

2024

A Seasonal Decomposition Comparison between Forest and Turf Habitats: Implications for Climate Change

Amanda Shirmer
DePaul University, ashirmer@depaul.edu

Follow this and additional works at: <https://via.library.depaul.edu/depaul-disc>



Part of the [Climate Commons](#), [Forest Biology Commons](#), [Natural Resources Management and Policy Commons](#), [Other Environmental Sciences Commons](#), and the [Soil Science Commons](#)

Recommended Citation

Shirmer, Amanda (2024) "A Seasonal Decomposition Comparison between Forest and Turf Habitats: Implications for Climate Change," *DePaul Discoveries*: Volume 13, Article 12.
Available at: <https://via.library.depaul.edu/depaul-disc/vol13/iss1/12>

This Article is brought to you for free and open access by the College of Science and Health at Digital Commons@DePaul. It has been accepted for inclusion in DePaul Discoveries by an authorized editor of Digital Commons@DePaul. For more information, please contact digitalservices@depaul.edu.

A Seasonal Decomposition Comparison between Forest and Turf Habitats: Implications for Climate Change

Acknowledgements

A special thank you to Dr. Christie Klimas for all her guidance, support, and patience on this project. I would also like to thank Dr. Liam Heneghan and Dr. James Montgomery for their continued advice throughout the process.

A Seasonal Decomposition Comparison Between Forest and Turf Habitats: Implications for Climate Change

Amanda Shirmer*

Department of Environmental Science and Studies

Christie Klimas, PhD; Faculty Advisor

Department of Environmental Science and Studies

ABSTRACT Decomposition is an essential ecosystem service in which microorganisms breakdown organic matter. This process improves soil health and acts as a vital step in global carbon cycles. In this study, we examined decomposition rates and associated soil properties in turf and forest habitats across summer and fall seasons in order to determine how land management practices and climate change may be altering local decomposition regimes. Our study determined that there was a statistically significant difference between decomposition rates in turf and forest ecosystems ($P=0.003$) and a significant difference in decomposition rate across season ($P<0.05$). These findings add to results supporting the temperature sensitive nature of decomposition. This may have potential positive feedback loop implications for global climate change.

INTRODUCTION

Decomposition is a vital phase in the cycling of nutrients in which organic matter is broken into simpler compounds via microorganisms. This breakdown is responsible for supplying essential plant nutrients, such as nitrogen and phosphorus. Humus, the result of organic matter decomposition, is also an essential component of healthy soils: improving texture, water holding potential, and aeration (Ontl & Schulte, 2012). Most importantly, decomposition facilitates the balance between carbon sequestration into the soil mineral—controlling soil functions, and the release of CO_2 into the atmosphere, thus regulating climate.

Soils contain approximately 3.1 times more carbon than the atmosphere (Oelkers & Cole, 2008). This poses potential for global soils to act as either a carbon source or sink as anthropogenic changes continue to alter soil ecology. Decomposition rates are one of the many patterns that must be examined to predict how soils will respond to these changes. Forest preserves and green spaces located near urban centers experience unique challenges that may influence the rate at which decomposition occurs. Often, managed spaces host a variety of vegetation types: turf grasses, native deciduous plants, or invasives such as Common Buckthorn, *Rhamnus cathartica*, which is known to increase decomposition rates in the Chicagoland area

* ashirmer@depaul.edu

Research Completed in Winter 2024

(Heneghan et al., 2002). Therefore, as soils evolve directly in response to the organisms that inhabit them, vegetation impacts the consumption patterns of microorganisms (McCary et al., 2016)

and furthermore, the composition of the soil itself (Larkin et al., 2014). Other management practices can influence a soil's ability to cycle nutrients. The removal of plant biomass, specifically common within turf grass areas, reduces the amount of organic matter available for decomposition (Ferlauto et al., 2024). The presence of nitrogen fertilizers commonly used in turf grasses slow decomposition rates by inhibiting microbial enzymes responsible for the breakdown of lignin (Jandl et al., 2006). Climate change is yet another factor that must be addressed when analyzing changes to decomposition regimes. This is especially important in the Midwest where droughts and other erratic climate events are increasingly frequent. As the world warms, both primary productivity and decomposition rates are predicted to increase (Jandl et al., 2006). The degree to which regions will be affected is still up for debate. However, experimental warming studies yielded a 20% increase in soil respiration rates across globally distributed sites suggesting that warming significantly increases microbial activity (Rustad et al., 2001). This may be especially important in settings, such as Chicago, where the urban heat island effect takes place.

The timeframe of this study seeks to determine how changing climate patterns may impact decomposition rates, with the summer testing period taking place during one of the wettest Julys on record after one of Illinois' driest springs (Ford, 2023). This work will add to the literature on multifaceted decomposition shifts. In conjunction with other work, it may help to document whether the decomposition window is shifting in time as climate change progresses.

We hypothesize that decomposition rates will be higher in the summer due to increased precipitation and warmer temperatures. We believe this will be especially pronounced within turf habitats due to a lack of vegetative coverage to provide microhabitat stability. The current study tests this by comparing decomposition rates, and soil properties, to determine patterns that may be influencing decomposition regimes.

METHODS

Field Methods

Forest preserves across the Chicagoland area were selected due to their variation in habitat type between managed deciduous forests and turf grass fields. To compare differences in decomposition rate and soil quality, testing was conducted at three randomly selected sites within the forested areas and at three randomly selected sites within the turf grass sections. This model was replicated during summer, beginning in July, and then again in September for comparison between seasons. At each field site, a minidisk infiltrometer was used to determine infiltration rates according to the manufacturers specifications (Decagon, 2012). Soil samples were taken at a depth of two to three inches, within the A horizon. Soils were then dried at 105°C for 24 hours before being ground and sieved to a uniform size. Soil analysis was conducted on soils collected at the beginning of each season. These results were used in conjunction with weekly cotton strip retrievals to assess decomposition over time.

Laboratory Methods

To determine pH, 30mL of deionized water was combined with 30.0g oven dried soil. Samples were then placed on a shaker for 15 minutes to hydrate. A digital pH meter was then used to measure pH levels for each sample. To analyze organic matter content within the soil, the loss on ignition (LOI) technique was used (De Vos et al., 2005). Oven dried crucibles were weighed before adding 5.0g dried and sieved soil. Each crucible was placed into the muffle furnace and slowly heated in increments of 25°C to 375°C. After reaching 375°C the samples were heated for 24 hours, before being cooled and weighed.

Plant Available Phosphorus was then determined using the USEPA1 PhosVer 3 (Ascorbic Acid) Method2 (Hach). Plastic cups were used to combine 2.0g oven dried soil with 20mL Mehlich-III extractant. The cups were then placed on the shaker at medium speed for 15 minutes. The filtrate was then collected. The filtrate was then diluted 10X with deionized water and placed into

spectrophotometer sample cells. A PhosVer 3 Phosphate Powder Pillow was added to each cell and shaken for 30 seconds. After two minutes, the PO_4 concentration was read using the spectrophotometer. For samples that exceeded the reading range, dilutions were made of either 100 times or 1000 times using the original filtrate and the concentration was taken again.

To determine microbial respiration via the Solvita CO_2 -Burst method, soils collected within 24-hours were gently dried at 35°C and lightly sieved. Soil was then wetted dropwise with water. Each sample was then placed into jars with an indicator paddle. Jars were then closed and left at room temperature for 24 hours before results were collected using the Solvita Digital Color Reader.

Cotton Strip Assay

A cotton strip assay was utilized as a method for assessing decomposition (Nachimuthu et al., 2007). Cotton strips were installed at a depth of approximately two to three inches within the A horizon. Strips were each removed at intervals of one, two, three, and five weeks. Removed strips were then cleaned of any remaining soil and air dried to prevent further microbial activity. Each strip then underwent tensile strength testing using a Test Resources P Series Tensimeter calibrated to each strip's dimensions (Figure 1). The maximum load was recorded for each strip. Strips that were more decomposed had lower max load values (in newtons). For strips that were under usable length, specifically for the fall season, epoxy resin was used to attach an additional fresh cotton strip to increase length. The resin was allowed to cure for 24 hours before continuing testing. We tested for differences in maximum load by habitat and season.



Figure 1. A fresh strip, left, tearing at one point versus a strip left in soil for five weeks, right, showing multiple point of weakness due to colonies of microbial decomposition.

Data Analysis

Data were compiled initially with Excel. Box plots, averages, and standard deviations were also calculated in Excel. To test for differences in maximum load and microbial respiration, we tested each of these variables for normality. We used a generalized linear model, with the appropriate distribution, to test for differences by habitat and season. All statistical analyses were done using R 4.3.1. Packages used included *fitdistrplus* (Delignette-Muller, 2015), *logspline* (Charles et al., 1997), *MASS* (Venables & Ripley, 2002), and *GlmTMB* (Brooks et al., 2017).

RESULTS

Soil Properties- pH

Turf grass habitats had an average pH (Figure 2) of $7.18 (\pm 0.54)$ and $6.18 (\pm 0.75)$ in the summer and fall, respectively. The pH for forest habitats (Figure 3) was $5.81 (\pm 0.51)$ and $6.22 (\pm 0.67)$ in the summer and fall, respectively.

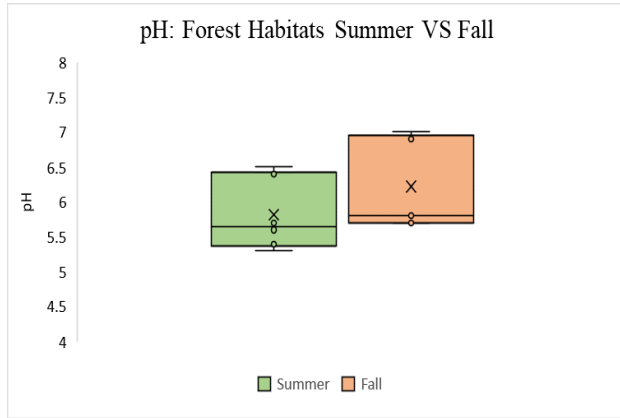


Figure 2. Box plots comparing turf habitat pH by season.

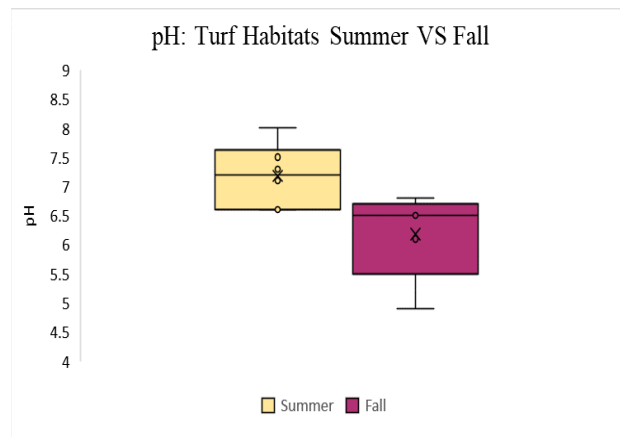


Figure 3. Box plots comparing forest habitat pH by season.

Microbial Respiration

Microbial respiration was normally distributed, so we used a Gaussian distribution within the generalized linear model. Microbial respiration rates were statistically significant between both habitat and seasonality (Table 1). Microbial respiration was significantly higher in the fall ($P < 0.05$) and the forest ($P = 0.0141$). Turf habitat (Figure 4) had a summer measurement of 22.25 (± 10.91) ppm CO₂ and a fall measurement of 52.36 (± 5.05) ppm CO₂. The forest habitat (Figure 5) had a summer measurement of 57.06 (± 9.77) ppm CO₂ and a fall measurement of 63.18 (± 3.93) ppm CO₂.

Although results were statistically significant from each other, there is little biologically relevant difference. Each of these respiration results, except for summer turf, fall within the category of medium biological activity as described by the manufacturer (Solvita, 2019).

Summer turf exhibited respiration within the low biological activity category. So, while statistically significant, these results do not deviate from the expected decomposition rates.

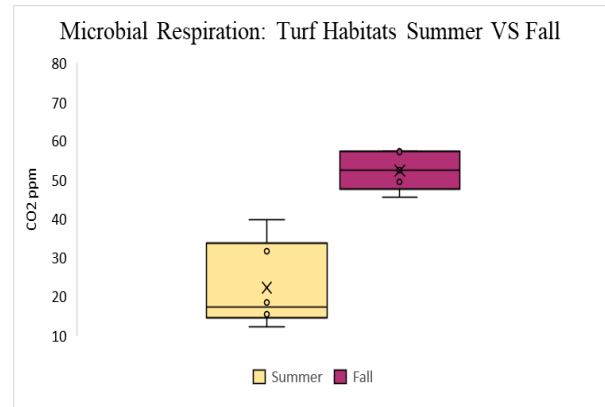


Figure 4. Box plots of microbial respiration within the turf habitats in Summer versus Fall.

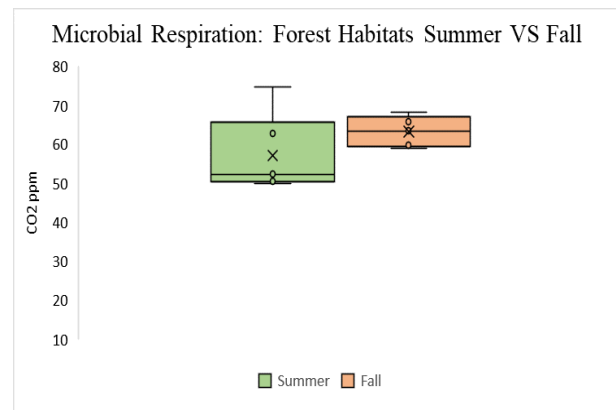


Figure 5. Box plots of microbial respiration within the forest habitats in Summer versus Fall.

	Estimate	std. error	z value	Pr (> z)
Intercept	491.527	27.079	18.152	< 2e-16
Week	-81.411	8.068	-10.09	< 2e-16
Habitat	-47.744	19.455	-2.454	0.0141
Season	-83.666	19.526	-4.285	1.83E-05

Table 1. Microbial respiration gaussian model results.

Phosphate

Phosphate concentrations varied widely across testing sites. Turf grass habitats (Figure 6) showed an average of 704.70 (± 337.14) mg/kg in the summer and 3453.62 (± 3948.03) mg/kg in the

fall. Forest concentrations (Figure 7) stood at 462.51 (± 175.40) mg/kg in the summer and 2543.59 (± 3735.92) mg/kg in the fall. Due to high variation in Phosphate levels, it is unclear whether we can determine if phosphate is having an effect on decomposition rate. Unique site management may vary highly from forest preserve to forest preserve, therefore, a higher number of replicates would be necessary to accurately determine phosphate trends.

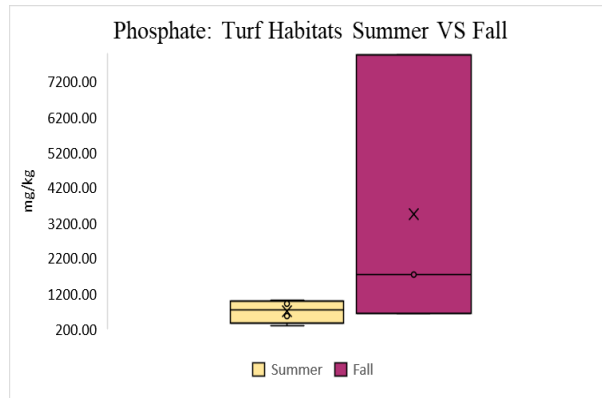


Figure 6. Box Plots comparing Phosphate concentration within the turf habitat across seasons.

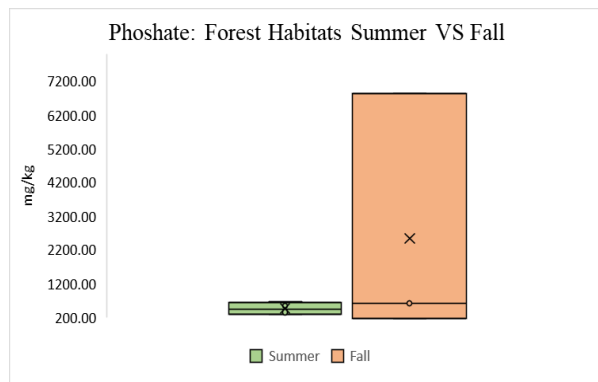


Figure 7. Box Plots of phosphate concentrations within the forest habitats from summer to fall.

Soil Organic Matter

During the summer testing period, the turf areas (Figure 8) had an average of 34.91 (± 24.39) % carbon. During the fall, turf areas tested at 36.03 (± 25.63) % carbon. Similarly, the forest habitat (Figure 9) had an average of 39.58 (± 10.19) % carbon in the summer and 41.90 (± 21.37) % carbon in the fall.

Again, high variability in the data prevent us from drawing consistent conclusions about the relationship between decomposition rate and soil organic matter.

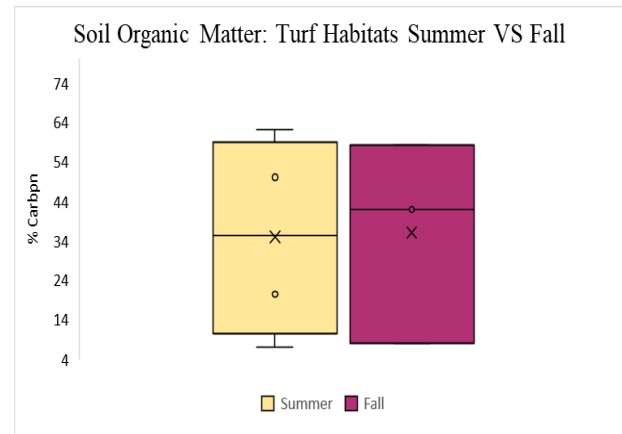


Figure 8. Box plots comparing percentage of organic matter (% carbon) in turf habitats from summer to fall.

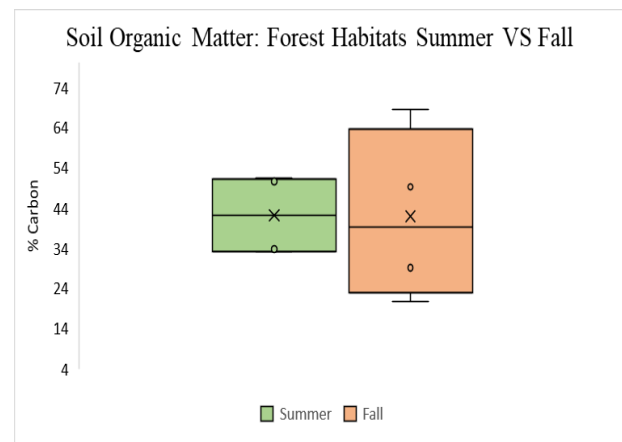


Figure 9. Box plots comparing percentage of organic matter (%carbon) in forest habitats between summer and fall.

Decomposition Rates

Maximum load was modeled by a gamma distribution within the generalized linear model. Decomposition rates were statistically significant between season ($p < 0.05$) and habitat type ($p = 0.003$) (Table 2). Decomposition was most rapid in turf habitats during the summer, followed by forest during summer, and forest during fall. The slowest decomposition occurred in turf habitats during the fall season (see Appendix). This is consistent with similar research focusing on the temperature dependency of microbial

activity in soils and temperature (Rustad et al., 2001) and patterns of ecosystem microclimate (Li et al., 2015).

	Estimate	Std. Error	Z Value	Pr (> z)
Intercept	7.03615	0.17044	41.28	< 2e-16
week	-0.52334	0.04655	-11.24	< 2e-16
habitat	-0.3234	0.10999	-2.94	0.00328
season	-0.68703	0.11188	-6.14	8.23E-10

Table 2. Generalized linear model results for loss of tensile strength.

DISCUSSION

Our results revealed a significant difference between decomposition rates across turf and forest habitats and a significant difference between summer and fall periods. These findings suggest differences in decomposition rate by land usage and potentially temperature. Although decomposition rates are believed to have region-specific limiting factors, both in-situ (Tumbore et al., 1996) and ex-situ (Pataki et al., 2003) experiments have come to similar conclusions: that globally, decomposition rates will increase as temperature increases (Davidson & Janssens, 2006).

In our study, there was a clear increase in decomposition rate during the summer months when temperatures were high. In addition, seasonal changes in decomposition reflect the vulnerability of each habitat to temperature changes. During the summer months, turf grass soils experience much hotter temperatures as coverage from vegetation is limited. Lack of vegetation also means that, in the fall, turf habitats are more susceptible to the cold due to evapotranspiration and albedo effects (Li et al., 2015). These trends were mirrored in our decomposition data with the most rapid decomposition occurring in turf during the summer, and the slowest decomposition occurring in turf during the fall.

However, past research suggests that forests may be even more susceptible to temperature changes than other habitat types. Rustad et al. 2001 utilized the Network of Experimental Warming Experiments (NEWS) to conduct soil respiration

analysis at 32 global sites including high tundra, low tundra, forest, and grasslands. Although all sites showed a positive relationship between warming and microbial respiration, forest respiration showed increased response even when controlled for other geographic, climatic, or environmental variables (Rustad et al., 2001).

It is possible that variation in our data may be explained by differences in methodology between summer and fall testing cycles. Cotton strip size and ripping methodology (use of epoxy) may have contributed to the appearance of reduced decomposition during the fall months. However, visual assessments of strip quality appeared consistent with lower degrees of decomposition in the fall. Further research is suggested to confirm this relationship. Changes to precipitation regimes brought upon by climate change may similarly alter decomposition, due to alterations in activity on a microbial level (Butenschoen et al., 2011). Above all, our data in conjunction with past research, suggest potential for a positive feedback loop associated with increased decomposition (Pataki et al., 2003). Increased temperatures brought upon by anthropogenic climate change may cause global soils to act as a source, rather than sink for carbon. One study found that experimental warming of 0.3-6.0°C significantly increased soil respiration rates by 20% (Rustad et al., 2001). In conjunction with research conducted by Lal et al. 1995, Rustad 2001 determined that “a 20% increase in soil respiration would correspond to an increased release of ~14–20 Pg C year⁻¹. This is 2–3 times the estimated ~7 Pg C year⁻¹ of CO₂ released to the atmosphere via combined fossil fuel combustion and land-use changes” (Lal et al., 1995). This increase would provide a basis for a strong positive feedback loop associated with soil decomposition and greenhouse gas emissions, dramatically accelerating climate change. However, there is much debate about whether increased carbon output due to rapid decomposition would exceed carbon inputs due to plant sequestration (Davidson & Janssens, 2006). Additional research aimed at determining potential for carbon sequestration in urban turf grasses, similar to the habitats looked at within this study, concluded that urban turf grass systems may function as a sink for soil carbon

sequestration (Qian et al., 2010) rather than a source.

Alterations to decomposition rate are multifaceted and dependent on much more than climate alone; therefore, it is hard to determine how diverse soil types will respond to climate change. Despite these challenges, it is important to continue examining soil-climate relationships due to the potential for carbon emissions from soil carbon stocks. This is especially important for carbon rich soils such as peatlands, permafrost, or wetlands, which hold a large fraction of the global carbon pool and are more susceptible to climate change due to their location (Davidson & Janssens, 2006).

Although it may be hard to determine how climate change will alter decomposition regimes, there is adequate evidence that we can influence its opposing cycle: carbon sequestration.

One of the key services of vegetation is its ability to sequester carbon from the atmosphere (Chen et al., 2020). Land management practices can contribute to increasing a soil's ability to sequester carbon from the atmosphere for storage within the soil mineral and within vegetative biomass (Post et al., 2004). While the influx of carbon into soils due to improved land management practices is quite small, estimated at 0.44 to 0.88 Pg carbon per year (Cole et al., 1997), it is possible that these practices may increase resistance to climate change pressures on soil ecology. Many of these practices such as no-till agriculture, growth of perennial vegetation, and alterations to liming, irrigation, and fertilizer usage increase soil sequestration while providing additional

ecosystem services such as reduced erosion, soil pH buffering, and increased organic matter thus offering many additional co-benefits (Post et al., 2004). One of the most impactful ways to increase carbon sequestration is through the conversion of agricultural land back to native states (Rodrigues et al., 2023). Although this may seem to conflict with agricultural goals, the adoption of climate-resilient agricultural methods on remaining cropland such as intercropping, cover cropping, and crop rotation may offer increased productivity alongside increased carbon sequestration (Rodrigues et al., 2023).

Overall, the results of this study confirm the notion that climate-soil interactions show potential for a positive feedback loop between temperature and decomposition rate. It remains critical that we monitor soil carbon flux as climate change progresses and continue research into methodology for remediating potential affects via sustainable land management practices.

ACKNOWLEDGEMENTS

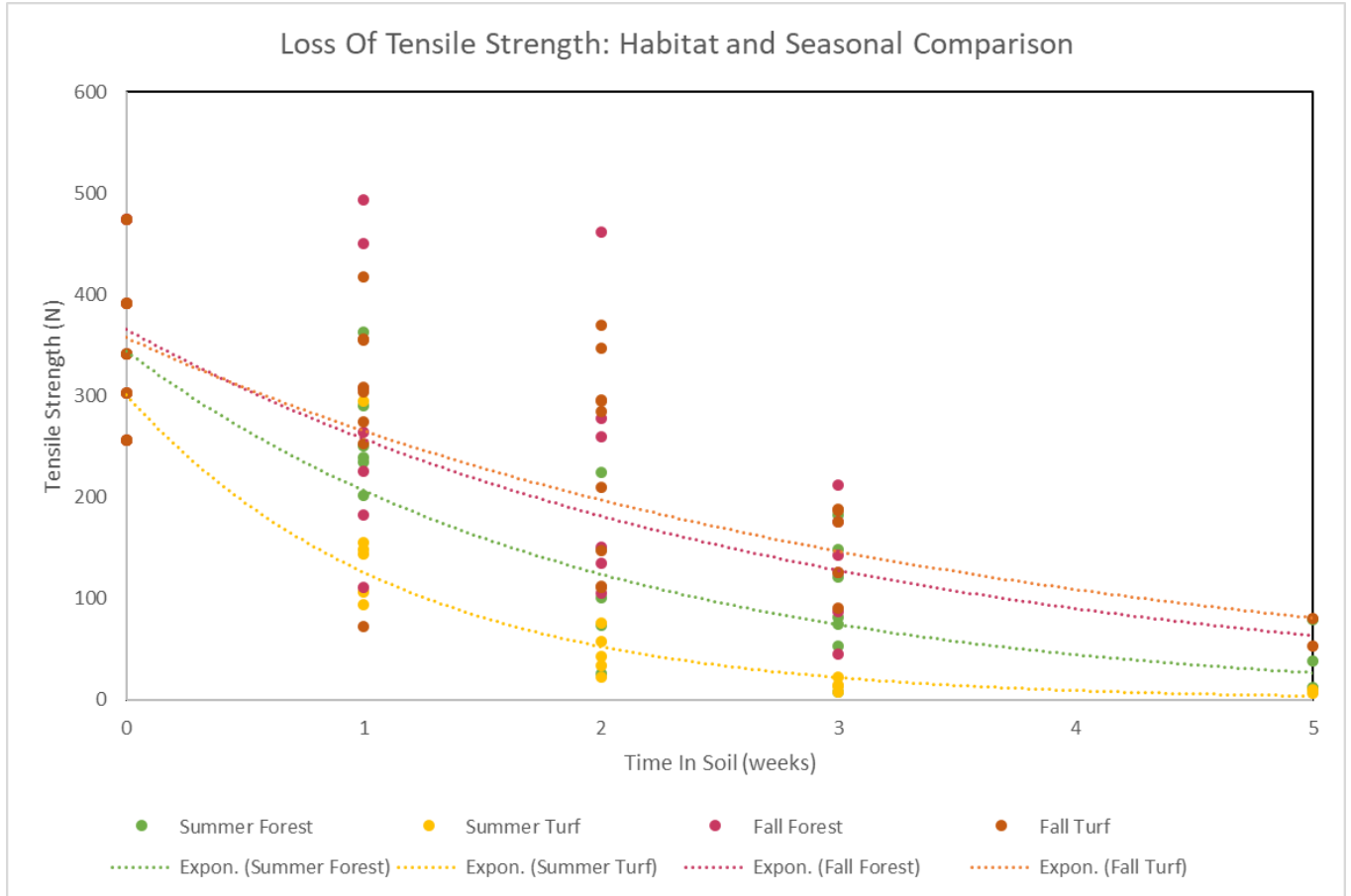
A special thank you to Dr. Christie Klimas for all her guidance, support, and patience on this project. I would also like to thank Dr. Liam Heneghan and Dr. James Montgomery for their continued advice throughout the process.

REFERENCES

- Brooks ME, Kristensen K, van Benthem KJ, Magnusson A, Berg CW, Nielsen A, Skaug HJ, Maechler M, and Bolker BM. “glmmTMB Balances Speed and Flexibility Among Packages for Zero-inflated Generalized Linear Mixed Modeling.” *The R Journal*, vol. 9, no. 2, 2017, pp. 378–400, doi:10.32614/RJ-2017-066.
- Butenschoen, Olaf, et al. “Interactive Effects of Warming, Soil Humidity and Plant Diversity on Litter Decomposition and Microbial Activity.” *Soil Biology and Biochemistry*, vol. 43, no. 9, Sept. 2011, pp. 1902–1907, <https://doi.org/10.1016/j.soilbio.2011.05.011>.
- Chen, Jiandong, et al. “Driving Factors of Global Carbon Footprint Pressure: Based on Vegetation Carbon Sequestration.” *Applied Energy*, vol. 267, June 2020, p. 114914, <https://doi.org/10.1016/j.apenergy.2020.114914>.
- Cole, C.V., et al. “Global Estimates of Potential Mitigation of Greenhouse Gas Emissions by Agriculture.” *Nutrient Cycling in Agroecosystems*, vol. 49, no. 1/3, 1997, pp. 221–228, <https://doi.org/10.1023/a:1009731711346>.
- Davidson, Eric A., and Ivan A. Janssens. “Temperature Sensitivity of Soil Carbon Decomposition and Feedbacks to Climate Change.” *Nature*, vol. 440, no. 7081, Mar. 2006, pp. 165–173, <https://doi.org/10.1038/nature04514>.
- De Vos, Bruno, et al. “Capability of Loss-on-Ignition as a Predictor of Total Organic Carbon in Non-Calcareous Forest Soils.” *Communications in Soil Science and Plant Analysis*, vol. 36, no. 19–20, Oct. 2005, pp. 2899–2921, <https://doi.org/10.1080/00103620500306080>.
- Delignette-Muller, Marie Laure, and Christophe Dutang. “**fitdistrplus**: An R package for Fitting Distributions.” *Journal of Statistical Software*, vol. 64, no. 4, 2015, <https://doi.org/10.18637/jss.v064.i04>.
- Ferlauto, Max, et al. “Legacy Effects of Long-Term Autumn Leaf Litter Removal Slow Decomposition Rates and Reduce Soil Carbon in Suburban Yards.” *PLANTS, PEOPLE, PLANET*, 22 Feb. 2024, <https://doi.org/10.1002/ppp3.10499>.
- Ford, Trent. “July Brought Sweetcorn... and Floods, Drought, Heat, Smoke, and Tornadoes.” *Illinois State Climatologist*, 3 Aug. 2023, stateclimatologist.web.illinois.edu/2023/08/03/july-brought-sweetcorn-and-floods-drought-heat-smoke-and-tornadoes/.
- Heneghan, L., et al. “Rapid Decomposition of Buckthorn Litter May Change Soil Nutrient Levels.” *Ecological Restoration*, vol. 20, no. 2, 1 June 2002, pp. 108–111, <https://doi.org/10.3368/er.20.2.108>.
- Jandl, Robert, et al. “How Strongly Can Forest Management Influence Soil Carbon Sequestration?” *Geoderma*, vol. 137, no. 3–4, Jan. 2007, pp. 253–268, <https://doi.org/10.1016/j.geoderma.2006.09.003>.
- Lal, R, et al. *Soil Management and Greenhouse Effect*, 6 Feb. 2018, <https://doi.org/10.1201/9780203739310>.

- Larkin, Daniel J., et al. "Ecosystem Changes Following Restoration of a Buckthorn-Invaded Woodland." *Restoration Ecology*, vol. 22, no. 1, 11 Apr. 2013, pp. 89–97, <https://doi.org/10.1111/rec.12016>.
- Li, Yan, et al. "Local Cooling and Warming Effects of Forests Based on Satellite Observations." *Nature Communications*, vol. 6, no. 1, 31 Mar. 2015, <https://doi.org/10.1038/ncomms7603>.
- Nachimuthu, Gunasekhar, et al. "Comparison of Methods for Measuring Soil Microbial Activity Using Cotton Strips and a Respirometer." *Journal of Microbiological Methods*, vol. 69, no. 2, May 2007, pp. 322–329, <https://doi.org/10.1016/j.mimet.2007.02.002>.
- Oelkers, E. H., and D. R. Cole. "Carbon Dioxide Sequestration a Solution to a Global Problem." *Elements*, vol. 4, no. 5, 1 Oct. 2008, pp. 305–310, <https://doi.org/10.2113/gselements.4.5.305>.
- Ontl, T., & Schulte, L. "Soil Carbon Storage." *Nature Education*, 2012, https://doi.org/https://www.researchgate.net/publication/313189912_Soil_carbon_storage
- Pataki, Diane E., et al. "Tracing Changes in Ecosystem Function Under Elevated Carbon Dioxide Conditions." *BioScience*, vol. 53, no. 9, 2003, p. 805, [https://doi.org/10.1641/0006-3568\(2003\)053\[0805:tciefu\]2.0.co;2](https://doi.org/10.1641/0006-3568(2003)053[0805:tciefu]2.0.co;2).
- Post, Wilfred M., et al. "Enhancement of Carbon Sequestration in US Soils." *BioScience*, vol. 54, no. 10, 2004, p. 895, [https://doi.org/10.1641/0006-3568\(2004\)054\[0895:eocsiu\]2.0.co;2](https://doi.org/10.1641/0006-3568(2004)054[0895:eocsiu]2.0.co;2).
- Qian, Yaling, et al. "Soil Organic Carbon Input from Urban Turfgrasses." *Soil Science Society of America Journal*, vol. 74, no. 2, Mar. 2010, pp. 366–371, <https://doi.org/10.2136/sssaj2009.0075>.
- Rodrigues, Cristina I., et al. "Soil Carbon Sequestration in the Context of Climate Change Mitigation: A Review." *Soil Systems*, vol. 7, no. 3, 3 July 2023, p. 64, <https://doi.org/10.3390/soilsystems7030064>.
- Rustad, L., et al. "A Meta-Analysis of the Response of Soil Respiration, Net Nitrogen Mineralization, and Aboveground Plant Growth to Experimental Ecosystem Warming." *Oecologia*, vol. 126, no. 4, Feb. 2001, pp. 543–562, <https://doi.org/10.1007/s004420000544>.
- Schlesinger, William H., and Jeffrey A. Andrews. "Soil Respiration and the Global Carbon Cycle." *Biogeochemistry*, vol. 48, no. 1, 2000, pp. 7–20, <https://doi.org/10.1023/a:1006247623877>.
- Stone, Charles J., et al. "Polynomial Splines and Their Tensor Products in Extended Linear Modeling: 1994 Wald Memorial Lecture." *The Annals of Statistics*, vol. 25, no. 4, 1 Aug. 1997, <https://doi.org/10.1214/aos/1031594728>.
- Solvita. *Solvita Instructions: Natural Soil Respiration, SOP Version 2021:3.0 (DCR Model 12.4)*, Woods End Laboratories, Mount Vernon, ME, 2019.
- Trumbore, Susan E., et al. "Rapid Exchange Between Soil Carbon and Atmospheric Carbon Dioxide Driven by Temperature Change." *Science*, vol. 272, no. 5260, 19 Apr. 1996, pp. 393–396, <https://doi.org/10.1126/science.272.5260.393>.
- Venables WN, Ripley BD. *Modern Applied Statistics with S*, Fourth edition. Springer, New York, 2002. ISBN 0-387-95457-0, <https://www.stats.ox.ac.uk/pub/MASS4/>

APPENDIX



Decomposition curves constructed comparing loss of tensile strength (represented by max load) vs time spent within soil.