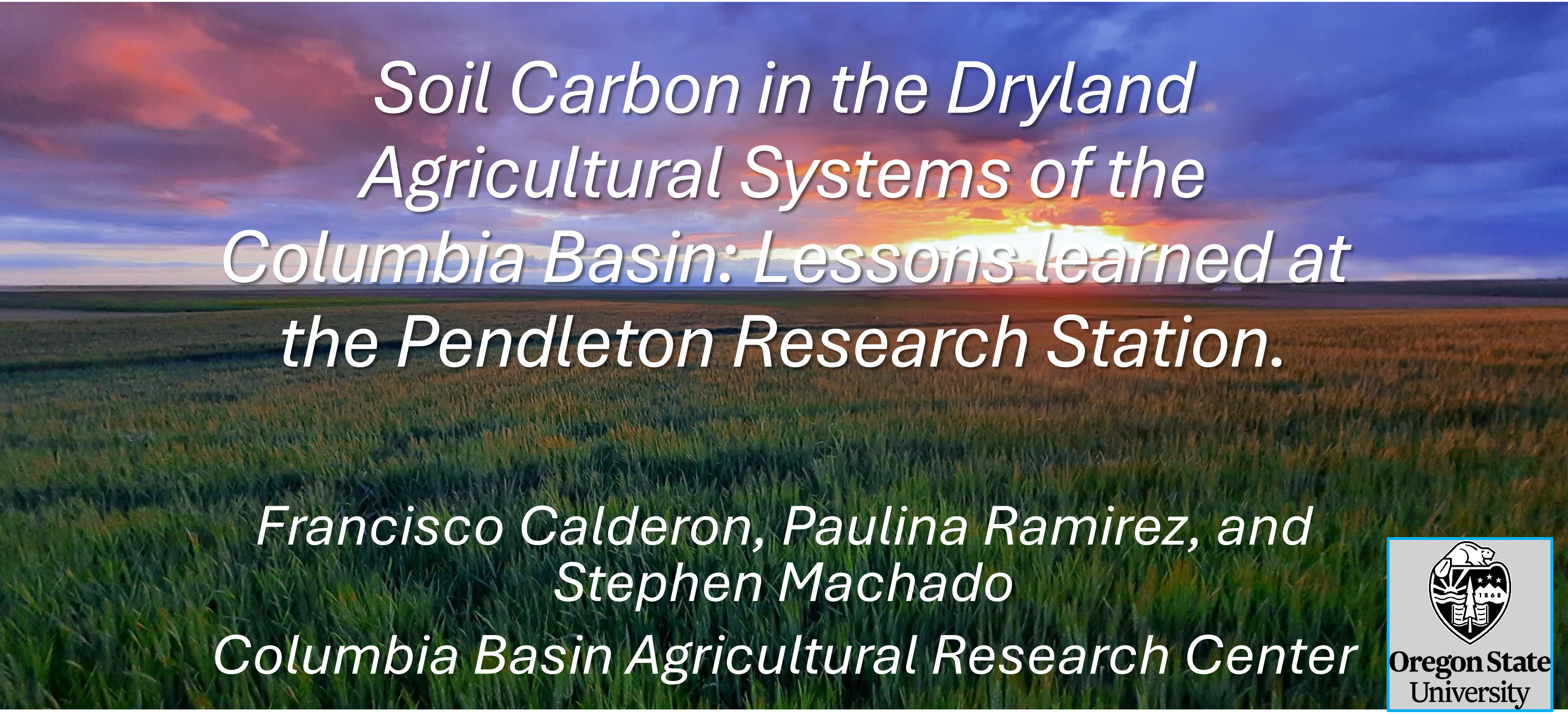

Soil Carbon in the Dryland Agricultural Systems of the Columbia Basin: Lessons learned at the Pendleton Research Station.

Francisco Calderon, Paulina Ramirez, and Stephen Machado

Columbia Basin Agricultural Research Center

Oregon State University

https://agsci.oregonstate.edu/cbarc

CBARC: OSU Columbia Basin Agricultural Research Center, Adams, OR

Oregon State University

USDA Agricultural Research Service
U.S. DEPARTMENT OF AGRICULTURE

Our mission at CBARC

- Ensuring the long-term **sustainability** of dryland agriculture and identifying cropping systems that are resilient and diverse, capable of maximizing carbon storage, and conserving water, nutrients, and energy—all while maintaining sufficient and profitable food production.
- In eastern Oregon, a significant portion of the land under wheat production follows a **wheat–fallow rotation system**, especially in low-rainfall zones.
- Estimates suggest that **up to 50% or more** of the wheat production area may be in fallow in any given season, particularly in regions receiving less than 12 inches of annual precipitation

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Our Inland Pacific Northwest soils (**loess**)

- The soils of the inland PNW, formed through a dramatic sequence of geologic events that started during the last Ice Age.
- Massive glaciers once covered much of the Pacific Northwest 115,000 years ago, grinding bedrock into fine particles.
- Around 15,000 to 20,000 years ago catastrophic floods that swept across eastern Washington, carving out the land and depositing vast amounts of sediment.
- Strong winds picked up the fine silt from floodplains and dry lakebeds, depositing thick layers of **loess**—especially in the rolling hills of the Palouse.
- Over time, volcanic ash from Cascade eruptions mixed with the loess, helping to enrich their mineral content.
- This “parent material” eventually of the most fertile soils in the United States, supporting the region’s thriving agriculture today.

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Our Inland Pacific Northwest soils

- Initially, the loess and other windblown sediments were **mineral-rich but carbon-poor**, lacking organic matter.
- Over time, **native vegetation**—such as bunchgrasses, wildflowers, and shrubs—began to colonize the surface.
- These plants contributed organic material through **root growth, leaf litter, and microbial interactions**, slowly building up **soil organic carbon**.
- As plant communities matured, they supported diverse microbial and fungal networks that further enhanced carbon cycling and storage.

Our Inland Pacific Northwest soils

- Land stewardship practices like controlled burns and seasonal harvesting, maintained prairie health and carbon stability.
- Later, with the onset of **tillage and cereal crops**, soil carbon dynamics shifted dramatically.
- While early tillage and monoculture farming often depleted carbon, modern conservation practices—like **no-till farming**—have helped rebuild organic matter in some areas.

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Carbon in Soil Organic Matter

- Soil organic carbon (SOC) makes up roughly 58% of soil organic matter (SOM).
- SOC enters the soil primarily through the breakdown of organic inputs such as plant and animal residues, root exudates, living and dead microbes, and other soil organisms.
- SOM serves as the primary energy source for soil microbial communities.
- SOC levels increase when the rate of SOM formation exceeds its breakdown by microbial activity or its loss through erosion.

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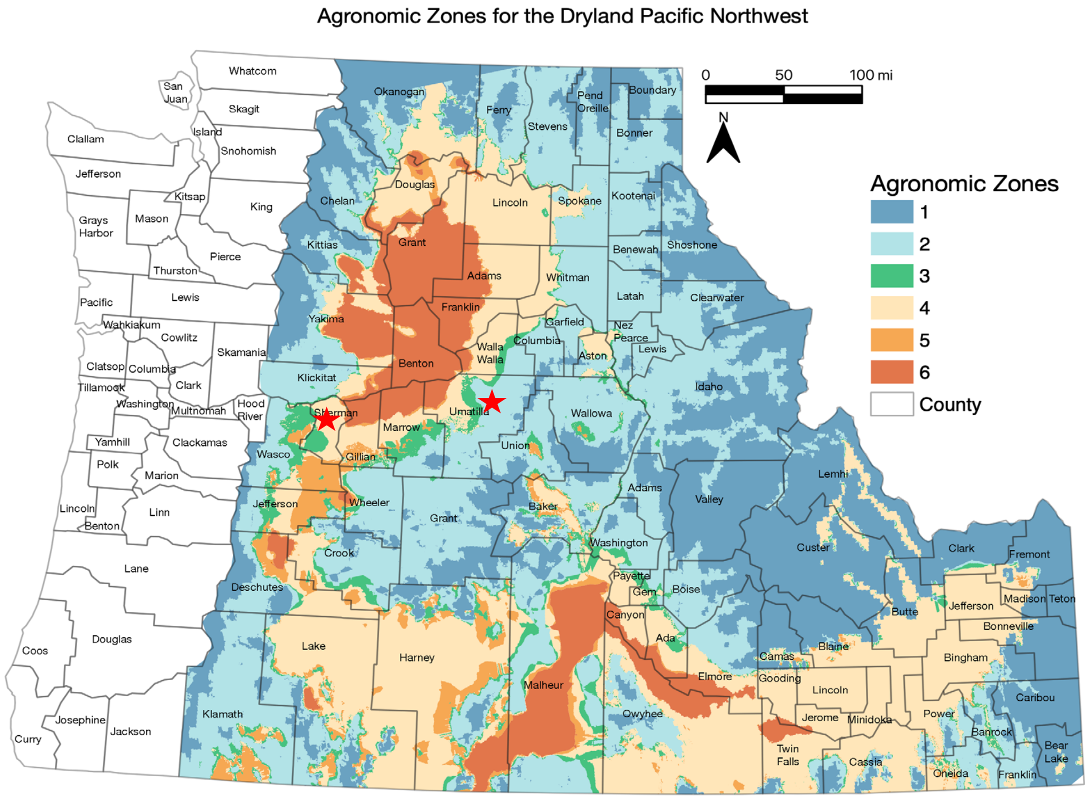

Hagerty et al. 2019

Agronomic Zones: The region is divided into agronomic zones based on precipitation, soil depth, and growing degree days. These zones help farmers tailor management strategies to local conditions, which in turn influence SOM levels.

Geographic Patterns in Soil Organic Matter

- Precipitation gradient: SOM tends to increase with annual rainfall across the iPNW.
  - Areas which receive up to 24 in of annual precipitation, generally have higher SOM than drier regions like north-central Oregon, which may receive as little as 6 in.
- North-to-South Gradient: Cooler northern zones retain more organic matter due to slower decomposition rates.
- Temperature/precipitation: As this ratio increases—especially under climate change—SOM levels are predicted to decline.
- *Management Influence: Tillage practices, crop rotations, and residue management also affect SOM. Intensified rotations tend to preserve more organic matter than wheat–fallow systems.*

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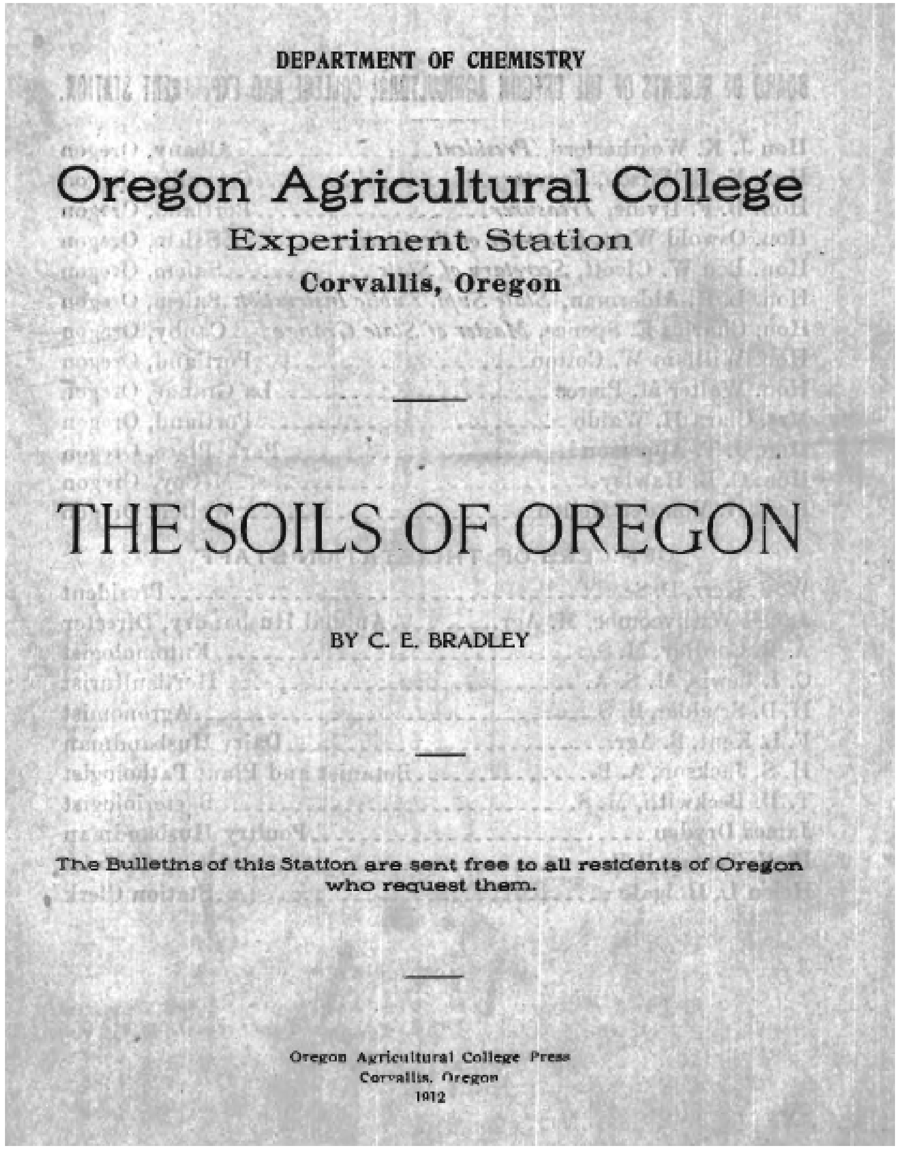
Early studies



DEPARTMENT OF CHEMISTRY

Oregon Agricultural College
Experiment Station
Corvallis, Oregon

THE SOILS OF OREGON

BY C. E. BRADLEY

The Bulletins of this Station are sent free to all residents of Oregon who request them.

Oregon Agricultural College Press
Corvallis, Oregon
1912

Early studies

- In 1909, C. E. Bradley conducted a pioneering soil study in the Sherman Station, collecting samples from paired sites—grassland or wheat-fallow rotation.
- 30 years of farming had reduced organic matter in both surface and subsoil by about 25 percent, with notable declines in nitrogen.
- Bradley published these findings in 1910, producing what is believed to be the first scientific paper based on research in Sherman County.
- He warned of worsening soil degradation over time, a prediction that influenced our focus on soil conservation.

A dilemma

- Even in high-yielding plots where fertilizers are used and crop residues are returned, long-term studies show a gradual decline in soil carbon levels.
- This highlights the challenge of sustaining soil organic matter under modern dryland farming practices.

Why do Perennial Grasses Preserve Soil Carbon?

- Perennial grasses act like carbon pumps—drawing CO_2 from the atmosphere and storing it in the soil, where it supports fertility, structure, and resilience.
- Prairies lost C upon agriculture not because of tillage, but because of the end of thousands of years of perennial grass (Wuest).
- Root Growth: Unlike annual crops, perennial grasses maintain living roots year-round.
- Deep Root Systems: Many perennial grasses have deep, fibrous roots that deposit carbon far below the surface. This deep carbon is less vulnerable to decomposition and erosion, making it more stable over time.

Why do Perennial Grasses Preserve Soil Carbon?

- At the surface: Dense root mats and ground cover reduce erosion, keeping carbon-rich topsoil in place and preventing runoff.
- Minimal Soil Disturbance: Perennial systems do not receive tillage, which helps protect soil aggregates and organic matter from oxidation and loss.
- High Biomass Production: Perennials produce abundant above- and below-ground biomass. When this material decomposes, it contributes significantly to soil organic carbon pools.
- Microbial Synergy: The stable root environment fosters diverse microbial communities that help convert plant residues into long-lasting soil organic matter.

Fallow

Advantages of Summer Fallow

- Used primarily to store winter precipitation
- Allow mineralization of nutrients (N, S)
- Allows for weed control
- Creates a clean, moist seedbed
- Economical where rainfall is less than ~12 in/y.
- *But…… in between crops there are no carbon inputs!*

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1911–1953 crop rotation experiment at Moro:

- Experiment Setup: In 1911, a study with 14 crop rotations across 60 plots was launched to explore alternatives to summer fallow and improve soil humus in eastern Oregon wheat soils.
- Rotation Strategies: Treatments included various combinations of small grains, row crops, and cover crops (pea, rye), with summer fallow occurring every 2–4 years or eliminated entirely in some rotations.
- Soil Findings: By 1922, Jones and Yates observed declining organic matter and nitrogen in summer fallow plots, while field peas helped maintain soil nitrogen but not organic matter.

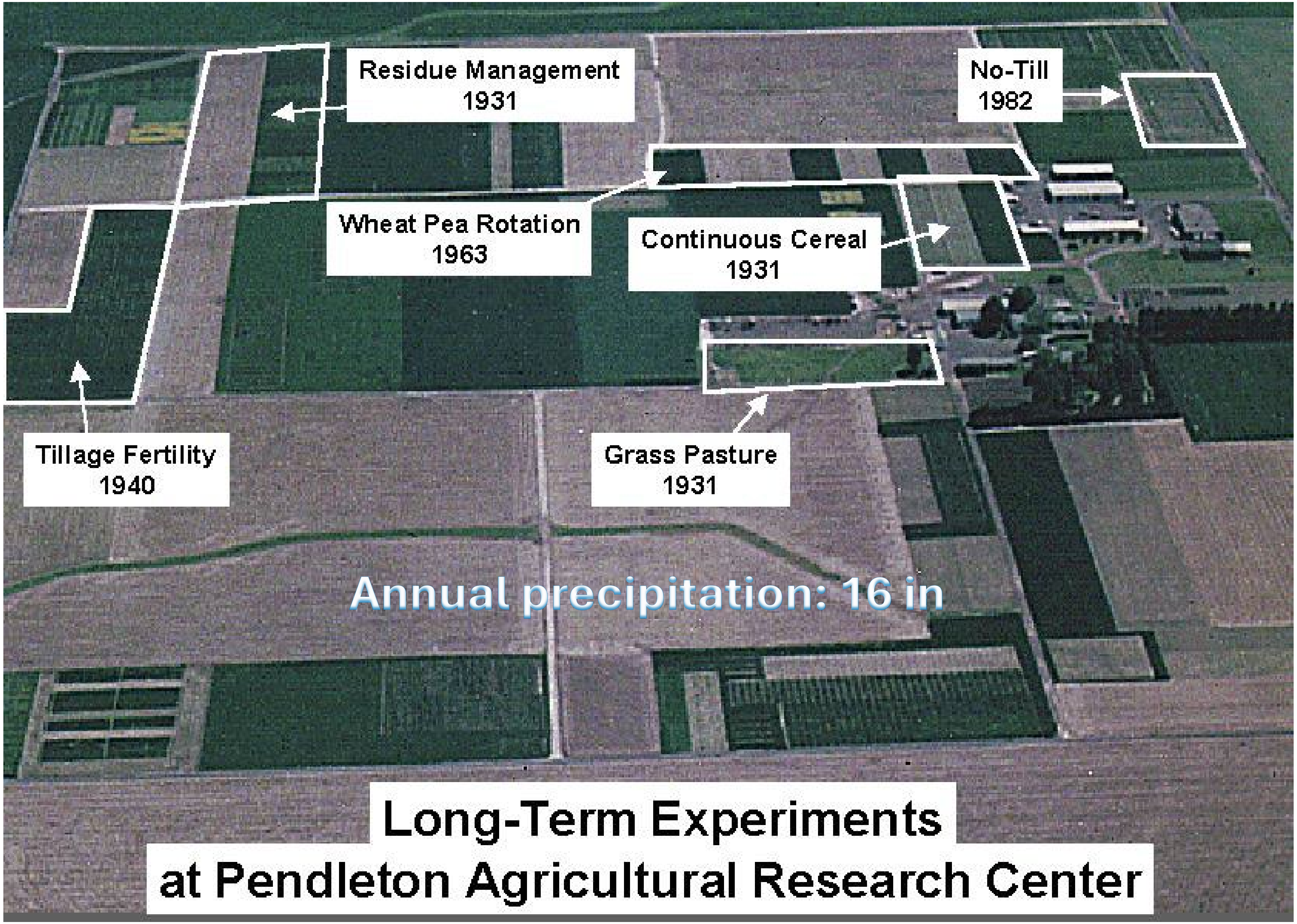
Jones, J. S., & Yates, W. W. (1924). The problem of soil organic matter and nitrogen in dry-land agriculture. Journal of the American Society of Agronomy, 16(11), 722–733.

1911–1953 crop rotation experiment at Moro:

- Carbon Depletion: Summer fallow accelerates the breakdown of organic matter due to increased microbial activity without replenishment from plant residues, leading to long-term carbon loss in surface soils.
- Reduced Carbon Inputs: Because no crops are grown during fallow periods, there's minimal biomass returned to the soil, resulting in lower carbon sequestration compared to continuous cropping systems.
- Legacy: The Moro rotation experiment continued until its termination in 1953.

Jones, J. S., & Yates, W. W. (1924). The problem of soil organic matter and nitrogen in dry-land agriculture. Journal of the American Society of Agronomy, 16(11), 722–733.

Long-Term Experiments at Pendleton Agricultural Research Center



Annual precipitation: 16 in

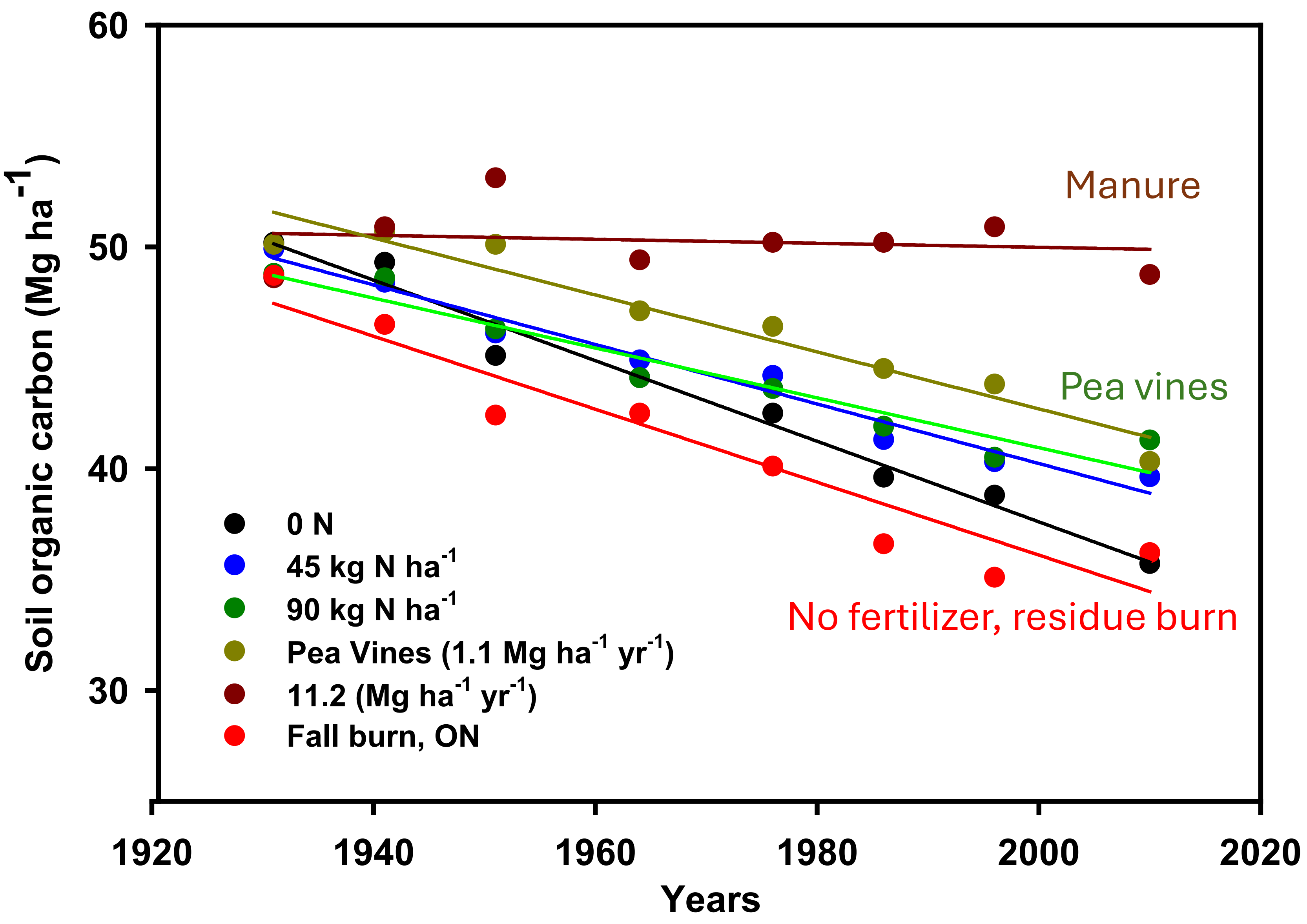


Figure 1. Changes in soil organic matter in the 0-30 cm soil depth profile from 1931 to 2010 in a crop residue study under a wheat/fallow cropping system at CBARC, Pendleton, Oregon

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Long-term Experiments

- Long-term Experiments revealed that dryland cropping systems that include long fallow periods and intensive tillage had lost 50–70% of the SOC.
- From 1931–2010, the SOC declined at the rate of **250 lbs/acre/year** in fall burn, at 0–30 cm depth. Note that the soils originally had about 45,000 lbs/acre at 0–12 in depth (grassland pasture data).
  - This means that soils in the plowed and fall burned plots were losing 5.6 percent of the original C in the soil every 10 years.
- The only treatment that maintained SOC in the top 12 in depth was manure treatment.
- Pendleton Long-term Experiments revealed that dryland cropping systems that include fallow periods, residue burning and intensive tillage had lost 50–70% of the SOC.
- A minimum biomass C input of about 3000 lbs per acre per year is required to maintain SOC in a WW-SF system in the IPNW drylands (Machado 2011).

Ghimire, R., Bista, P., Machado, S. (2022). Crop Yield Limitation by Soil Organic Matter Decline: A Case Study from the US Pacific Northwest. In: Saljnikov, E., Mueller, L., Lavrishchev, A., Eulenstein, F. (eds) Advances in Understanding Soil Degradation. Innovations in Landscape Research. Springer

The importance of wheat straw residue

The importance of wheat straw residue

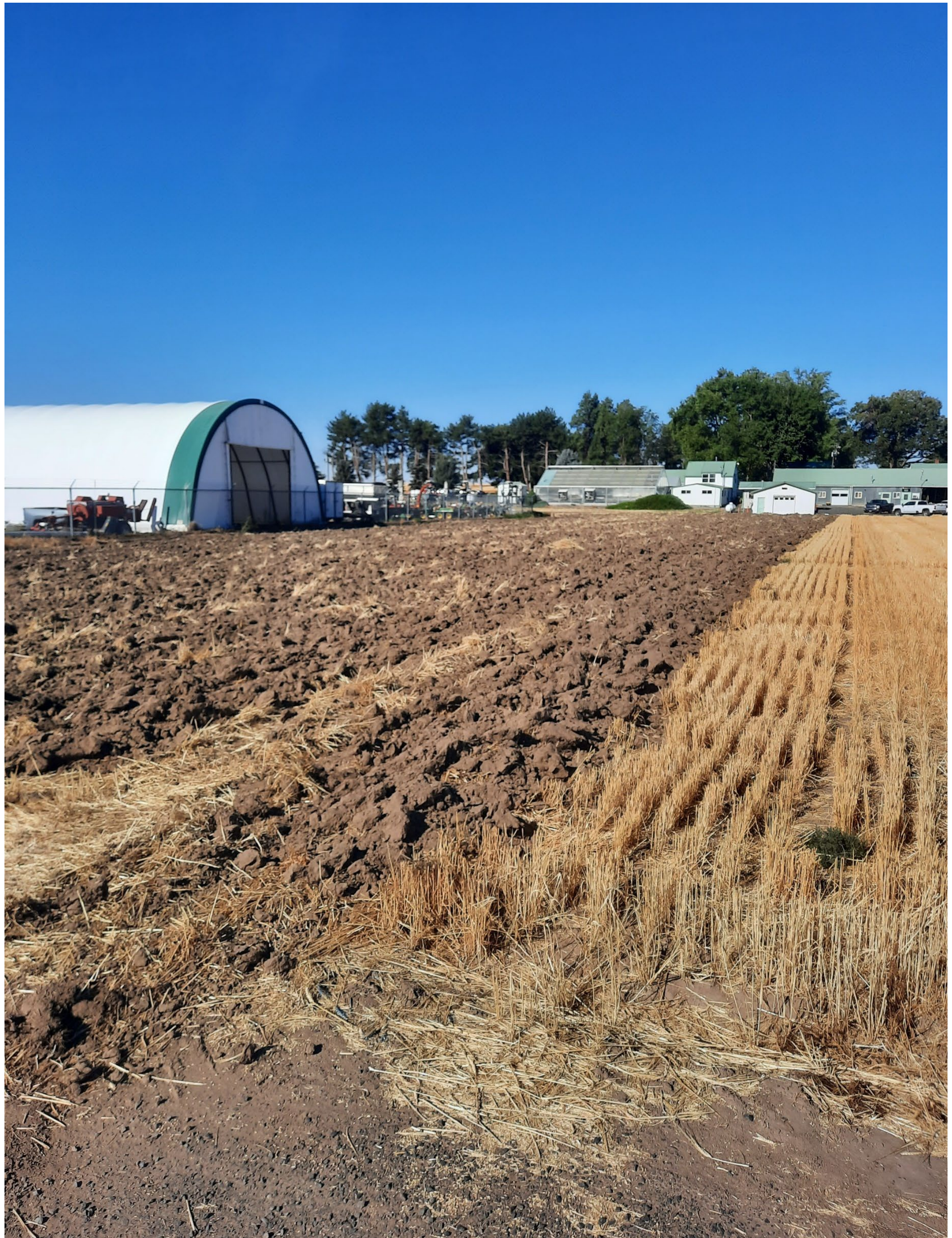
- A wheat crop, depending on the harvest index, produces about 100 lbs residue per bushel of grain (one bushel of wheat is 60 lbs).
- To maintain soil C stocks, 2.5 tons (3000-5000 lbs) per acre of residues should be left in the field every year (Huggins).
- A wheat field that produces 100 bushel yield will have 10,000 lbs of residue per acre, so about half of the residue could be conceivably baled and sold.
- Burning the residue will have different outcomes in terms of how much of the C is left in the field. Burning in the spring, when the residue is moist, will possibly leave more residue than burning in the fall, when the straw is dry.

Dr. Stuart Wuest’s Research

- Soil was analyzed in soils that had received a variety of carbon amendments for five years in a row. Twelve years later…
- Municipal biosolid produced the largest gain, followed by manure and alfalfa foliage. Straw, sucrose, and sawdust were not different than no addition.
- Soil which was growing a wheat crop or perennial grass still has much greater soil organic carbon than where the soil was fallow for the five-year period. **Wheat roots feed soil C!** The effect lasts for decades.
- Unlike surface residues, root-derived carbon is more likely to become integrated into deeper, more protected soil layers, enhancing its longevity.

Wuest, S.B. 2023. Soil carbon increase from crop roots and amendments still present twelve years later. Soil Science Society of America Journal. 87(6):1498-1502. https://doi.org/10.1002/saj2.20597.
DOI: https://doi.org/10.1002/saj2.20597

Tillage



Tillage

- Conservation tillage plays a vital role in promoting sustainable agriculture by maintaining crop residues on the soil surface, which:
  - improves water infiltration
  - reduces evaporation
  - protects against erosion caused by wind and water.
- These practices also contribute to building soil organic matter (SOM) at the soil surface, where it has marked benefits, enhancing water and nutrient retention, strengthening soil structure, and supporting diverse microbial communities.

NT and soil C

- But….. soil samples that include the top two to three feet, however, rarely show a substantial increase in carbon after switching to no-till.
- Machado and Wuest conducted a study on the variation in soil organic carbon (SOC) over time in no-till versus minimum tillage dryland wheat-fallow systems.
- The study found that the tilled treatment had an SOC equivalent to the no-till treatment.
- They concluded that no-till did not result in more soil carbon in these systems and that judicious tillage could be an option for sustainable production.

Wuest, S.B., Schillinger, W.F. and Machado, S. (2023) Variation in Soil Organic Carbon over Time in No-Till versus Minimum Tillage Dryland Wheat-fallow. Soil and Tillage Research, 229, Article ID: 105677.

Key Findings on mineral associated organic matter (MAOM). Ramirez et al.

- Legume Rotations Boost MAOM: Incorporating spring peas into wheat rotations (WW–SP) significantly increased carbon levels in the MAOM fraction compared to wheat–fallow systems.
- No-Till Enhances Carbon Sequestration: Under no-till management, the WW–SP system led to a 60% increase in MAOM carbon over nearly 60 years.
- Conventional tillage loses MAOM: The WW–SF system was susceptible to carbon losses with tillage.
- Carbon Sequestration Rates in the wheat-pea rotation:
  - Under conventional tillage: ~ 143 pounds of carbon per acre per year. Under no-till: ~ 223 pounds of carbon per acre per year.

Ramirez, P. B., et al. (2024). Legume-based cropping systems enhance mineral-associated carbon in dryland soils.

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Key Findings on mineral associated organic matter (MAOM). Ramirez et al.

- POM (particulate organic matter) is younger and more dynamic:
- Radiocarbon dating showed that POM contains relatively recent carbon, reflecting fresh plant inputs and rapid turnover. It’s sensitive to management changes and tends to fluctuate with crop residue and tillage practices.
- MAOM carbon showed older radiocarbon signatures, indicating that the carbon had been stabilized in the soil for 50 to over 100 years.

Ramirez, P. B., et al. (2024). Legume-based cropping systems enhance mineral-associated carbon in dryland soils.

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Key Findings on mineral associated organic matter (MAOM). Ramirez et al.

- Climate and Policy Implications: These findings suggest that legume-based rotations and conservation practices could help offset agricultural CO_2 emissions and support carbon credit initiatives in the Inland Pacific Northwest.

Ramirez, P. B., et al. (2024). Legume-based cropping systems enhance mineral-associated carbon in dryland soils.

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Biochar

- Pendleton Scientists investigated how wood biochar and fertilizer combinations affect soil properties and winter wheat biomass in greenhouse conditions.
- Biochar Characteristics: Used biochar with high pH and carbon content; applied at rates of 0, 10, 20, and 40 tons/acre to acidic soil (pH 4.8).
- Plant Growth Results: Wheat shoot and root growth improved at 10 tons/acre; higher rates did not enhance growth and suppressed it in unfertilized soil.
- Soil pH Impact: Biochar raised soil pH proportionally, with increases of 0.5 and 1.2 units at 10 and 40 tons/acre, respectively.
- Recommendation: Suggested biochar rates below 22.4 Mg/ha (≈10 tons/acre) for optimal wheat growth and soil improvement.

Bista, P., Ghimire, R., Machado, S., & Pritchett, L. (2019). Biochar effects on soil properties and wheat biomass vary with fertility management. *Agronomy*, 9(12), 837.

Summary

- Wheat–fallow systems deplete SOM due to low residue and frequent tillage.
- Legume rotations (like wheat–pea) boost stable carbon, especially MAOM, under no-till.
- Biochar improves SOM, soil pH, and Cn increase wheat yields in acidic soils.
- Conservation practices—no-till, residue retention—enhance SOM and soil health.
- Although WW–SF has historically helped mitigate drought risk in low-rainfall regions, it also contributes to the depletion of soil organic matter, deterioration of soil health, and poses a threat to the long-term viability of agriculture in the Pacific Northwest.

Thanks!

COLLEGE OF AGRICULTURAL SCIENCES » AGRICULTURAL EXPERIMENT STATION »

COLUMBIA BASIN AGRICULTURAL RESEARCH CENTER

Key Findings on Soil Erosion and Carbon in Pendleton

- NT and higher SOM preserve large soil pores and worm holes and soil aggregation, which aid water infiltration.
- Erosion Depletes Surface Carbon: Wind and water erosion remove the topsoil, which contains the highest concentrations of organic carbon. This loss is especially severe in conventionally tilled wheat-fallow systems.
- Tillage Intensifies Carbon Loss: Conventional tillage breaks up soil aggregates and exposes organic matter to oxidation, accelerating carbon loss and making soils more vulnerable to erosion.
- No-Till and Cover Crops Help: Long-term no-till experiments in Pendleton show that reducing soil disturbance and maintaining residue cover significantly lowers erosion rates and helps retain soil organic carbon.
- Carbon Monitoring: Scientists at Pendleton have monitored soil organic carbon across various cropping systems, confirming that practices like wheat-pea rotations and reduced tillage improve carbon retention compared to traditional wheat-fallow systems.
- Erosion-Carbon Feedback Loop: As erosion strips away carbon-rich soil, the remaining soil becomes less fertile and less able to support plant growth, which in turn reduces biomass inputs and further limits carbon recovery.
- These findings underscore the importance of conservation practices—like no-till, residue retention, and diversified rotations—in preserving soil health and carbon stocks in the Columbia Basin region.

Climate is changing

- Warming: Average temperatures in Idaho, Oregon, and Washington have risen by 2–3°F since 1900.
- Record Heat: The past decade has included some of the hottest years on record, with 2024 being globally the hottest year ever.

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Soil organic matter

- Soil organic matter (SOM), composed largely of soil organic carbon (SOC), is a vital indicator of soil health and productivity. It plays a key role in nutrient supply, pH buffering, water retention, and supporting beneficial microbial communities.
- Carbon sequestration in soil occurs when carbon from plant residues and microbial activity is retained in SOM rather than released as CO_2.
  - Maintaining or increasing SOM depends on a balance between biomass inputs and losses through microbial decomposition and erosion.
- In dryland systems like the winter wheat–summer fallow (WW–SF) rotation, low biomass production and conventional tillage accelerate SOM decline and leave soil vulnerable to erosion.
- Despite its long-term unsustainability, WW–SF remains widely used due to its reliability in conserving moisture and ensuring consistent wheat yields in variable climates. Since efforts to replace it have been largely unsuccessful, the focus must shift toward modifying the system to enhance SOC levels and improve long-term sustainability.

Biochar

- Dr. Machado launched greenhouse and field experiments to assess biochar's impact on winter wheat growth.
- Biochar Properties: Biochar had a high pH (10.6), a carbon-to-nitrogen ratio of 500:1, and was composed of 90% carbon and <2% nitrogen.
- Greenhouse Results: Applying 10 tons/acre improved wheat shoot and root growth; higher rates didn't enhance growth and suppressed it in unfertilized soil.
- Soil pH & Field Yield: Biochar raised soil pH proportionally; in field tests, 10 tons/acre increased pH by 0.2 and boosted wheat yield by 12 bushels/acre.
- Adoption Considerations: Due to high production and transport costs, biochar is more appealing to organic farmers, with limited interest in rates above 10 tons/acre.

Collins et al. (1992) study:

- Grass vs. Cropped Soils: Grass plots had the highest total carbon (TC), microbial biomass carbon (MBC), and microbe populations, outperforming all cropped treatments in soil health indicators.
- Impact of Burning and Cropping: Fall-burned plots had the lowest TC (**1.05% by weight**) and MBC, losing 53% of original TC over 60 years. Continuous wheat-pea cropping retained more carbon, recovering 23% relative to fall burn.
- Nitrogen and Carbon Losses: Cropping led to proportionally greater nitrogen loss (51%) than carbon (40%) compared to grass. N fertilizer did not affect TC or total N in wheat-fallow (WF) plots but did acidify the soil.
- Labile Carbon and Microbial Dynamics: Water-soluble carbon in grass was 0.23 g/kg—twice that of cropped soils. Labile C proportions remained unchanged across cultivated treatments, but MBC was highest in February and declined with residue removal.
- Residue and Manure Effects: Straw plus manure plots matched TC levels of continuous cropping but remained below grass. MBC increased with manure but not with N fertilizer, highlighting MBC as a sensitive indicator of soil health under different management regimes.

Collins et al. 1992. Crop Rotation and Residue Management Effects on Soil Carbon and Microbial Dynamics. Soil Sci. Soc. Am. J. 56:783-788

Long-term Experiments

- Ghimire et al. investigated the long-term effects of various management practices on soil organic carbon (SOC) in wheat-fallow systems.
- They evaluated the impact of fall burning, no burning, manure application, and pea vine incorporation on SOC and wheat yield over several decades.
- Their key findings revealed a gradual decline in SOC and soil nitrogen (N) levels in the fall burning and no burning treatments. In contrast, manure application helped maintain SOC levels.
- Wheat yields decreased over time in fall burn and no burn treatments, while initially increasing but eventually decreasing in manure and pea vine treatments. The study underscored the importance of matching organic matter and nitrogen inputs to sustain SOC, N levels, and crop yields for sustainable dryland wheat production.

Ghimire, R., Machado, S. & Bista, P. Decline in soil organic carbon and nitrogen limits yield in wheat-fallow systems. Plant Soil 422, 423–435 (2018).

Dr. Stuart Wuest's Research

- Water and Carbon Interplay: Dr. Wuest emphasized that soil water availability influences root growth and carbon cycling.
  - In dryland systems, moisture stress can limit root depth and biomass, affecting how much carbon is returned to the soil through root turnover.
- Crop Residue Management: He observed that residue from wheat and other crops plays a critical role in maintaining soil structure and organic matter.
- These findings support the idea that farming practices—especially tillage and residue management—strongly influence how wheat roots contribute to soil carbon.

Bill Schillinger’s research at WSU

- William F. Schillinger's research on soil carbon in wheat production has focused on the impact of different tillage practices and crop rotations on soil organic carbon (SOC) levels.
- One of his notable findings is that **no-till farming** can increase SOC at the surface level (0-5 cm depth) compared to conventional tillage methods.
- However, the increase in SOC is not always consistent across different soil depths and can vary based on factors such as crop rotation and residue management.

William F. Schillinger, Douglas L. Young, Ann C. Kennedy, Timothy C. Paulitz, Diverse no-till irrigated crop rotations instead of burning and plowing continuous wheat, Field Crops Research, Volume 115, Issue 1, 2010, Pages 39-49, ISSN 0378-4290, https://doi.org/10.1016/j.fcr.2009.10.001.