Digging Deeper:
Land-use Effects on Soil-water Nutrients in the Kansas Prairie Precipitation Gradient

Annalise Guthrie
Haskell Environmental Research Studies Institute
July 2021

Abstract

Over half of the habitable land in the world is used for agricultural purposes; while the impacts of agriculture on soil mechanisms are well known, the effects on holistic biogeochemical cycles are not well understood. We investigate how nutrient concentrations are influenced by agriculture across the Kansas prairie precipitation gradient. Past research focusing on biogeochemical effects of agriculture were limited to shallower soils, typically less than 30 cm in depth. This research will be informed by the analysis of soil-water nutrient concentrations of dissolved organic carbon, nitrate, phosphate, calcium, and potassium collected every two weeks using vacuum lysimeters. Lysimeters are installed at depths of 10 cm, 40 cm, and 120 cm in agriculture, restored, and native prairie sites across Kansas in areas of low, medium, and high precipitation. Results from analysis will likely convey significantly lower nutrient concentrations in restored plots intensifying with depth and lower precipitation. The results will serve as variables to model future conditions of land-use conditions while inputting interdependent variables like evapotranspiration, soil pore geometry, and microbial activity. Modeling future conditions allows for better understanding of the degree to which humans can influence soil processes and the future economy of farmers and food security.

Literature Review

Soil is sometimes referred to as the “skin of the earth” in ecological literature, alluding to the important role soil has within ecosystem processes. Soil serves as the foundation for food security, regulates water quality, and acts as a sink for greenhouse gases. Proliferation of vegetation relies on high functioning soils defined by physical, chemical, and biological properties (Karlen et al. 1997). According to the United Nations Food and Agriculture Organization, 11 million km^2 of the habitable land in the world is utilized for cultivating cropland

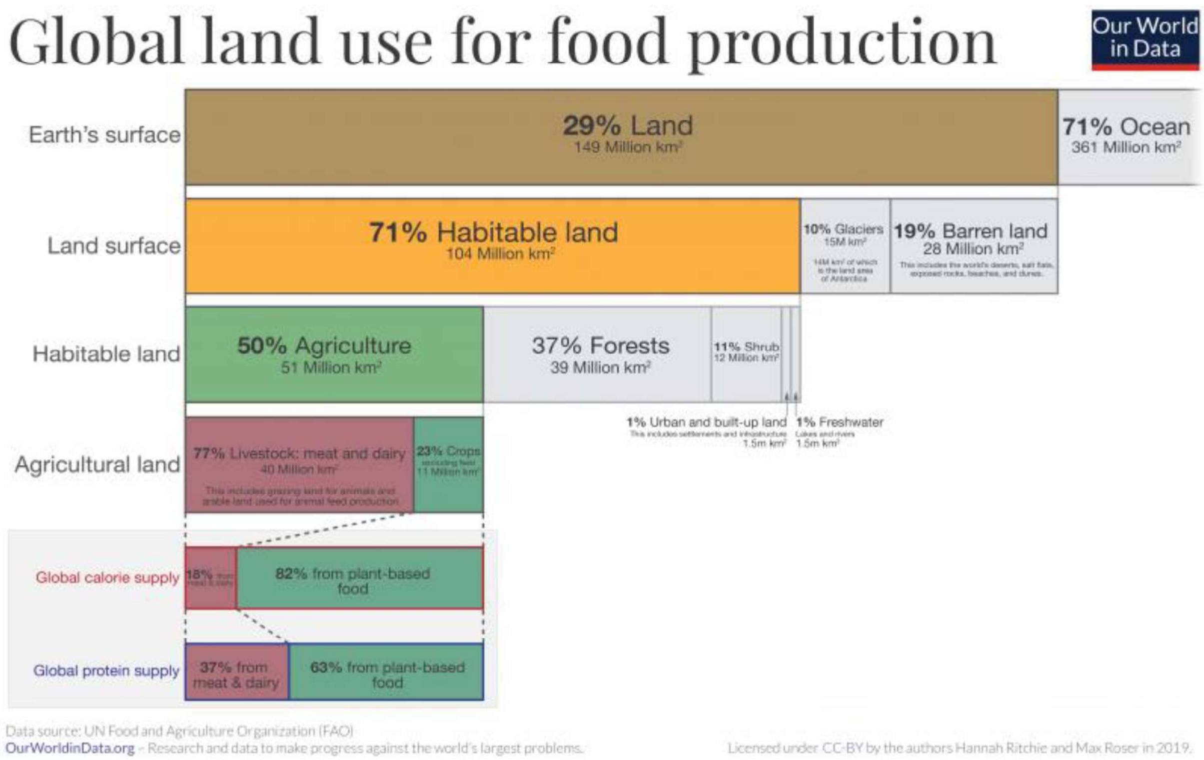


Figure 1 Percentage of land use globally and nutritional data from the UN Food and Agriculture Organization (Ritchie and Roser 2019)

and 82% of global caloric supply comes from plant based food (Figure 1) (Ritchie and Roser 2019). Agriculture is indispensable to modern day survival. However, anthropogenic, or human caused disturbances through intensive agricultural tilling are influencing soil's capacity to function causing degradation of nutrients when compared to non-tilled areas, (Zhang et al. 2015; Moges, Dagnachew, and Yimer 2013; McLauchlan 2006). Different land-uses alter the soil structure and ultimately determine what nutrients are available in the soil. Decreased nutrient availability stems from diminished soil organic matter located in the topsoil which provides a large proportion of nutrients and keeps soil fertile (Karlen et al. 1997).

The use and application of fertilizers by farmers for higher crop yields is commonplace but becomes necessary and sometimes ineffective after years of intense tillage due to decreased nutrients available in the soil. Fertilizer applications become necessary due to loss of organic matter and become ineffective when soil pores, where most nutrient exchanges occur, close from soil compaction limiting infiltration of new nutrients. Negative feedbacks between tillage practices and nutrients result in reduced microbial activity, compacted subsoils, and root elongation which are vital to fertile soils (Wander 2004; Knappe, Haferkorn, and Meissner 2002). Numerous researchers have illuminated the effects of land use on soil nutrients in the context of agricultural cropland. In 2013, Moges, Dangnachew, and Yimer investigated land-use effects on soil nutrients in farmland, grasslands, forests, and grazing lands to decreasing soil organic matter, carbon to nitrogen ratio, and percent base saturation when compared to forested and grassland areas (Moges, Dagnachew, and Yimer 2013). A long-term, 28-year study on the effects of tilling found that non-tilled soils had significantly higher carbon availability, cation exchange capacity, and up to 28% more water holding capacity than tilled soils in soil depths up to 15cm (Mahboubi, Lal, and Faussey 1993). Nutrient degradation caused by agriculture is a well-known and an obvious concern for ecologists and land managers who are often looking to implement innovative solutions to improve yields, lower costs, and increase the longevity of soil fertility. In a 2020, Yost and Hartemink reviewed four soil journals spanning 30 years and observed most of the past research on soil was limited to depths of 30cm or less. Depth limitations in previous research were most likely due to time and resources, thus, the effects of tilling on deeper soils remains elusive and lacks a broad foundation of research (Yost and Hartemink 2020).

In the midst of the Anthropocene, a time of rapid global ecosystems and climate changes caused by humans, an emerging appreciation for climate change impact research on baseline resources like soil has increased (Hermans et al. 2019; Billings et al. 2018). Soil formation and processes, typically thought to be temporally slow, now have the potential to parallel the rapidness of the Anthropocene (Billings et al. 2018). Nutrients in the soil can also vary depending on precipitation rates which are fluctuating as climate change intensifies (US EPA 2016). Precipitation infiltrates the soil, introducing new nutrients and forcing percolation of previously present nutrients deeper into the soil but can also limit nutrients when precipitation becomes more infrequent (University of Hawaii Monoa n.d.). For example, nitrogen, one of the most important nutrients for vegetation, relies on microbiota fixation and precipitation simultaneously; water availability within soil pores is tied to nitrogen mineralization (the ability to make itself available to plants). Less precipitation decreases microbial activities and therefore, less nitrogen is available for plants to use for growth (Cregger et al. 2014).

While the effects of agriculture and precipitation are independently well-known, the coupling of agriculture and precipitation on deep soils (greater than 30cm) has not been well studied. This study leverages the driving forces of soil fertility, land-use and precipitation, to determine the impacts on soil-water nutrients in deep soils. Soil-water is the saturation found in the soil pores and contains the nutrients available for root uptake and soil formation processes.

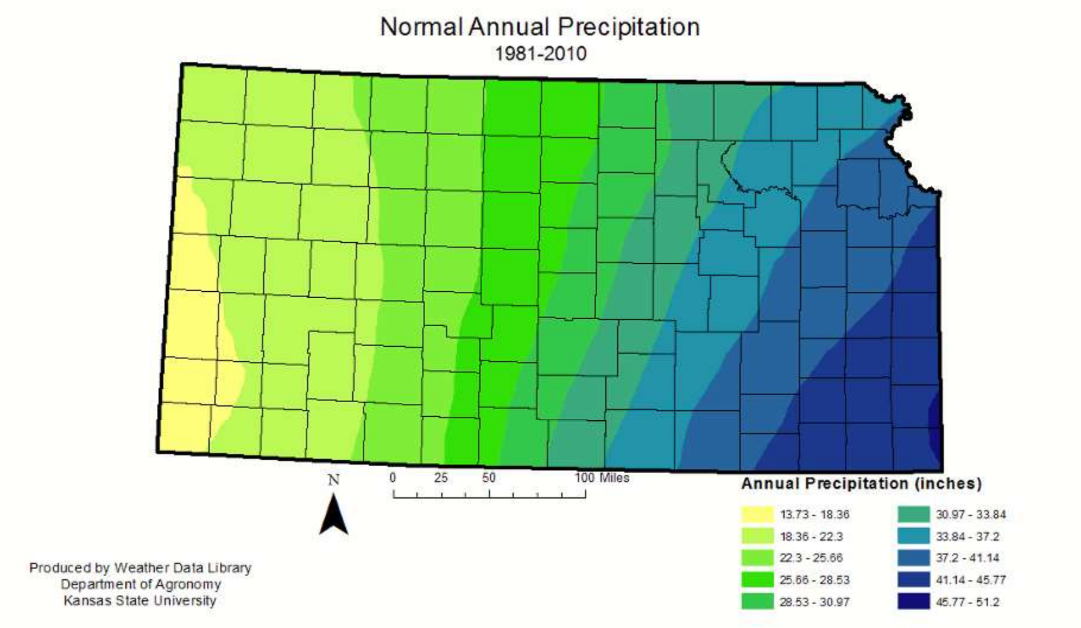


Figure 2 Precipitation gradient of Kansas between 1981-2010 which ranges from 400mm/yr in west to 1000mm/yr in the east (Kansas Office of the State Climatologist n.d.)

Taking advantage of the distinct Kansas precipitation gradient, which ranges from 400mm/year in the west to 1000mm/yr in the east (Kansas Office of the State Climatologist n.d.) (Figure 2), we investigate how nutrients fluctuate with land-use, precipitation, and depth in a prairie ecosystem. Study sites within Kansas are categorized into agricultural, restored grasslands (from agriculture), and native grasslands. Agriculture is defined as sites with crops currently present and where tilling practices have occurred, restored grasslands are sites have been actively or passively replenished with native or non-native vegetation after a period of no agriculture use, and native grasslands are sites without any historical agriculture practices. Due to the unique precipitation gradient and native prairie sites, Kansas allows us to compare three land-use types and precipitation dynamics as driving forces for variations in soil-water nutrient concentrations. The quantification and correlation of soil conditions and climate/land-use interactions is valuable to better understand the complex mechanisms which drive resilient soils.

Research Design

The objectives of this study are twofold. The first aim is to determine soil-water nutrient concentrations which are important for vegetation productivity and soil formation including: dissolved organic carbon, nitrate, phosphate, ammonium, potassium, calcium, sulfur, and magnesium for native, restored, and agriculture land-use plots. The second aim is model current and future projections of vertical soil-water nutrient concentration profiles from the data collected in the first aim and pair the results with a variety of interdependent factors to examine land-use effects and biogeochemical inputs (e.g. evapotranspiration, temperature, soil pore geometry, microbial activity, and groundwater flow). Site selection is key to conclusions we can draw about the effects on biogeochemical cycles from the scope of this study. Three locations in

Kansas are being investigated: Hays, KS (low precipitation), Konza Prairie in Manhattan, KS (medium precipitation), and Welda, KS/Ottawa, KS (high precipitation) (Figure 3).

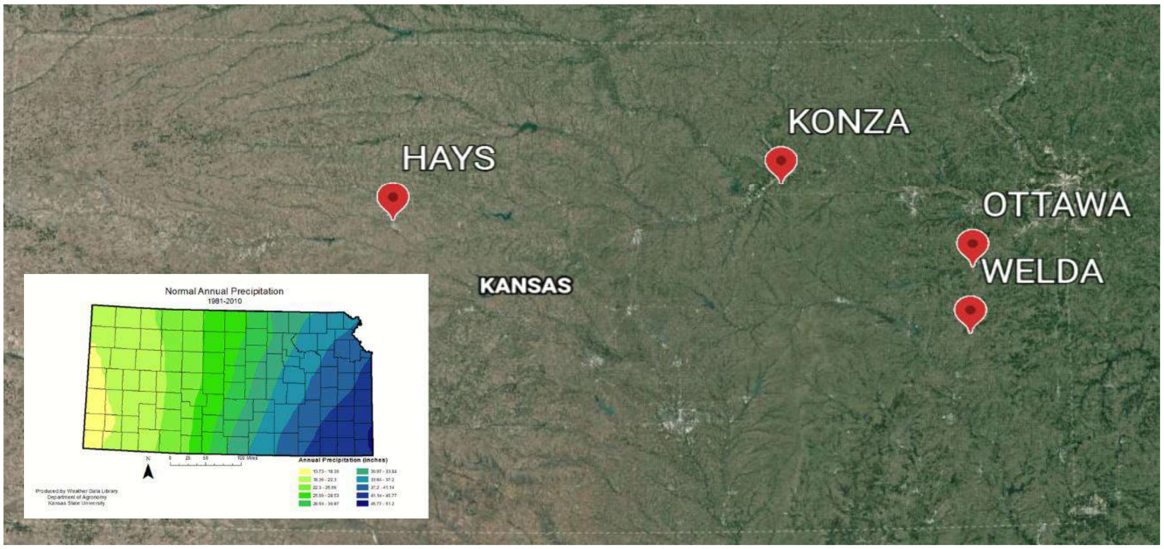


Figure 3 Map of collection sites in Kansas with an inset of the precipitation gradient. Hays, KS-low precipitation, Konza-medium precipitation, and Welda/Ottawa-high precipitation

To meet the first aim each location site three different land-use types are studied: native, restored, and agriculture (Figure 4). Each site contains lysimeters (Figure 5) installed at depths of 10cm, 40cm, and 120cm or until the point of depth refusal for a total of 27 lysimeters. Lysimeters were installed at a 45-degree angle from the surface of each the pit to allow

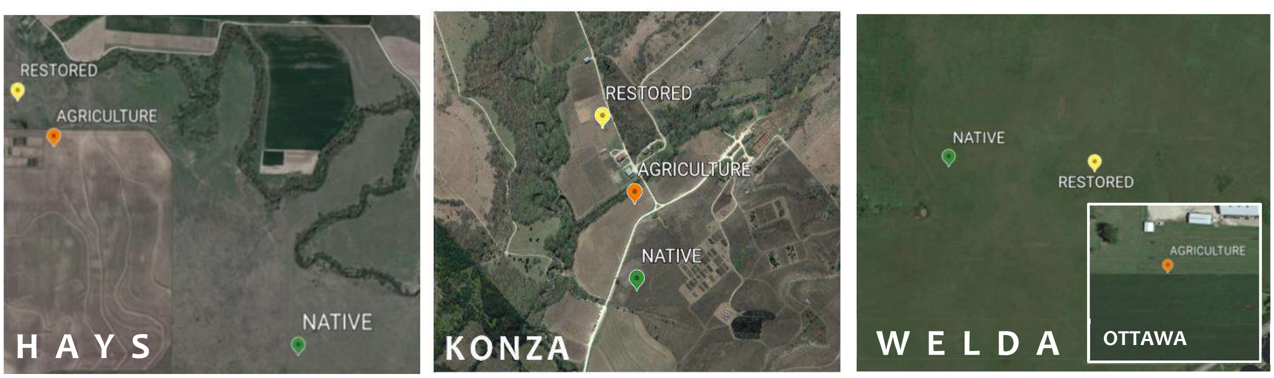
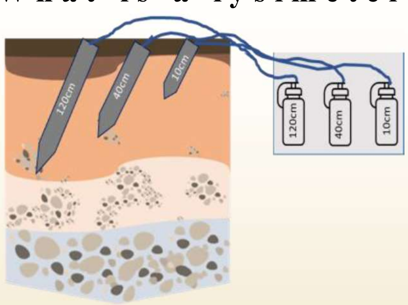


Figure 4 Map of land use sites in respective location: yellow-restored, orange-agriculture, green-native

effective extraction of soil-water. Each lysimeter will be connected by hydrophilic tubing to a collection jar which is housed in a separate weatherproof box. Samples are collected on a biweekly basis. Generally, the aim is to collect samples from the lysimeters on a bi-weekly schedule. Three situations can occur when bi-weekly sampling is not applicable: no amount of rainfall has occurred within the two-week sampling period, snowfall has occurred and not melted or temperatures are below freezing, an extreme precipitation event has occurred warranting additionally sampling. Additionally, if a rainfall event occurs on the day before or the day of the scheduled collection, a 48-hour window should pass before collection to allow for adequate percolation.

What is a lysimeter?



- **A lysimeter is a probe buried in the ground and collects water found in soil pores**
- **The lysimeter is buried underneath the soil at a 45-degree angle with tubing connected to collection jars**
- **Collection jars are housed in a separate box and negative pressure is applied to pull water up through the tubing**
- **Using lysimeters as a collection method allows for undisturbed soil to be analyzed**

Figure 4 Schematic of site installation and description of lysimeter

The pH of samples is measured immediately in the laboratory to avoid carbon sequestration which could alter accurate measurements. The remaining sample is frozen immediately at -4°C for later analysis of nutrients. While we cannot calculate the volume of water nutrients are being collected from, we can use the amount of precipitation as a concentration of the soil-water nutrients. Using analysis of variance to assess the data I will compare land-use type, with depth, and across the different precipitation levels. Following, I will conduct post-hoc tests if statistical significance is found ($p<0.05$) and will employ multivariate statistical methods to determine what degree of forcing each factor has on nutrient concentrations. Based on past studies, results will likely show higher nutrient concentrations in the native and cropland which is to be expected. However, what will be most interesting are the nutrient concentrations found in restored areas. This will give us insight into the resiliency of areas that were once subjected to agricultural conditions.

Our second aim serves as the future direction for this study. We will use the distribution spatially and temporally of collected nutrient concentrations to model future conditions of the sites while inputting interdependent variables like evapotranspiration, soil pore geometry, and microbial activity all of which have been previously collected by other researchers. Modeling future conditions allows us to better understand just how much humans have the ability to influence soil processes and unintentionally the future economy of farmers and food security. Independent factors will be compared against dependent factors. For example, I can utilize depth (independent factor) and nutrient concentration (dependent factor) to determine the distribution or correlation of the relationship. Finally, I will run tests multiple times with every combination of independent and dependent factors. Further research and collaboration are needed to determine the type of modeling best suited for the objective of this aim. Modeling and analysis will likely reveal the variables that have the most influence on nutrient concentration. Modeling will allow future predictions of land-use and precipitation conditions on nutrient concentrations and to make inferences about how soil formation and vegetation will change over time.

Academic Preparation

I have participated in a multitude of undergraduate experiences through private, governmental, and tribal organizations which have prepared with the skills required to successfully conduct research. During my undergraduate, I was an Educational Partnership Program National Oceanic and Atmospheric Scholar for two years, designing and completing two formal research projects around ocean acidification and outreach. I also participated in the University of Kansas Post-baccalaureate Research Education Program where I was able to bolster my skills in R programming to explore agricultural effects on deep soil structure properties in a large NRCS data set with over 25 million datapoints. Most recently, I completed research with the Haskell Environmental Research Institute which focused on writing intensive workshops, data carpentry, and best practices for integrating traditional ecological knowledge into academic research. All of my experiences have solidified my interests in conducting research around climate change and ecosystem processes, biogeochemistry, education and outreach, and science communication.

For this research I will be advised by Dr. Sharon Billings, a biogeochemist, at the University of Kansas (KU). The Billings' Lab explores grassland biogeochemical cycling of nutrients and anthropogenic disturbance regimes. We will have unlimited access to the three sites in Kansas which have numerous data sets established relating to the soil analytics of pore geometry, rooting abundances, and soil organic matter content. This allows for potential expansion of how soil is influenced by climate by using soil structure data to determine other relationships that may not be evident from lysimeter data.

Conclusion

The linking of anthropogenic disturbances, precipitation, and deeper soil profile relationships is very timely and compelling to understanding rapid global ecosystem changes which are still to be realized in the new age of the Anthropocene. Using lysimeters to analyze how nutrient concentrations are being influenced by agriculture coupled with precipitation will reveal deep soil responses from which we can make assumptions about soil's resiliency to anthropogenic disturbances. Comparing the restored plots to native and agricultural plots can contribute evidence toward the degree to which soil-water nutrients are changing. Leveraging the distribution of nutrient concentration results spatially and temporally of collected nutrient concentrations we will be able to model future conditions. The results from this research will foster a better understanding of how nutrient concentrations beyond 30cm depths in the soil are governed by precipitation factors and agriculture and can inform future agricultural decisions, water quality issues, and food security concerns. Additionally, the linking of anthropogenic climate change and deeper soil profile relationships is very timely and compelling to understanding rapid global ecosystem changes.

I plan to share my research findings with the scientific community through a variety of platforms and plan to promote my research in a way that is easy for the public to understand. Often the public lacks the knowledge about the effects of anthropogenic disturbances. Framing my research in a way that can improve adaptation or mitigation strategies around anthropogenic disturbance consequences is a priority for disseminating this research. Additionally, I will be conducting research near my undergraduate institution Haskell Indian Nations University (HINU). HINU is a minority serving institution for students from federally recognized tribes. Many of the students come from areas that suffer from regions suffering from food security and compromised water quality. I plan to remain an active and visible mentor to my fellow Indigenous scholars to encourage knowledge about climate change issues and to increase minority students to participate in STEM academics.

References

"Billings et al. - 2018 - Loss of Deep Roots Limits Biogenic Agents of Soil .Pdf." n.d. Accessed June 16, 2021. https://kuscholarworks.ku.edu/bitstream/handle/1808/29767/Loss%20of%20Deep%20roots.pdf?sequence=1&isAllowed=y.

Billings, Sharon A., Daniel Hirmas, Pamela L. Sullivan, Christoph A. Lehmeier, Samik Bagchi, Kyungjin Min, Zachary Brecheisen, et al. 2018. "Loss of Deep Roots Limits Biogenic Agents of Soil Development That Are Only Partially Restored by Decades of Forest

Regeneration." Edited by Oliver Chadwick. *Elementa: Science of the Anthropocene* 6 (January): 34. https://doi.org/10.1525/elementa.287.

Cregger, Melissa A., Nate G. McDowell, Robert E. Pangle, William T. Pockman, and Aimée T. Classen. 2014. "The Impact of Precipitation Change on Nitrogen Cycling in a Semi-Arid Ecosystem." *Functional Ecology* 28 (6): 1534–44. https://doi.org/10.1111/1365-2435.12282.

"Frequent Tillage and Its Impact on Soil Quality | Integrated Crop Management." n.d. Accessed July 28, 2021. https://crops.extension.iastate.edu/encyclopedia/frequent-tillage-and-its-impact-soil-quality.

Hermans, Kathleen, Esteban Jobbagy, Werner Kurz, Diqiang Li, Denis Jean Sonwa, Lindsay Stringer, Joris Eekhout, and Richard Houghton. 2019. "1 Chapter 4: Land Degradation," 186.

"Kansas Office of the State Climatologist · Kansas Climate." n.d. Accessed July 30, 2021. https://climate.k-state.edu/basics/.

Karlen, D. L., M. J. Mausbach, J. W. Doran, R. G. Cline, R. F. Harris, and G. E. Schuman. 1997. "Soil Quality: A Concept, Definition, and Framework for Evaluation (A Guest Editorial)." *Soil Science Society of America Journal* 61 (1): 4–10. https://doi.org/10.2136/sssaj1997.03615995006100010001x.

Knappe, Siegfried, Ulrike Haferkorn, and Ralph Meissner. 2002. "Influence of Different Agricultural Management Systems on Nitrogen Leaching: Results of Lysimeter Studies." *Journal of Plant Nutrition and Soil Science* 165 (1): 73–77. https://doi.org/10.1002/1522-2624(200202)165:1<73::AID-JPLN73>3.0.CO;2-O.

Li, Chenhua, Kai Yan, Lisong Tang, Zhongjun Jia, and Yan Li. 2014. "Change in Deep Soil Microbial Communities Due to Long-Term Fertilization." *Soil Biology and Biochemistry* 75 (August): 264–72. https://doi.org/10.1016/j.soilbio.2014.04.023.

Mahboubi, A. A., R. Lal, and N. R. Faussey. 1993. "Twenty-Eight Years of Tillage Effects on Two Soils in Ohio." *Soil Science Society of America Journal* 57 (2): 506–12. https://doi.org/10.2136/sssaj1993.03615995005700020034x.

McLauchlan, Kendra. 2006. "The Nature and Longevity of Agricultural Impacts on Soil Carbon and Nutrients: A Review." *Ecosystems* 9 (8): 1364–82. https://doi.org/10.1007/s10021-005-0135-1.

Moges, Awdenegest, Melku Dagnachew, and Fantaw Yimer. 2013. "Land Use Effects on Soil Quality Indicators: A Case Study of Abo-Wonsho Southern Ethiopia." *Applied and Environmental Soil Science* 2013 (June): e784989. https://doi.org/10.1155/2013/784989.

Ritchie, Hannah, and Max Roser. 2019. "Land Use." *Our World in Data*, November. https://ourworldindata.org/land-use.

University of Hawaii Monoa. n.d. "Soil Management." Accessed July 30, 2021. https://www.ctahr.hawaii.edu/mauisoil/a_factor_form.aspx#biota.

US EPA, OAR. 2016. "Climate Change Indicators: Heavy Precipitation." Reports and Assessments. June 27, 2016. https://www.epa.gov/climate-indicators/climate-change-indicators-heavy-precipitation.

Wander, Michelle. 2004. "Soil Organic Matter Fractions and Their Relevance to Soil Function." In *Soil Organic Matter in Sustainable Agriculture*, edited by Fred Magdoff and Ray Weil. Vol. 20042043. Advances in Agroecology. CRC Press. https://doi.org/10.1201/9780203496374.ch3.

Yost, Jenifer L., and Alfred E. Hartemink. 2020. “How Deep Is the Soil Studied – an Analysis of Four Soil Science Journals.” *Plant and Soil* 452 (1): 5–18. https://doi.org/10.1007/s11104-020-04550-z.

Zhang, Kerong, Haishan Dang, Quanfa Zhang, and Xiaoli Cheng. 2015. “Soil Carbon Dynamics Following Land-Use Change Varied with Temperature and Precipitation Gradients: Evidence from Stable Isotopes.” *Global Change Biology* 21 (7): 2762–72. https://doi.org/10.1111/gcb.12886.