EFFECTS OF GRAZING AFTER WILDFIRE ON SOIL HEALTH IN EASTERN MONTANA

By

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ABSTRACT

Rangelands are resilient to grazing and fire. However, the resilience of rangelands may be degraded by livestock grazing too soon after wildfire. Due to the growing interest in soil health and its link to sustainable grazing, following a large wildfire (109,346 ha, Lodgepole complex in 2017) we tested the effect of grazing (grazed verses no grazing) on three indicators of soil health in ponderosa pine savvanas of the northern Great Plains. We measured indicators of soil hydrologic function (i.e., soil hydraulic conductivity), properties related to nutrient cycling (i.e., soil organic matter, plant available nutrients, pH), and soil structure (i.e., aggregate stability) in 2019 and 2020. Grazing occurred two out of three years following the fire. Most indicators of soil health were not appreciably affected by grazing post-fire. However, we detected a marginally significant negative effect of grazing on soil organic matter. Specifically, soil organic matter was 7% greater in ungrazed than grazed areas. No other grazing treatment effects were detected. Several soil health metrics varied between sampling years. Our results suggest that grazing(two out of the three years) following fire is unlikely to negatively affect many indicators of soil health of ponderosa pine savannas in the northern Great Plains. The increased organic matter observed by resting did not have an appreciable impact on the other soil health metrics. These findings suggest that soil health indicators are relatively resilient to grazing after wildfire and have implications for grazing policy post-fire.

CHAPTER ONE

LITERATURE REVIEW

Introduction

Soil health is assessed as a collection of soil properties to indicate the capacity of soil to function as an ecosystem sustaining plants, animals, and humans (Doran and Zeiss 2000). With this in mind, assessment of soil degradation and recovery may provide insight into improved rangeland management decisions (Karl et al. 2017). When assessing soil health, direction and rate of change of soil health indicators are very important for land management (Karlen et al. 1997). Effective assessment recognizes that different types and intensities of disturbances are associated with variable rates of change and potential short and/or long-term impacts on soil. Fires varying in intensities will have differing impacts on the soils ability to function and therefore affects the soil health post wildfire (Kennard and Gholz 2001; Keeley 2009). Soil health response to fire greatly depends on many local biotic and abiotic interactions and therefore, post wildfire management is different across ecoregions and even property boundary lines (Lentile et al. 2007). However, West-wide Bureau of Land Management (BLM) fire recovery recommendations are to defer grazing post fire two years to allow for seeds to establish and burned plants to regain vigor (Blaisdell et al. 1982; Bureau of Land Management 2007). Post fire management becomes further disjointed when the fire history of local plant communities is added to management recommendations. For example, fire scars from the Black Hills in South Dakota show that ponderosa pine savannas burn twice as frequently (10-12 year FRI) as ponderosa pine forests (20-24 year FRI) in the same ecotone (Brown and Sieg 1999). In an

attempt to reconcile some of this apparent disparity, this literature review will evaluate soil health responses to fire and grazing with a focus on East Central Montana ponderosa pine (*Pinus ponderosa*) savannas.

Rangelands are diverse landscapes that vary across different spatial scales. Managing these landscapes for resilience requires vast array of knowledge about how they operate and function. Understanding ecosystem function plays an important role in interpreting soil health measures as well (Brown and Herrick 2016). Soil function and processes focus on stable, in place soil profiles that allow water, energy, and nutrients to cycle throughout the ecosystem (Printz et al. 2014). The following sections describe field and lab measurements taken to assess these processes as a measure of soil health. An effort has been made to review those process related measures useful in tracking soil recovery in grazed ponderosa pine savannas following wildfire.

Hydraulic conductivity

Infiltration is defined, “as the meters per unit time of water entering into the soil regardless of the types of values of forces or gradients” while hydraulic conductivity is defined, “as the meters per day of water seeping into the soil under the pull of gravity or under a hydraulic gradient” (Kirkham 2004). These measurements are closely linked because infiltration rate is highly affected by the hydraulic conductivity of the soil (Sheikh Leiveci et al. 2016). Hydraulic conductivity measurements identify the maximum hydraulic gradient to constrict preferential flow into large macropores. Thus, large macropores interconnected to the soil surface are associated with high infiltration rates (Kirkham, 2004).

Productive and functioning rangelands capture, store, and release precipitation back into the site. Integral to this interaction, hydraulic conductivity can be affected by disturbance. Recovery of pre fire soil hydraulic properties depend on ground cover, soil organic matter, vegetation, and persistence of soil-water repellency (Ebel and Martin 2017). During fire, the soil surface undergoes chemical and physical processes that affect water entering the soil profile (DeBano 2000). Fire consumes the vegetation and creates bare ground influencing surface organic matter, aggregate stability, and water repellency (Fox et al. 2007) and may affect infiltration into the soil. The recovery period of post fire soil surface conditions vary based on severity of the fire (Keeley 2009).

Different ecosystems have different soil responses to fire due to differences in pre-fire vegetative conditions, fire characteristics, and post-fire vegetation recovery. For example, under high severity fires ponderosa pine forests on volcanic soil had over two times lower infiltration rates (mm hr^{-1}) than unburned soils under the same forest type and lower infiltration than severely burned soils under mixed coniferous forests on volcanic soils or granitic soils derived soils under ponderosa pine (Martin and Moody 2001). However, low severity prescribed fire did not alter soil hydraulic conductivity in Mediterranean pine ecosystems under unsaturated conditions (Plaza-Álvarez et al. 2019). The contrasting responses may have been caused by water repellant compounds formed during fuel combustion.

In ash cap soils, ground cover and water repellency affect the infiltration capacity. After a high intensity fire in a western Montana conifer forest, ash capped soils generated increased soil water repellency compared to unburned sites through one year, but was not different in year two. Surprisingly, infiltration rates did not differ between burned and unburned sites in years one and

two post-fire (Robichaud et al. 2016). In another study sampling soil surface hydraulic conductivity and water repellency within a month after a June Colorado front fire, hydraulic conductivity was different between low verses moderate burn severity, but low vs. high and medium vs. high differences were not observed. Water repellency was not significant between any of the burn severities. The lack of difference in the high severity burn was water repellency occurring at 5-50mm below the soil surface that their surface test did not measure (Lewis et al. 2006). Vegetation response decreased sediment runoff yield comparable to the control five years after the fire. Grazing after fire may limit vegetation response and further impact the effects of water repellency on infiltration by limiting post-fire ground cover. Changes in infiltration arising from surface repellency could also be expected to lower soil hydraulic conductivity.

Field saturated hydraulic conductivity recovered before the next fire cycle in an analysis of five studies across the world lasting longer than three years (Ebel and Martin 2017). Because field saturated hydraulic conductivity has a low resistance and moderate to high resilience against wildfires, impacted watersheds will provide the ecosystem services after a brief period of impairment (Ebel and Martin 2017). These authors believe the resiliency of hydraulic conductivity would not be dampened as long as fire frequency, spatial extent, and severity do not change vegetation type (Ebel and Martin 2017). Throughout these studies, grazing was not a factor in post fire disturbance

In a South Dakota study (Comer 2019) comparing ungrazed, grazed, and burned sites, infiltration rates were not significantly different among treatments. Fire and grazing were looked at as separate disturbances. Volumetric water content (soil moisture) was different between the three treatments. They concluded that the largest difference of 0.06 m^3/m^3 or 6% from the three

soil depth measurements: 6,12, and 24 inches was not sufficient to cause a biological effect. In a West African Savanna study looking at grazing post fire, increasing grazing pressure decreased infiltration rates, but there was no statistical interaction between fire and grazing for an early growing season burn (Savadogo et al. 2007). United States studies indicate that increasing grazing pressure beyond a site-specific threshold reduces infiltration by decreasing soil organic matter and soil aggregate stability which increases soil surface crusting effectively reducing soil surface porosity (Blackburn 1984; Briske et al. 2011)

Aggregate stability

When soil structure decreases from aggregates breaking down and decreasing pore spaces, infiltration and hydraulic conductivity decrease (Oades 1984). Soil aggregates are defined by diameter as micro- < 0.25mm or macroaggregates >0.25mm and the arrangement of these particles and pores form soil structure (Fernández-Ugalde et al. 2014). Aggregate stability refers to the structural integrity necessary for soil to remain intact when subjected to outside forces such as rain drop or hoof impact (Mataix-Solera et al. 2011). The complex involvement of the abiotic and biotic factors in aggregate formation is one reason it is used as an important indicator of soil health (Mataix-Solera et al. 2011). Loss of aggregate stability causes soil crusting and surface sealing which can lead to reduced water infiltration and increased soil erosion (Mataix-Solera et al. 2011). However, a similar correlation between aggregate stability and infiltration was not found in the northern Great Plains (Reinhart et al. 2019). The lack of uniform landscape response could be explained in part by soil organic matter.

When organic matter is the major particle binding agent, as in the temperate northern Great Plains, macroaggregates are responsive to management changes, but microaggregates are

not as responsive (Oades 1984; Fernández-Ugalde et al. 2014). However, not all macroaggregates(>0.25mm) may not consistently respond the to same management. In the northern Great Plains, small macroaggregates(0.25-1mm) stability was reduced by grazing where larger macroaggregates (1-2mm) had no detectible effect (Reinhart et al. 2019). Because soil aggregates are formed with organic matter, they provide physical protection of SOM from microbial activity and are considered an important mechanism for carbon stabilization (Wiesmeier et al. 2019). Consequently, if fire and grazing reduce SOM inputs to the site, aggregate stability may decrease.

Mass of soil detachment from sheep and goat grazing on cropland two weeks after a low to moderate intensity fire was positively correlated with increasing stocking rates. Even with a slight increase in soil wettability with increasing stock rates, a higher risk of erosion on semi-arid croplands exists (Stavi et al. 2016). However, when grazing was looked at as a single disturbance, there was no consistent effect on soil aggregate stability from livestock grazing in the northern Great Plains (Reinhart et al. 2019). These outcomes suggest mixed effects. Even though soil aggregate stability is unaffected in the NGP, grazing burned lands too soon after a fire increases erosion risk as well as reduced forage availability. Burned vegetation and litter leaves the soil exposed to rain drop impact, effectively reducing precipitation storage in the soil and increasing erosion risk (Shakesby and Doerr 2006). Grazing can amplify this negative response post fire by limiting recovery of grass roots that stabilize macro-aggregates (Oades 1984).

Organic matter (SOM)

Soil organic matter(SOM) is primarily made up of soil organic carbon(SOC) and soil organic nitrogen (Tiessen et al. 1994). Total soil carbon content results from inputs of organic carbon (plant root and shoot litter) and losses of carbon from microbial mineralization (Kitchen et al. 2009). Organic matter decreases with increased temperature and increases with increasing moisture (Sikora and Stott 1996). Organic matter may play an essential role in plant productivity due to its water holding capacity important for plant growth. Biomass production of wheat with suboptimum irrigation in a greenhouse study with 4% OM and no fertilizer produced equivalent to 2% OM with fertilizer (Oldfield et al. 2020). This could suggest that under non-fertilized and low precipitation rangelands, higher SOM would increase in vegetative production, due in part to the increased soil water holding capacity (Sikora and Stott 1996).

Soil organic matter has a high (r=0.97) correlation with water-holding capacity (Oldfield et al. 2020). Low forest-floor moisture was associated with negative impacts on physical and chemical soil properties during severe fires and may be as critical as fuel management in determining post fire response (Switzer et al. 2012). During fires, litter burned on the surface is reduced to particles and mixes with the organic horizon of soil causing a net increase of soil carbon (González-Pérez et al. 2004).

In nutrient poor ecosystems with low soil fertility, grazing does not provide positive feedbacks to the system because mechanisms such as compensatory growth following herbivory will not occur (Bardgett and Wardle 2003). If fire in the northern mixed-grass prairie causes low soil fertility, then it would be expected that grazing post-fire would not benefit plant productivity. These results indicate that increasing SOC in grazing lands following disturbance is essential for sustainable land productivity and improving many ecosystem services (Sarkar et al.

2020). Decomposition rates of SOM are affected by soil texture and site environmental conditions (Sikora and Stott 1996) and factors influencing carbon incorporated into the soil are soil texture, soil management, vegetation, and climatic variation (Augustin and Cihacek 2016).

Grazing can shift SOM inputs in the short-term by removing aboveground material from the site and affect plant survival by altering the plant's carbon allocation and root exudation patterns. Therefore, long-term excessive herbivory can shift plant communities to less productive states, ultimately decreasing SOM inputs to the site (Bardgett and Wardle 2003; Chen et al. 2015). Decreased yearly plant yields lead to reduced plant residue additions and therefore can result in net negative SOM input to the site (Sikora and Stott 1996). The lack of appropriate grazing management alters above ground productivity which in turn affects root production, biomass, and turnover ultimately decreasing carbon influx into the soil and lowering SOM (Chen et al. 2015). Management strategies for increasing SOM may vary between regions as well. Over a five year period in the northern mixed grass prairie, soil organic carbon did not differ between grazed mixed-grass prairie, nongrazed mixed-grass prairie, and grazed western wheatgrass sites (Frank et al. 2002). Plant productivity, the primary source or soil organic matter, is also affected by soil nutrient levels.

Nutrient profile

Soil mineral nitrogen (N), phosphorous (P), and potassium (K) are important for predicting potential plant productivity (Allan and Killorn 1996), so it is helpful to understand how disturbances such as fire and grazing affect the respective levels.

Losses of C and N from fires depend on the amount of the forest floor consumed (Switzer et al. 2012). Under five different pre fire fuel management practices, no significant effect was

found in mineral soil carbon (C) and nitrogen (N) content after prescribed fires in Rocky Mountain Douglas-Fir forests (Switzer et al. 2012). In the tallgrass prairie following 13 years of annual burning alone did not decrease C and N concentrations whereas mowing post burn to simulate grazing decreased C and N concentrations by 20% and 17%, respectively (Kitchen et al. 2009). Unlike grazing, mowing removes vegetation nutrients and does not redeposit any of the N from the biomass, as does grazing (Kitchen et al. 2009). Under grazing and fire in West Africa, reduction in C and N was proportional to increasing levels of grazing. Carbon and nitrogen values declined 0.3% and 0.02 mg kg^{-1}, respectively, however values were not significant among the five levels of grazing including a control and fire. The authors attributed this to taking composite samples of the top 10cm and acknowledged that there could have been differences if they had focused on more of the surface/top soil (Savadogo et al. 2007).

Inorganic nitrogen did not vary in mineral soil between stand classes from old-growth to sapling stands in Arizona ponderosa pine forests prior to burning. Immediately after burning though, ammonium significantly increased with direct correlation to initial forest floor weight and the amount of floor vegetation consumed by fire. Nitrate-nitrogen did not significantly change immediately post fire. A year after burning ammonium levels had declined substantially and showed up as nitrate-nitrogen in all stand age classes (Covington and Sackett 1992).

Total nitrogen (g kg^{-1}) and mineralizable nitrogen (mg kg^{-1}) were not different in a low severity burned understory ponderosa pine stands, but the unburned control had higher phosphorous while burned areas had higher sulfur. Differences among all nutrients were insignificant 4-5 years post burn and a “flush” of nutrients was not observed post-fire (Busse et

al. 2000). Timing of burn and post burn weather conditions may affect nutrient quantity and availability.

In an Israel Mediterranean climate, total soil nitrogen in a burned Aleppo pine (*Pinus* halepensis) forest was 25% lower than the unburned, but plant available forms of nitrogen were commonly higher in burned (Kutiel and Naveh 1987). In the same study, ammonium (NH_4^+), nitrite (NO_2^-), and nitrate (NO_3^-) levels were more than twice as high in burned vs unburned sites eight months after the fire. The different levels in nitrogen availability were postulated to have been from decreasing C:N after the fire, which allows for higher nitrogen mineralization. They hypothesized that ammonium and nitrate levels were not from the fire, but subsequent mineralization. This allows a window where the nutrients could be leached from the landscape if plants do not gradually utilize them before a heavy precipitation event. Phosphorous increased by 300% after the fire. It was in a mobile form and returned to pre-fire levels following rain and subsequent erosion and leaching (Kutiel and Naveh 1987).

No consistent soil nutrient response was found between a mix of fire and grazing treatments using PRS (Plant root simulator) probes in a South Dakota grassland fire. Mowing after fire did not change soil nutrient properties with most of the nutrients highest in first sampling date 5 months after the fire (Kral 2014). In a Rocky Mountain Douglas-fir forest following prescribed fire, phosphate, calcium, and magnesium increased after prescribed burn treatments (Switzer et al. 2012).

Grazing can cause no effect, increase, or decrease nitrogen deposition in mesic rangelands (Evans et al. 2017). In general, soil fertility increases with grazing on high fertility soils and decreases with grazing on low fertility soils (Bardgett and Wardle 2003; Evans et al.

2017). Precipitation and soil nutrient interaction can affect plant responses to grazing (Biondini et al. 1998; Augustine and McNaughton 2006). Augustine and McNaughton (2006) found in low-rainfall environments grazing reduced plant production under both high and low soil fertility. Conversely, under high rainfall, grazing increased annual plant production on fertile soils and suppressed production on soils with low fertility. Nitrogen pool fluxes followed rainfall patterns (Augustine and McNaughton 2006). In a seven year northern mixed grass prairie grazing study, annual plant production was driven by climatic variations, but no relationships were found between grazing intensities (ungrazed, 50% use, 90% use) and total soil C and N (Biondini et al. 1998). In another northern mixed grass prairie study, ammonium and nitrate percentages were both higher in grazed than ungrazed treatments and higher stocking rates(0.2 ha/AUM) had higher levels than low stocking(0.8 ha/AUM), which they partly attributed to increased excreta (Dormaar et al. 1990)

Soil pH and Electrical Conductivity

Values of pH between 6 and 7.5 generally promote plant growth and microbial activity (Smith and Doran 1996). Soil pH increases after fire because of the organic acid denaturation that comes from soil heating (Certini 2005). After a Douglas-Fir fire, pH increased in the forest floor and only in the mineral soil in the high intensity burn treatment. The increase was the major determinant of the community decline of microbial groups after fire treatments (Switzer et al. 2012). Raised pH levels remained one year after fire treatments (Switzer et al. 2012). In a low severity ponderosa pine understory spring burn, pH levels were not significantly higher that fall and 4-5 years after (Busse et al. 2000). The difference could be from fire intensity because the

rise in pH was when the forest floor was converted to ash, which is an indicator of high intensity (Switzer et al. 2012).

In a degraded Chinese arid desert steppe, year-long continuous grazing produced higher soil pH levels than those reported for a two-year exclosure. In the same study, a six year exclosure had the lowest soil pH (Pei et al. 2008).

Under Mediterranean climate conditions, both pH and EC increased after fire but decreased rapidly (2 months) to levels similar of unburned soil (Kutiel and Naveh 1987). The significant rise was hypothesized as a flux in soluble cations in the ash (DeBano et al. 1977; Kutiel and Naveh 1987).

Electrical conductivity generally determines soil salinity, but is also related to available nutrients for plant uptake (Smith and Doran 1996). Soil salinity can greatly influence physical, chemical, and biological processes in soil as well as broader ecological processes (Smith and Doran 1996). Values of EC between 0-1.5 mS/cm generally promote plant growth and microbial activity (Smith and Doran 1996). However, both EC and pH both need to be measured in soil solutions because an apparently good range of EC measure can be found in acidic soil unsuited for plant growth (Smith and Doran 1996). While EC and pH are good initial indicators for soil health, more measured factors are need to be looked at for a complete understanding (Smith and Doran 1996).

Summary

Soil health response to disturbances is variable across different biomes as well as the following abiotic factors on the site. Fire and subsequent grazing are common disturbances that have helped shape the northern Great Plains. When comparing the differences between grazed

and ungrazed plots in this ponderosa pine savanna in the northern Great Plains, I would expect no difference in soil health indicators. Differences that may arise could be due to increased litter on site, but due to the ecosystem evolving under fire and grazing I would not expect that to impact soil health indicators.

References Cited

Allan DL, Killorn R (1996) Assessing Soil Nitrogen, Phosphorus, and Potassium for Crop Nutrition and Environmental Risk. In: Methods for Assessing Soil Quality. John Wiley & Sons, Ltd, pp 187–201

Anderson RC (2006) Evolution and Origin of the Central Grassland of North America: Climate, Fire, and Mammalian Grazers. The Journal of the Torrey Botanical Society 133:626–647

Augustin C, Cihacek LJ (2016) Relationships Between Soil Carbon and Soil Texture in the Northern Great Plains: Soil Science 181:386–392. https://doi.org/10.1097/SS.0000000000000173

Augustine DJ, Derner JD (2014) Controls over the strength and timing of fire–grazer interactions in a semi-arid rangeland. Journal of Applied Ecology 51:242–250. https://doi.org/10.1111/1365-2664.12186

Augustine DJ, McNaughton SJ (2006) Interactive Effects of Ungulate Herbivores, Soil Fertility, and Variable Rainfall on Ecosystem Processes in a Semi-arid Savanna. Ecosystems 9:1242–1256. https://doi.org/10.1007/s10021-005-0020-y

Ball DF (1964) Loss-on-Ignition as an Estimate of Organic Matter and Organic Carbon in Non-Calcareous Soils. Journal of Soil Science 15:84–92. https://doi.org/10.1111/j.1365-2389.1964.tb00247.x

Bardgett RD, Wardle DA (2003) Herbivore-Mediated Linkages Between Aboveground and Belowground Communities. Ecology 84:2258–2268. https://doi.org/10.1890/02-0274

Bates D, Mächler M, Bolker B, Walker S (2015) Fitting Linear Mixed-Effects Models Using lme4. J Stat Softw 67:1–48. https://doi.org/10.18637/jss.v067.i01

Biondini ME, Patton BD, Nyren PE (1998) Grazing Intensity and Ecosystem Processes in a Northern Mixed-Grass Prairie, Usa. Ecological Applications 8:469–479. https://doi.org/10.1890/1051-0761(1998)008[0469:GIAEPI]2.0.CO;2

Blackburn WH (1984) Impacts of grazing intensity and specialized grazing systems on watershed characteristics and responses. In: Developing Strategies for Rangeland Management. Westview Press, Boulder, CO, USA, pp 927–983

Bongiorno G, Bünemann EK, Oguejiofor CU, et al (2019) Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. Ecological Indicators 99:38–50. https://doi.org/10.1016/j.ecolind.2018.12.008

Briske DD, Derner JD, Milchunas DG, Tate KW (2011) An evidence-based assessment of prescribed grazing practices. In: In Conservation benefits of rangeland practices: Assessment, recommendations, and knowledge gaps. United States Department of Agriculture, Natural Resource Conservation Service, Washington, DC, pp 22–74

Brown JR, Herrick JE (2016) Making soil health a part of rangeland management. Journal of Soil and Water Conservation 71:55A-60A. https://doi.org/10.2489/jswc.71.3.55A

Brown PM, Sieg CH (1999) Historical variability in fire at the ponderosa pine - Northern Great Plains prairie ecotone, southeastern Black Hills, South Dakota. Écoscience 6:539–547. https://doi.org/10.1080/11956860.1999.11682563

Busse MD, Simon SA, Riegel GM (2000) Tree-Growth and Understory Responses to Low-Severity Prescribed Burning in Thinned Pinus ponderosa Forests of Central Oregon. for sci 46:258–268. https://doi.org/10.1093/forestscience/46.2.258

Certini G (2005) Effects of fire on properties of forest soils: a review. Oecologia 143:1–10. https://doi.org/10.1007/s00442-004-1788-8

Chen W, Huang D, Liu N, et al (2015) Improved grazing management may increase soil carbon sequestration in temperate steppe. Scientific Reports 5:10892. https://doi.org/10.1038/srep10892

Comer J (2019) Effects of Grazing and Fire on Soil Microbial Communities and Hydrological Processes in the Northern Great Plains Grassland. Thesis - Open Access, South Dakota State University

Covington WW, Sackett SS (1992) Soil mineral nitrogen changes following prescribed burning in ponderosa pine. Forest Ecology and Management 54:175–191. https://doi.org/10.1016/0378-1127(92)90011-W

DeBano LF (2000) The role of fire and soil heating on water repellency in wildland environments: a review. Journal of Hydrology 231–232:195–206. https://doi.org/10.1016/S0022-1694(00)00194-3

DeBano LF, Dunn PH, Conrad CE (1977) Proceedings of the Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems, August 1-5, 1977, Palo Alto, California. Forest Service, U.S. Department of Agriculture

Derner JD, Smart AJ, Toombs TP, et al (2018) Soil Health as a Transformational Change Agent for US Grazing Lands Management. Rangeland Ecology & Management 71:403–408. https://doi.org/10.1016/j.rama.2018.03.007

Dijkstra FA, Zhu B, Cheng W (2021) Root effects on soil organic carbon: a double-edged sword. New Phytologist 230:60–65. https://doi.org/10.1111/nph.17082

Doran JW, Zeiss MR (2000) Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology 15:3–11. https://doi.org/10.1016/S0929-1393(00)00067-6

Dormaar JF, Smoliak S, Willms WD (1990) Distribution of nitrogen fractions in grazed and ungrazed fescue grassland Ah horizons. Rangeland Ecology & Management / Journal of Range Management Archives 43:6–9

Ebel BA, Martin DA (2017) Meta-analysis of field-saturated hydraulic conductivity recovery following wildland fire: Applications for hydrologic model parameterization and resilience assessment. Hydrological Processes 31:3682–3696. https://doi.org/10.1002/hyp.11288

Evans RD, Gill RA, Eviner VT, Bailey V (2017) Soil and Belowground Processes. In: Briske DD (ed) Rangeland Systems: Processes, Management and Challenges. Springer International Publishing, Cham, pp 131–168

Fernández-Ugalde O, Virto I, Barré P, et al (2014) Mechanisms of macroaggregate stabilisation by carbonates: implications for organic matter protection in semi-arid calcareous soils. Soil Res 52:180–192. https://doi.org/10.1071/SR13234

Fox DM, Darboux F, Carrega P (2007) Effects of fire-induced water repellency on soil aggregate stability, splash erosion, and saturated hydraulic conductivity for different size fractions. Hydrological Processes 21:2377–2384. https://doi.org/10.1002/hyp.6758

Fox J, Weisberg S (2019) An R Companion to Applied Regression, Third. Sage, Thousands Oaks, CA

Frank AB, Liebig MA, Hanson JD (2002) Soil carbon dioxide fluxes in northern semiarid grasslands. Soil Biology and Biochemistry 34:1235–1241. https://doi.org/10.1016/S0038-0717(02)00062-7

Franzluebbers AJ (2002) Water infiltration and soil structure related to organic matter and its stratification with depth. Soil and Tillage Research 66:197–205. https://doi.org/10.1016/S0167-1987(02)00027-2

Fuhlendorf SD, Engle DM, Kerby J, Hamilton R (2009) Pyric Herbivory: Rewilding Landscapes through the Recoupling of Fire and Grazing. Conservation Biology 23:588–598. https://doi.org/10.1111/j.1523-1739.2008.01139.x

Gates EA, Vermeire LT, Marlow CB, Waterman RC (2017) Reconsidering rest following fire: Northern mixed-grass prairie is resilient to grazing following spring wildfire. Agriculture, Ecosystems & Environment 237:258–264. https://doi.org/10.1016/j.agee.2017.01.001

Gifford GF, Hawkins RH (1978) Hydrologic impact of grazing on infiltration: A critical review. Water Resources Research 14:305–313. https://doi.org/10.1029/WR014i002p00305

González-Pérez JA, González-Vila FJ, Almendros G, Knicker H (2004) The effect of fire on soil organic matter—a review. Environment International 30:855–870. https://doi.org/10.1016/j.envint.2004.02.003

Helalia AM (1993) The relation between soil infiltration and effective porosity in different soils. Agricultural Water Management 24:39–47. https://doi.org/10.1016/0378-3774(93)90060-N

Karl JW, Herrick JE, Pyke DA (2017) Monitoring protocols: Options, approaches, implementation, benefits. Springer, pp 527–567

Karlen DL, Mausbach MJ, Doran JW, et al (1997) Soil Quality: A Concept, Definition, and Framework for Evaluation (A Guest Editorial). Soil Science Society of America Journal 61:4–10. https://doi.org/10.2136/sssaj1997.03615995006100010001x

Keeley JE (2009) Fire intensity, fire severity and burn severity: a brief review and suggested usage. International Journal of Wildland Fire 18:116. https://doi.org/10.1071/WF07049

Kennard DK, Gholz HL (2001) Effects of high- and low-intensity fires on soil properties and plant growth in a Bolivian dry forest. Plant and Soil 234:119–129. https://doi.org/10.1023/A:1010507414994

Kirkham MB (2004) Principles of Soil and Plant Water Relations. Elsevier Science & Technology, Burlington, UNITED STATES

Kitchen DJ, Blair JM, Callaham MA (2009) Annual fire and mowing alter biomass, depth distribution, and C and N content of roots and soil in tallgrass prairie. Plant Soil 323:235–247. https://doi.org/10.1007/s11104-009-9931-2

Koerner SE, Smith MD, Burkepile DE, et al (2018) Change in dominance determines herbivore effects on plant biodiversity. Nature Ecology & Evolution 2:1925–1932. https://doi.org/10.1038/s41559-018-0696-y

Kral KC-A (2014) Impact of Wildfire and Targeted Grazing Effects on Northern Great Plains Range and Pasture Lands. Thesis - Open Access, North Dakota State University

Kutiel P, Naveh Z (1987) The effect of fire on nutrients in a pine forest soil. Plant Soil 104:269–274. https://doi.org/10.1007/BF02372541

Lenth RV (2021) Emmeans: Estimated Marginal Means, aka Least-Squares Means

Lentile LB, Morgan P, Hudak AT, et al (2007) Post-Fire Burn Severity and Vegetation Response Following Eight Large Wildfires Across the Western United States. fire ecol 3:91–108. https://doi.org/10.4996/fireecology.0301091

Lewis SA, Wu JQ, Robichaud PR (2006) Assessing burn severity and comparing soil water repellency, Hayman Fire, Colorado. Hydrological Processes 20:1–16. https://doi.org/10.1002/hyp.5880

Limb RF, Fuhlendorf SD, Engle DM, Miller RF (2016) Synthesis Paper: Assessment of Research on Rangeland Fire as a Management Practice. Rangeland Ecology & Management 69:415–422. https://doi.org/10.1016/j.rama.2016.07.013

Martin BS, Cooper S, Heidel B, et al (1998) Natural community inventory within landscapes in the Northern Great Plains Steppe Ecoregion of the United States

Martin DA, Moody JA (2001) Comparison of soil infiltration rates in burned and unburned mountainous watersheds. Hydrological Processes 15:2893–2903. https://doi.org/10.1002/hyp.380

Mataix-Solera J, Cerdà A, Arcenegui V, et al (2011) Fire effects on soil aggregation: A review. Earth-Science Reviews 109:44–60. https://doi.org/10.1016/j.earscirev.2011.08.002

Neary DG, Klopatek CC, DeBano LF, Ffolliott PF (1999) Fire effects on belowground sustainability: a review and synthesis. Forest Ecology and Management 122:51–71. https://doi.org/10.1016/S0378-1127(99)00032-8

Necpálová M, Anex RP, Kravchenko AN, et al (2014) What does it take to detect a change in soil carbon stock? A regional comparison of minimum detectable difference and experiment duration in the north central United States. Journal of Soil and Water Conservation 69:517–531. https://doi.org/10.2489/jswc.69.6.517

Oades JM (1984) Soil organic matter and structural stability: mechanisms and implications for management. In: Tinsley J, Darbyshire JF (eds) Biological Processes and Soil Fertility. Springer Netherlands, Dordrecht, pp 319–337

Obalum SE, Chibuike GU, Ouyang Y (2017) Soil organic matter as sole indicator of soil degradation. Environ Monit Assess 189:. https://doi.org/10.1007/s10661-017-5881-y

Oldfield EE, Wood SA, Bradford MA (2020) Direct evidence using a controlled greenhouse study for threshold effects of soil organic matter on crop growth. Ecological Applications 30:e02073. https://doi.org/10.1002/eap.2073

Pei S, Fu H, Wan C (2008) Changes in soil properties and vegetation following exclosure and grazing in degraded Alxa desert steppe of Inner Mongolia, China. Agriculture, Ecosystems & Environment 124:33–39. https://doi.org/10.1016/j.agee.2007.08.008

Plaza-Álvarez PA, Lucas-Borja ME, Sagra J, et al (2019) Changes in soil hydraulic conductivity after prescribed fires in Mediterranean pine forests. Journal of Environmental Management 232:1021–1027. https://doi.org/10.1016/j.jenvman.2018.12.012

Poirier V, Roumet C, Munson AD (2018) The root of the matter: Linking root traits and soil organic matter stabilization processes. Soil Biology and Biochemistry 120:246–259. https://doi.org/10.1016/j.soilbio.2018.02.016

Powell J, Martin B, Dreitz VJ, Allred BW (2018) Grazing Preferences and Vegetation Feedbacks of the Fire-Grazing Interaction in the Northern Great Plains. Rangeland Ecology & Management 71:45–52. https://doi.org/10.1016/j.rama.2017.09.003

Printz JL, Toledo D, Boltz SC (2014) Rangeland health assessment: The key to understanding and assessing rangeland soil health in the Northern Great Plains. Journal of Soil and Water Conservation 69:73A-77A. https://doi.org/10.2489/jswc.69.3.73A

PRISM Climate Group PRISM Climate Group. http://prism.oregonstate.edu. Accessed 15 Apr 2021

R Core Team (2021) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria

Reinhart KO, Nichols KA, Petersen M, Vermeire LT (2015) Soil aggregate stability was an uncertain predictor of ecosystem functioning in a temperate and semiarid grassland. Ecosphere 6:art238. https://doi.org/10.1890/ES15-00056.1

Reinhart KO, Rinella MJ, Waterman RC, et al (2019) Testing rangeland health theory in the Northern Great Plains. Journal of Applied Ecology 56:319–329. https://doi.org/10.1111/1365-2664.13273

Robichaud PR, Wagenbrenner JW, Pierson FB, et al (2016) Infiltration and interrill erosion rates after a wildfire in western Montana, USA. CATENA 142:77–88. https://doi.org/10.1016/j.catena.2016.01.027

Ryle GJA, Powell CE (1975) Defoliation and Regrowth in the Graminaceous Plant: The Role of Current Assimilate. Annals of Botany 39:297–310. https://doi.org/10.1093/oxfordjournals.aob.a084943

Sarkar R, Corriher-Olson V, Long C, Somenahally A (2020) Challenges and Potentials for Soil Organic Carbon Sequestration in Forage and Grazing Systems. Rangeland Ecology & Management 73:786–795. https://doi.org/10.1016/j.rama.2020.04.002

Savadogo P, Sawadogo L, Tiveau D (2007) Effects of grazing intensity and prescribed fire on soil physical and hydrological properties and pasture yield in the savanna woodlands of Burkina Faso. Agriculture, Ecosystems & Environment 118:80–92. https://doi.org/10.1016/j.agee.2006.05.002

Shakesby RA, Doerr SH (2006) Wildfire as a hydrological and geomorphological agent. Earth-Science Reviews 74:269–307. https://doi.org/10.1016/j.earscirev.2005.10.006

Sheikh Leiveci K, Abbas Kazemi G, Damough N (2016) Measuring infiltration rate and hydraulic conductivity in a dry well in a thin overburden. JGeope 6:63–73

Sikora LJ, Stott DE (1996) Soil Organic Carbon and Nitrogen. In: Methods for Assessing Soil Quality. John Wiley & Sons, Ltd, pp 157–167

Smith JL, Doran JW (1996) Measurement and Use of pH and Electrical Conductivity for Soil Quality Analysis. In: Methods for Assessing Soil Quality. John Wiley & Sons, Ltd, pp 169–185

Snedecor GW, Cochran WG (1991) Statistical Methods, 8th Edition | Wiley, Eighth

Sokol NW, Bradford MA (2019) Microbial formation of stable soil carbon is more efficient from belowground than aboveground input. Nature Geoscience 12:46–53. https://doi.org/10.1038/s41561-018-0258-6

Sousa WP (1984) The Role of Disturbance in Natural Communities. Annual Review of Ecology and Systematics 15:353–391. https://doi.org/10.1146/annurev.es.15.110184.002033

Stavi I, Barkai D, Knoll YM, Zaady E (2016) Livestock grazing impact on soil wettability and erosion risk in post-fire agricultural lands. Science of The Total Environment 573:1203–1208. https://doi.org/10.1016/j.scitotenv.2016.03.126

Switzer JM, Hope GD, Grayston SJ, Prescott CE (2012) Changes in soil chemical and biological properties after thinning and prescribed fire for ecosystem restoration in a Rocky Mountain Douglas-fir forest. Forest Ecology and Management 275:1–13. https://doi.org/10.1016/j.foreco.2012.02.025

Tamura M, Tharayil N (2014) Plant litter chemistry and microbial priming regulate the accrual, composition and stability of soil carbon in invaded ecosystems. New Phytologist 203:110–124. https://doi.org/10.1111/nph.12795

Thompson SE, Harman CJ, Heine P, Katul GG (2010) Vegetation-infiltration relationships across climatic and soil type gradients. Journal of Geophysical Research: Biogeosciences 115:. https://doi.org/10.1029/2009JG001134

Tiessen H, Cuevas E, Chacon P (1994) The role of soil organic matter in sustaining soil fertility. Nature 371:783–785. https://doi.org/10.1038/371783a0

VandenBygaart AJ, Angers DA (2011) Towards accurate measurements of soil organic carbon stock change in agroecosystems. Canadian Journal of Soil Science. https://doi.org/10.4141/S05-106

Vermeire LT, Crowder JL, Wester DB (2014) Semiarid Rangeland Is Resilient to Summer Fire and Postfire Grazing Utilization. Rangeland Ecology & Management 67:52–60. https://doi.org/10.2111/REM-D-13-00007.1

Vermeire LT, Strong DJ, Waterman RC (2018) Grazing History Effects on Rangeland Biomass, Cover and Diversity Responses to Fire and Grazing Utilization. Rangeland Ecology & Management 71:770–775. https://doi.org/10.1016/j.rama.2018.05.001

Wakimoto RH, Willard EE, Reid B (2004) Historic Fire Regimes and Changes Since European Settlement on the Northern Mixed Prairie: Effect on Ecosystem Function and Fire Behavior. University of Montana

Wiesmeier M, Urbanski L, Hobley E, et al (2019) Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. Geoderma 333:149–162. https://doi.org/10.1016/j.geoderma.2018.07.026

Williams A (2020) Evaluating grazing and defoliation effects on Ponderosa Pine grassland following the Lodgepole complex wildfire. Thesis - Open Access, Montana State University

CHAPTER TWO

EFFECTS OF GRAZING AFTER WILDFIRE ON INDICATORS OF SOIL HEALTH IN EASTERN MONTANA

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EFFECTS OF GRAZING AFTER WILDFIRE ON INDICATORS OF SOIL HEALTH IN EASTERN MONTANA

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Abstract

Background Rangelands are often resilient to grazing and fire. However, the resilience of rangelands may be degraded by livestock grazing too soon after wildfire. Due to the growing interest in soil health and its link to sustainable grazing, following a large wildfire (109,346 ha, Lodgepole complex in 2017) we tested the effect of grazing (grazed verses no grazing) on five indicators of soil health in ponderosa pine savannas of the northern Great Plains. We measured indicators of soil hydrologic function (i.e., soil hydraulic conductivity), properties related to nutrient cycling (i.e., soil organic matter, plant available nutrients, pH), and soil structure (i.e., aggregate stability) in 2019 and 2020. Grazing was excluded for three years or occurred two out of three years following the fire.

Results Most indicators of soil health were not appreciably affected by grazing post-fire. However, we detected a marginally significant negative effect of grazing after fire on soil organic matter (3.11 vs 2.90%). No other grazing treatment effects were detected. Several soil health metrics varied between sampling years.

Conclusions Our results indicate that grazing (two out of the three years) following fire is unlikely to negatively affect many indicators of soil health of ponderosa pine savannas in the northern Great Plains. These results are largely consistent with results for vegetation studies. The implications for post-fire grazing policy are that soil health is resilient to grazing after wildfire, based on indicators measured.

Key Words: Soil health, grazing, fire, wildfire, ponderosa pine, *Pinus ponderosa*, soil organic matter

Introduction

The northern Great Plains steppe ecoregion of North America includes multiple plant communities that were largely shaped by periodic drought, grazing animals, and frequent fires

(Martin et al. 1998; Anderson 2006). Grasslands that evolved with these disturbances have the ability to recover quicker than ecosystems where fire was not ecosystem-shaping (Sousa 1984). Depending on the community type within the ecoregion, wildfires were common and occurred at varying fire return intervals (Wakimoto et al. 2004). In the ponderosa pine savannas, fires burned the understory vegetation every 10-12 years (Brown and Sieg 1999). Ungulate grazers (e.g. bison, elk) are often attracted to recently burned areas because of subsequent vegetative growth. The spatial-temporal interaction of fire and secondary herbivory, referred to as pyric-herbivory, is thought to drive vegetation mosaics in the Great Plains (Fuhlendorf et al. 2009). Despite this ecological dynamic, current Bureau of Land Management (BLM) and Forest Service (USFS) recommendations are to rest pastures from livestock grazing two years after fire to allow for seeds to establish and burned plants to regain vigor (Blaisdell et al. 1982, Bureau of Land Management 2007, USDA Forest Service 2006). However, recent research suggests that the ecoregion's grassland/savanna may not require rest periods from grazing (Vermeire et al. 2014; Gates et al. 2017; Powell et al. 2018; Williams 2020).

Related studies in the ecoregion have focused mainly on the effect of post-fire grazing on vegetation. Grazers tend to focus on recently burned areas, specifically when the vegetation is growing (Augustine and Derner 2014; Powell et al. 2018). However, similar herbaceous biomass and productivity between grazed and ungrazed sites following fire has been observed in the northern Great Plains (Vermeire et al. 2014; Gates et al. 2017; Powell et al. 2018). In a review on grazing effects on biodiversity, disturbances that removed biomass (i.e. fire and grazing) and lead to decreased plant dominance on the site had increased plant diversity in grasslands and savannas (Koerner et al. 2018). In the NGP ecoregion, grazing history, grazing utilization, and

fire each affected species composition or site production, but did not have interacting effects (Vermeire et al. 2018). Recent studies have observed neutral to positive vegetative responses to the fire-grazing interaction in the northern Great Plains. Less is known about these disturbances affecting key soil properties and hence rangeland sustainability (Neary et al. 1999; Limb et al. 2016).

Soil health is assessed as a collection of soil properties to indicate the capacity of soil to function as an ecosystem sustaining plants, animals, and humans (Doran and Zeiss 2000). This study investigated soil function by testing the hydrologic function (i.e., soil hydraulic conductivity), properties related to nutrient cycling (i.e., soil organic matter, plant available nutrients, pH), and soil structure (i.e., aggregate stability). Field saturated hydraulic conductivity (HC) reflects the effects of several physical characteristic such as soil texture, organic matter, soil structure, and water repellency on soil moisture levels (Ebel and Martin 2017). Because of this, measured changes in HC suggest alterations in the soil's ability to capture precipitation (Kirkham 2004). Soil organic matter (SOM) impacts the physical, chemical, and biological functions in soils and is the leading choice when one soil metric is needed to asses soil health (Obalum et al. 2017). Soil organic carbon (SOC) makes up a large portion of SOM (Tiessen et al. 1994) therefore, increasing SOC in grazing lands tends to increase land productivity and improves many ecosystem services (Sarkar et al. 2020). Soil mineral nitrogen (N) and phosphorous (P) are important for predicting potential plant productivity (Allan and Killorn 1996). Soil pH affects plant growth and is a good initial indicator for soil health (Smith and Doran 1996). Lastly, stable soil aggregates provide site stabilization and physical protection of SOM (Wiesmeier et al. 2019). Understanding ecosystem function plays an important role in

applying and interpreting soil health measures (Brown and Herrick 2016). Soil health has been of growing interest in recent years because of its link with sustainable grazing lands (Derner et al. 2018). Hence, monitoring soil degradation or recovery may provide insight into improving rangeland management decisions (Karl et al. 2017).

We tested the effect of grazing after fire (moderate versus no grazing) on 12 soil properties in a ponderosa pine savanna ecosystem. We used soil health metrics to determine effects of the recommended two years of rest from grazing after fire. We hypothesized that moderate grazing after fire might negatively affect some soil properties related to the savanna's hydrologic function, nutrient cycling, and soil structure. If grazing after fire reduces soil organic matter, then we predict hydraulic function, nutrient cycling, and soil structure will be negatively impacted. Properly managing these savanna landscapes requires understanding whether their function can be easily disrupted by disturbances (fire and grazing). The objectives were to improve 1) understanding the impact of grazing after fire on soil properties related to several important ecosystem functions and 2) strategies for grazing management post-fire. Soil health data from this study are complemented with vegetation data from Williams (2020) to show the soil and plant community response to grazing after fire in northern Great Plains ponderosa pine savannas.

Methods

A large wildfire on mixed private, state, and federal lands in central Montana provided an opportunity to investigate the effects of grazing after fire on indicators of soil health. This experiment evaluated the effect of grazing two out of three years post-fire verses complete rest on soil properties related to hydrologic function, nutrient cycling, and soil stability. We

quantified the effects of livestock grazing at four sites per pasture over two pastures (8 total sites). At each site, two plots (15 x 25m) were established on similar burn severity sites and randomly assigned a grazing treatment (grazed versus not grazed) in June 2018. Fencing was erected on one plot per site. All sampling was conducted in 2019 and 2020.

Wildfire & Study Sites

The Lodgepole Complex Fire started by lightning on 19 July 2017 and was 90% contained by 30 July. It burned 109,346 ha of private, BLM, state, and Charles M. Russell National Wildlife Refuge lands across Garfield and Petroleum counties in Montana. Our study was conducted on inter-mixed private property and BLM administered land 27 km northwest of Sand Springs, MT. We sampled two pastures averaging 700 ha that were both burned in 2017. One of the pastures burned 14 years earlier from a prescribed fire by the BLM.

All sites were randomly selected within the Cabbart soil series (Loamy, mixed, superactive, calcareous, frigid, shallow Aridic Ustorthents, 2 to 75 % slopes) which is a common soil for ponderosa pine savanna communities in eastern Montana. Placing study sites on the same soil series helped to control for plot-to-plot variability within and between sites and pastures. Common C_3 graminoids were *Pascopyrum smithii* (Rydb.) Á. Löve*, Hesperostipa comata* (Trin. & Rupr.) Barkworth*, Carex filifolia* Nutt., and the common C_4 grass was *Bouteloua gracilis* (*Willd. Ex Kunth*) *Lag. Ex Griffiths*. Common forbs were *Ratibida columnifera* (Nutt.) Wooton & Standl.*, Psoralidium tenuiflorum* (Pursh) Rydb.*, and Logfia arvensis* (L.) Holub., *Artemisia frigida* Willd. was the most common shrub and *Pinus ponderosa* (Lawson & C. Lawson) the dominant tree species.

Total annual site precipitation averaged 390 mm (2000-2020). The majority of precipitation coming April through June, which averaged 185 mm (2000-2020). Precipitation values were 224 mm in 2017, 444 mm in 2018, 521 mm in 2019, and 340 mm in 2020. Following the fire in 2017, summer precipitation values between April and June were 234 mm, 181 mm, and 210 mm in 2018, 2019, and 2020, respectively (PRISM Climate Group 2020).

Post-Fire Grazing

Our aim was to graze both pastures the first year (2018) after wildfire, but that was prevented by fence reconstruction complications. Thereafter, the grazing treatment applied to both pastures was defined as grazing once within the first two growing seasons and a total of twice within the first three growing seasons (Table 1). Pastures were moderately grazed with approximately 50% forage utilization during the grazing period of July-September. By the end of 2019, the exclosures in both pastures represented the recommended two-year rest from grazing post-fire.

Sampling

We collected samples in 2019 and 2020 two weeks before cattle came into the pasture and two weeks after they were removed. To obtain a robust picture of the effect of grazing on post-fire soil recovery, we measured five soil characteristics thought to embrace the concept of soil health: Soil hydraulic conductivity, soil organic matter, soil aggregate stability, anion nutrients, and soil pH (Brown and Herrick 2016).

Soil hydraulic conductivity Hydraulic conductivity measurements were taken using a Mini-Disk Infiltrometer (MDI, Decagon Devices, Inc. Pullman, W.A., 2018). Suction rate was

set at 2 mm across all sites. At each site, MDI measurements were taken at three randomly selected locations within each exclosure and three in each grazed plot. Litter was removed from the surface without disrupting the mineral soil surface. To ensure consistent contact between the MDI and soil on slopes, 20 g of 70-grit silica were poured on top of the soil. Time began when contact was made with the sand, but to avoid skewed HC values from the sand, infiltration recordings from 0-30 seconds were not used in calculating HC. Beginning at 30 seconds, ml recordings were taken at 30 second intervals. Recordings ended after 20 ml of water had infiltrated from the 30 second reference or 15.5 minutes passed, whichever came first. Measurements were taken in sampling periods 1 and 3 prior to grazing (Table 1).

Soil organic matter To evaluate the effect of post-fire grazing on soil organic matter, we used loss on ignition (LOI, % wt. loss) to obtain SOM levels. Three samples were collected before and after grazing with a 97 cm^3 corer to a depth of at least 10 cm and instantly bagged. In the lab cores were weighed, then placed in the drying oven at 40° C for 16 hrs and re-weighed to determine water content at time of collection. Any vegetation attached to the core surface was ground and added into the sample. Soil and roots were ground to pass a 2 mm sieve. Then six 10 g subsamples were pulled from each plot sample, placed in crucibles and put in a muffle furnace at 375° C for 16 hrs (Ball 1964). Percent weight loss during ignition is reported as SOM. Values represent post-grazing from sampling periods 2 and 4 (Table 1).

Soil nutrients We measured plant available nutrients in plots with PRS® probes (Western Ag Innovations Inc., Saskatoon, Canada). The probes were inserted per manufacturer

instructions by cutting a slit in the soil and vertically inserting the probe to cover the depth range of 3.5-9 cm and to capture plant available anions. Probes were inserted 24 June 2019 and retrieved 18 October 2019 (116 days) and inserted 7 July 2020 and retrieved 5 November 2020 (121 days). Removal occurred beyond 116 days during 2020 due to weather and management actions. At each of the eight sites, two probes were placed in the exclosure plot and two were placed in grazed plot. Probes were sent to Western Ag Innovations (Saskatoon, SK, Canada) for analysis (NO_3-N, P, S, Fe, Mn, Zn, and B with units reported in µg ion/10 cm^2). Some nutrient concentrations were below mean detection level (MDL), which means the ion concentration is not greater than zero at $P<0.01$. These values were used in analysis, but inferences were limited for these nutrients.

Soil pH Six pH measurements were made in the lab on SOM cored samples using pH and conductivity combination handheld unit HI 98130 (Hanna Instruments, RI, USA). A subsample (20g) of soil collected for soil organic matter evaluation was mixed with DI water to a consistent paste state for measurements. Values were calculated after grazing from periods 2 and 4 (Table 1).

Soil aggregate stability Soil aggregate stability was determined following field protocol of Herrick et al. (2001). We collected 5 surface samples in each exclosure and grazed plot. Samples were taken prior to grazing during periods 1 and 3 (Table 1).

Statistical Analysis

Outliers were identified using the maximum normed residual (Snedecor and Cochran 1991) method and replaced with the plot mean. Prior to analysis, plot averages were calculated from subsamples or plot samples on all soil metrics. The effects of grazing and year after fire on measured physical and chemical soil parameters were analyzed using ANOVA (Fox and Weisberg 2019) with a generalized linear mixed models package (Lme4 package) (Bates et al. 2015) including grazing treatment, year, and a grazing by year interaction as fixed effects and site nested within pasture as a random intercept to account for autocorrelation of multiple plots at each site within pasture. Data were plotted and log transformed if needed to satisfy assumptions of normality and homogeneity of variance. Transformed data were back transformed for presentation and least squared means were calculated using the 'emmeans' package (Lenth 2021). An alpha ≤ 0.10 was considered significant and all statistical analyses were performed in R (R Core Team 2021).

Results

No interactions between treatment and year were observed ($P \geq 0.14$). Therefore, data are displayed as treatment and year main effects (Table 2 and 3). We detected only one marginally significant effect ($P<0.1$) of grazing after fire on soil properties related to ecosystem function. Specifically, SOM was 7% greater in ungrazed than grazed areas. Other soil properties were not appreciably affected by grazing post-fire (Table 2).

Differences between 2019 and 2020 were detected in 8 out of the 11-soil metrics measured (Table 3). Hydraulic conductivity, soil aggregate stability, iron, zinc, and pH decreased from 2019 to 2020. Two different people sampled aggregate stability between years and subjectivity in measurements could have influenced yearly differences observed. Nitrate,

phosphorous, and manganese increased from 2019 to 2020. Nitrate had multiple values fall below MDL as well in 2019 so year effect may not be meaningful.

Discussion

The majority of soil measurements studied did not vary by grazing treatment after fire. Most of our results suggest grazing after fire, specifically the first two out of three years post-fire, did not impact hydrologic function, nutrient cycling, or soil stability. However, we did detect more SOM in ungrazed than grazed plots. This result may be ecologically important. For example, grazing after fire could reduce SOM because defoliated plants are less likely to translocate resources belowground (Ryle and Powell 1975; Kitchen et al. 2009). However, several factors may drive a change in SOM. For example, total SOM may be mediated by variation in carbon inputs (e.g. quantity, quality, depth, timing) and/or rates of microbial decomposition (e.g. inputs may prime microbial activity and increase mineralization (Tamura and Tharayil 2014; Poirier et al. 2018; Dijkstra et al. 2021). Microbial decomposition may also be affected by carbon inputs and other factors related to grazing effects such as a change(s) to bulk density, soil temperature, etc.

If the grazing effects on SOM after fire persisted beyond three years, grazing management would have to be reassessed to prevent decreasing SOM to the site and possibly affecting the plant community and ecosystem processes (Bardgett and Wardle 2003; Chen et al. 2015). Among the soil properties measured, SOM may be the most sensitive to grazing after fire and may function as a leading (not trailing) indicator of change to other ecosystem functions (Bongiorno et al. 2019) For example, variation in SOM is often related to many other soil functions (e.g. infiltration, soil structure, nutrient cycling) (Obalum et al. 2017). If SOM is

persistently less in areas grazed after fire than ungrazed areas, then prolonged differences could affect other ecosystem functions. However, with the decrease of SOM in grazed plots, we found no evidence that either hydrological function (i.e. infiltration) or plant available nutrients (N, P) were impacted. Because our study did not measure SOM pre-treatment, we cannot rule out the possibility that effects were at least partly related to pre-existing differences and spatial variation in SOM (VandenBygaart and Angers 2011; Necpálová et al. 2014).

We observed no effect of grazing treatments on soil water infiltration. This is somewhat surprising because grazing often reduces infiltration (Gifford and Hawkins 1978). Some studies in the ecoregion also reported no effect of grazing treatments on infiltration (Comer 2019; Reinhart et al. 2019). Water infiltration is important because it relates to hydrologic functioning and is often positively related to plant production (Thompson et al. 2010; Reinhart et al. 2015). Infiltration is also thought to be positively correlated with SOM (Franzluebbers 2002). While we detected effects of grazing treatment on SOM, we found no effects on infiltration. Grazing is known to reduce aggregate stability through compaction and there is some evidence that reductions in aggregate stability relate to less infiltration (Blackburn 1984; Briske et al. 2011). However, we found no grazing effects on aggregate stability. Furthermore, others report no relationship between soil aggregate stability and infiltration in this ecoregion (Reinhart et al. 2019). Our findings further suggest that SOM and aggregate stability may be weak predictors of variation in infiltration (Reinhart et al. 2019). The grazing intensity applied in the two years may have not been extreme enough to impact infiltration and/or aggregate stability (Blackburn 1984; Briske et al. 2011). This suggests moderate stocking rate applied after fire may have few if any negative effects on key soil functions of savanna sites in the northern Great Plains.

Another study measured vegetative properties for our experiment and reported less litter in 2018 in grazed than ungrazed treatments (Williams 2020). However, litter may have not been the driver of the SOM differences we observed. Others suggested SOM in mineral soil is mainly a product of root and microbial biomass and not litter (Sokol and Bradford 2019; Dijkstra et al. 2021). We suspect that litter incorporation is sufficiently slow in these semiarid savannas and that SOM in mineral soil is likely more a product of roots and soil microbes.

Conclusion

We found few effects of grazing twice during the three years after fire on soil properties related to hydrologic function, soil stability, and nutrient cycling. Soil organic matter was less in grazed than ungrazed treatments. Because SOM may relate to multiple soil processes, this result is evidence of some potential benefit to resting pastures from grazing after wildfire. However, nearly all other soil properties were unaffected by grazing including functions (e.g. hydrologic, nutrient cycling) that are thought to be affected by SOM. By 2020, we found no appreciable grazing treatment effect on water infiltration, plant available nutrients, or aggregate stability. The overall soil response supports the hypothesis that ponderosa pine savannas in the northern Great Plains ecoregion are relatively resilient to grazing after fire.

Tables

Table 1. Timing of wildfire, livestock grazing, and sampling from 2017 to 2020. Sampling periods 1 and 3 were taken approximately 2 weeks prior to cattle coming into the pastures and periods 2 and 4 were taken approximately two weeks after cattle came out of the pastures.

	2017	2018	2019			2020		
Pasture 1	Burned	**Grazed**	*1*	Rested	*2*	*3*	**Grazed**	*4*
Pasture 2	Burned	Rested	*1*	**Grazed**	*2*	*3*	**Grazed**	*4*

Table 2. Soil organic matter (SOM) at 0-10cm, hydraulic conductivity, soil aggregate stability, nitrate (NO3), phosphorous (P), iron (Fe), manganese (Mn), zinc (Zn), boron (B), sulfur (S), pH at 0-10cm means, standard errors of the mean and P-values of grazing exclosure and grazed plots from eastern Montana in 2019 and 2020. Soil organic matter (%), hydraulic conductivity (mm/hr), all nutrients (µg ion/10cm^2). Bolded p-values are significant (P< 0.1)

	Exclosure	Grazed	SE	p-value
SOM[b]	3.11	2.90	0.25	**0.08**
Conductivity[a]	23.82	19.40	4.38	0.34
Stability[a]	5.55	5.37	0.17	0.21
NO3[c]	5.16	7.89	1.95	0.15
P[c]	1.92	1.89	0.61	0.93
Fe[c]	1.79	1.78	0.51	0.98
Mn[c]	0.72	0.72	0.13	0.98
Zn[c]	0.58	0.55	0.07	0.70
B[c]	0.08	0.06	0.01	0.30
S[c]	6.79	7.61	0.76	0.36
pH[b]	7.40	7.38	0.13	0.85

[a] Sampled pre grazing
[b] Sampled post grazing
[c] Values for entire period from 2 weeks before to 2 weeks after grazing

Table 3. Soil organic matter (SOM) at 0-10cm, hydraulic conductivity, soil aggregate stability, nitrate (NO3), phosphorous (P), iron (Fe), manganese (Mn), zinc (Zn), boron (B), sulfur (S), pH at 0-10cm means, standard errors of the mean and P-values of soil metrics from eastern Montana in 2019 and 2020. Soil organic matter (%), hydraulic conductivity (mm/hr), all nutrients (µg ion/10cm^2). Bolded p-values are significant (P< 0.1).

	2 years after fire	3 years after fire	SE	p-value
SOM[b]	2.94	3.08	0.25	0.22
Conductivity[a]	27.51	15.71	4.23	**0.01**
Stability[a]	5.95	4.97	0.13	**<0.01**
NO3[c]	1.12	11.93	1.46	**<0.01**
P[c]	1.53	2.36	0.62	**0.05**
Fe[c]	2.35	1.35	0.52	**0.02**
Mn[c]	0.60	0.84	0.12	**0.07**
Zn[c]	0.83	0.38	0.05	**<0.01**
B[c]	0.06	0.08	0.01	0.14
S[c]	6.70	7.70	0.76	0.26
pH[b]	7.57	7.21	0.13	**<0.01**

[a] Sampled pre grazing
[b] Sampled post grazing
[c] Values for entire period from 2 weeks before to 2 weeks after grazing

References Cited

Allan DL, Killorn R (1996) Assessing Soil Nitrogen, Phosphorus, and Potassium for Crop Nutrition and Environmental Risk. In: Methods for Assessing Soil Quality. John Wiley & Sons, Ltd, pp 187–201

Anderson RC (2006) Evolution and Origin of the Central Grassland of North America: Climate, Fire, and Mammalian Grazers. The Journal of the Torrey Botanical Society 133:626–647

Augustin C, Cihacek LJ (2016) Relationships Between Soil Carbon and Soil Texture in the Northern Great Plains: Soil Science 181:386–392. https://doi.org/10.1097/SS.0000000000000173

Augustine DJ, Derner JD (2014) Controls over the strength and timing of fire–grazer interactions in a semi-arid rangeland. Journal of Applied Ecology 51:242–250. https://doi.org/10.1111/1365-2664.12186

Augustine DJ, McNaughton SJ (2006) Interactive Effects of Ungulate Herbivores, Soil Fertility, and Variable Rainfall on Ecosystem Processes in a Semi-arid Savanna. Ecosystems 9:1242–1256. https://doi.org/10.1007/s10021-005-0020-y

Ball DF (1964) Loss-on-Ignition as an Estimate of Organic Matter and Organic Carbon in Non-Calcareous Soils. Journal of Soil Science 15:84–92. https://doi.org/10.1111/j.1365-2389.1964.tb00247.x

Bardgett RD, Wardle DA (2003) Herbivore-Mediated Linkages Between Aboveground and Belowground Communities. Ecology 84:2258–2268. https://doi.org/10.1890/02-0274

Bates D, Mächler M, Bolker B, Walker S (2015) Fitting Linear Mixed-Effects Models Using lme4. J Stat Softw 67:1–48. https://doi.org/10.18637/jss.v067.i01

Biondini ME, Patton BD, Nyren PE (1998) Grazing Intensity and Ecosystem Processes in a Northern Mixed-Grass Prairie, Usa. Ecological Applications 8:469–479. https://doi.org/10.1890/1051-0761(1998)008[0469:GIAEPI]2.0.CO;2

Blackburn WH (1984) Impacts of grazing intensity and specialized grazing systems on watershed characteristics and responses. In: Developing Strategies for Rangeland Management. Westview Press, Boulder, CO, USA, pp 927–983

Bongiorno G, Bünemann EK, Oguejiofor CU, et al (2019) Sensitivity of labile carbon fractions to tillage and organic matter management and their potential as comprehensive soil quality indicators across pedoclimatic conditions in Europe. Ecological Indicators 99:38–50. https://doi.org/10.1016/j.ecolind.2018.12.008

Briske DD, Derner JD, Milchunas DG, Tate KW (2011) An evidence-based assessment of prescribed grazing practices. In: In Conservation benefits of rangeland practices: Assessment, recommendations, and knowledge gaps. United States Department of Agriculture, Natural Resource Conservation Service, Washington, DC, pp 22–74

Brown JR, Herrick JE (2016) Making soil health a part of rangeland management. Journal of Soil and Water Conservation 71:55A-60A. https://doi.org/10.2489/jswc.71.3.55A

Brown PM, Sieg CH (1999) Historical variability in fire at the ponderosa pine - Northern Great Plains prairie ecotone, southeastern Black Hills, South Dakota. Écoscience 6:539–547. https://doi.org/10.1080/11956860.1999.11682563

Busse MD, Simon SA, Riegel GM (2000) Tree-Growth and Understory Responses to Low-Severity Prescribed Burning in Thinned Pinus ponderosa Forests of Central Oregon. for sci 46:258–268. https://doi.org/10.1093/forestscience/46.2.258

Certini G (2005) Effects of fire on properties of forest soils: a review. Oecologia 143:1–10. https://doi.org/10.1007/s00442-004-1788-8

Chen W, Huang D, Liu N, et al (2015) Improved grazing management may increase soil carbon sequestration in temperate steppe. Scientific Reports 5:10892. https://doi.org/10.1038/srep10892

Comer J (2019) Effects of Grazing and Fire on Soil Microbial Communities and Hydrological Processes in the Northern Great Plains Grassland. Thesis - Open Access, South Dakota State University

Covington WW, Sackett SS (1992) Soil mineral nitrogen changes following prescribed burning in ponderosa pine. Forest Ecology and Management 54:175–191. https://doi.org/10.1016/0378-1127(92)90011-W

DeBano LF (2000) The role of fire and soil heating on water repellency in wildland environments: a review. Journal of Hydrology 231–232:195–206. https://doi.org/10.1016/S0022-1694(00)00194-3

DeBano LF, Dunn PH, Conrad CE (1977) Proceedings of the Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems, August 1-5, 1977, Palo Alto, California. Forest Service, U.S. Department of Agriculture

Derner JD, Smart AJ, Toombs TP, et al (2018) Soil Health as a Transformational Change Agent for US Grazing Lands Management. Rangeland Ecology & Management 71:403–408. https://doi.org/10.1016/j.rama.2018.03.007

Dijkstra FA, Zhu B, Cheng W (2021) Root effects on soil organic carbon: a double-edged sword. New Phytologist 230:60–65. https://doi.org/10.1111/nph.17082

Doran JW, Zeiss MR (2000) Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology 15:3–11. https://doi.org/10.1016/S0929-1393(00)00067-6

Dormaar JF, Smoliak S, Willms WD (1990) Distribution of nitrogen fractions in grazed and ungrazed fescue grassland Ah horizons. Rangeland Ecology & Management / Journal of Range Management Archives 43:6–9

Ebel BA, Martin DA (2017) Meta-analysis of field-saturated hydraulic conductivity recovery following wildland fire: Applications for hydrologic model parameterization and resilience assessment. Hydrological Processes 31:3682–3696. https://doi.org/10.1002/hyp.11288

Evans RD, Gill RA, Eviner VT, Bailey V (2017) Soil and Belowground Processes. In: Briske DD (ed) Rangeland Systems: Processes, Management and Challenges. Springer International Publishing, Cham, pp 131–168

Fernández-Ugalde O, Virto I, Barré P, et al (2014) Mechanisms of macroaggregate stabilisation by carbonates: implications for organic matter protection in semi-arid calcareous soils. Soil Res 52:180–192. https://doi.org/10.1071/SR13234

Fox DM, Darboux F, Carrega P (2007) Effects of fire-induced water repellency on soil aggregate stability, splash erosion, and saturated hydraulic conductivity for different size fractions. Hydrological Processes 21:2377–2384. https://doi.org/10.1002/hyp.6758

Fox J, Weisberg S (2019) An R Companion to Applied Regression, Third. Sage, Thousands Oaks, CA

Frank AB, Liebig MA, Hanson JD (2002) Soil carbon dioxide fluxes in northern semiarid grasslands. Soil Biology and Biochemistry 34:1235–1241. https://doi.org/10.1016/S0038-0717(02)00062-7

Franzluebbers AJ (2002) Water infiltration and soil structure related to organic matter and its stratification with depth. Soil and Tillage Research 66:197–205. https://doi.org/10.1016/S0167-1987(02)00027-2

Fuhlendorf SD, Engle DM, Kerby J, Hamilton R (2009) Pyric Herbivory: Rewilding Landscapes through the Recoupling of Fire and Grazing. Conservation Biology 23:588–598. https://doi.org/10.1111/j.1523-1739.2008.01139.x

Gates EA, Vermeire LT, Marlow CB, Waterman RC (2017) Reconsidering rest following fire: Northern mixed-grass prairie is resilient to grazing following spring wildfire. Agriculture, Ecosystems & Environment 237:258–264. https://doi.org/10.1016/j.agee.2017.01.001

Gifford GF, Hawkins RH (1978) Hydrologic impact of grazing on infiltration: A critical review. Water Resources Research 14:305–313. https://doi.org/10.1029/WR014i002p00305

González-Pérez JA, González-Vila FJ, Almendros G, Knicker H (2004) The effect of fire on soil organic matter—a review. Environment International 30:855–870. https://doi.org/10.1016/j.envint.2004.02.003

Helalia AM (1993) The relation between soil infiltration and effective porosity in different soils. Agricultural Water Management 24:39–47. https://doi.org/10.1016/0378-3774(93)90060-N

Karl JW, Herrick JE, Pyke DA (2017) Monitoring protocols: Options, approaches, implementation, benefits. Springer, pp 527–567

Karlen DL, Mausbach MJ, Doran JW, et al (1997) Soil Quality: A Concept, Definition, and Framework for Evaluation (A Guest Editorial). Soil Science Society of America Journal 61:4–10. https://doi.org/10.2136/sssaj1997.03615995006100010001x

Keeley JE (2009) Fire intensity, fire severity and burn severity: a brief review and suggested usage. International Journal of Wildland Fire 18:116. https://doi.org/10.1071/WF07049

Kennard DK, Gholz HL (2001) Effects of high- and low-intensity fires on soil properties and plant growth in a Bolivian dry forest. Plant and Soil 234:119–129. https://doi.org/10.1023/A:1010507414994

Kirkham MB (2004) Principles of Soil and Plant Water Relations. Elsevier Science & Technology, Burlington, UNITED STATES

Kitchen DJ, Blair JM, Callaham MA (2009) Annual fire and mowing alter biomass, depth distribution, and C and N content of roots and soil in tallgrass prairie. Plant Soil 323:235–247. https://doi.org/10.1007/s11104-009-9931-2

Koerner SE, Smith MD, Burkepile DE, et al (2018) Change in dominance determines herbivore effects on plant biodiversity. Nature Ecology & Evolution 2:1925–1932. https://doi.org/10.1038/s41559-018-0696-y

Kral KC-A (2014) Impact of Wildfire and Targeted Grazing Effects on Northern Great Plains Range and Pasture Lands. Thesis - Open Access, North Dakota State University

Kutiel P, Naveh Z (1987) The effect of fire on nutrients in a pine forest soil. Plant Soil 104:269–274. https://doi.org/10.1007/BF02372541

Lenth RV (2021) Emmeans: Estimated Marginal Means, aka Least-Squares Means

Lentile LB, Morgan P, Hudak AT, et al (2007) Post-Fire Burn Severity and Vegetation Response Following Eight Large Wildfires Across the Western United States. fire ecol 3:91–108. https://doi.org/10.4996/fireecology.0301091

Lewis SA, Wu JQ, Robichaud PR (2006) Assessing burn severity and comparing soil water repellency, Hayman Fire, Colorado. Hydrological Processes 20:1–16. https://doi.org/10.1002/hyp.5880

Limb RF, Fuhlendorf SD, Engle DM, Miller RF (2016) Synthesis Paper: Assessment of Research on Rangeland Fire as a Management Practice. Rangeland Ecology & Management 69:415–422. https://doi.org/10.1016/j.rama.2016.07.013

Martin BS, Cooper S, Heidel B, et al (1998) Natural community inventory within landscapes in the Northern Great Plains Steppe Ecoregion of the United States

Martin DA, Moody JA (2001) Comparison of soil infiltration rates in burned and unburned mountainous watersheds. Hydrological Processes 15:2893–2903. https://doi.org/10.1002/hyp.380

Mataix-Solera J, Cerdà A, Arcenegui V, et al (2011) Fire effects on soil aggregation: A review. Earth-Science Reviews 109:44–60. https://doi.org/10.1016/j.earscirev.2011.08.002

Neary DG, Klopatek CC, DeBano LF, Ffolliott PF (1999) Fire effects on belowground sustainability: a review and synthesis. Forest Ecology and Management 122:51–71. https://doi.org/10.1016/S0378-1127(99)00032-8

Necpálová M, Anex RP, Kravchenko AN, et al (2014) What does it take to detect a change in soil carbon stock? A regional comparison of minimum detectable difference and experiment duration in the north central United States. Journal of Soil and Water Conservation 69:517–531. https://doi.org/10.2489/jswc.69.6.517

Oades JM (1984) Soil organic matter and structural stability: mechanisms and implications for management. In: Tinsley J, Darbyshire JF (eds) Biological Processes and Soil Fertility. Springer Netherlands, Dordrecht, pp 319–337

Obalum SE, Chibuike GU, Ouyang Y (2017) Soil organic matter as sole indicator of soil degradation. Environ Monit Assess 189:. https://doi.org/10.1007/s10661-017-5881-y

Oldfield EE, Wood SA, Bradford MA (2020) Direct evidence using a controlled greenhouse study for threshold effects of soil organic matter on crop growth. Ecological Applications 30:e02073. https://doi.org/10.1002/eap.2073

Pei S, Fu H, Wan C (2008) Changes in soil properties and vegetation following exclosure and grazing in degraded Alxa desert steppe of Inner Mongolia, China. Agriculture, Ecosystems & Environment 124:33–39. https://doi.org/10.1016/j.agee.2007.08.008

Plaza-Álvarez PA, Lucas-Borja ME, Sagra J, et al (2019) Changes in soil hydraulic conductivity after prescribed fires in Mediterranean pine forests. Journal of Environmental Management 232:1021–1027. https://doi.org/10.1016/j.jenvman.2018.12.012

Poirier V, Roumet C, Munson AD (2018) The root of the matter: Linking root traits and soil organic matter stabilization processes. Soil Biology and Biochemistry 120:246–259. https://doi.org/10.1016/j.soilbio.2018.02.016

Powell J, Martin B, Dreitz VJ, Allred BW (2018) Grazing Preferences and Vegetation Feedbacks of the Fire-Grazing Interaction in the Northern Great Plains. Rangeland Ecology & Management 71:45–52. https://doi.org/10.1016/j.rama.2017.09.003

Printz JL, Toledo D, Boltz SC (2014) Rangeland health assessment: The key to understanding and assessing rangeland soil health in the Northern Great Plains. Journal of Soil and Water Conservation 69:73A-77A. https://doi.org/10.2489/jswc.69.3.73A

PRISM Climate Group PRISM Climate Group. http://prism.oregonstate.edu. Accessed 15 Apr 2021

R Core Team (2021) R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria

Reinhart KO, Nichols KA, Petersen M, Vermeire LT (2015) Soil aggregate stability was an uncertain predictor of ecosystem functioning in a temperate and semiarid grassland. Ecosphere 6:art238. https://doi.org/10.1890/ES15-00056.1

Reinhart KO, Rinella MJ, Waterman RC, et al (2019) Testing rangeland health theory in the Northern Great Plains. Journal of Applied Ecology 56:319–329. https://doi.org/10.1111/1365-2664.13273

Robichaud PR, Wagenbrenner JW, Pierson FB, et al (2016) Infiltration and interrill erosion rates after a wildfire in western Montana, USA. CATENA 142:77–88. https://doi.org/10.1016/j.catena.2016.01.027

Ryle GJA, Powell CE (1975) Defoliation and Regrowth in the Graminaceous Plant: The Role of Current Assimilate. Annals of Botany 39:297–310. https://doi.org/10.1093/oxfordjournals.aob.a084943

Sarkar R, Corriher-Olson V, Long C, Somenahally A (2020) Challenges and Potentials for Soil Organic Carbon Sequestration in Forage and Grazing Systems. Rangeland Ecology & Management 73:786–795. https://doi.org/10.1016/j.rama.2020.04.002

Savadogo P, Sawadogo L, Tiveau D (2007) Effects of grazing intensity and prescribed fire on soil physical and hydrological properties and pasture yield in the savanna woodlands of Burkina Faso. Agriculture, Ecosystems & Environment 118:80–92. https://doi.org/10.1016/j.agee.2006.05.002

Shakesby RA, Doerr SH (2006) Wildfire as a hydrological and geomorphological agent. Earth-Science Reviews 74:269–307. https://doi.org/10.1016/j.earscirev.2005.10.006

Sheikh Leiveci K, Abbas Kazemi G, Damough N (2016) Measuring infiltration rate and hydraulic conductivity in a dry well in a thin overburden. JGeope 6:63–73

Sikora LJ, Stott DE (1996) Soil Organic Carbon and Nitrogen. In: Methods for Assessing Soil Quality. John Wiley & Sons, Ltd, pp 157–167

Smith JL, Doran JW (1996) Measurement and Use of pH and Electrical Conductivity for Soil Quality Analysis. In: Methods for Assessing Soil Quality. John Wiley & Sons, Ltd, pp 169–185

Snedecor GW, Cochran WG (1991) Statistical Methods, 8th Edition | Wiley, Eighth

Sokol NW, Bradford MA (2019) Microbial formation of stable soil carbon is more efficient from belowground than aboveground input. Nature Geoscience 12:46–53. https://doi.org/10.1038/s41561-018-0258-6

Sousa WP (1984) The Role of Disturbance in Natural Communities. Annual Review of Ecology and Systematics 15:353–391. https://doi.org/10.1146/annurev.es.15.110184.002033

Stavi I, Barkai D, Knoll YM, Zaady E (2016) Livestock grazing impact on soil wettability and erosion risk in post-fire agricultural lands. Science of The Total Environment 573:1203–1208. https://doi.org/10.1016/j.scitotenv.2016.03.126

Switzer JM, Hope GD, Grayston SJ, Prescott CE (2012) Changes in soil chemical and biological properties after thinning and prescribed fire for ecosystem restoration in a Rocky Mountain Douglas-fir forest. Forest Ecology and Management 275:1–13. https://doi.org/10.1016/j.foreco.2012.02.025

Tamura M, Tharayil N (2014) Plant litter chemistry and microbial priming regulate the accrual, composition and stability of soil carbon in invaded ecosystems. New Phytologist 203:110–124. https://doi.org/10.1111/nph.12795

Thompson SE, Harman CJ, Heine P, Katul GG (2010) Vegetation-infiltration relationships across climatic and soil type gradients. Journal of Geophysical Research: Biogeosciences 115:. https://doi.org/10.1029/2009JG001134

Tiessen H, Cuevas E, Chacon P (1994) The role of soil organic matter in sustaining soil fertility. Nature 371:783–785. https://doi.org/10.1038/371783a0

VandenBygaart AJ, Angers DA (2011) Towards accurate measurements of soil organic carbon stock change in agroecosystems. Canadian Journal of Soil Science. https://doi.org/10.4141/S05-106

Vermeire LT, Crowder JL, Wester DB (2014) Semiarid Rangeland Is Resilient to Summer Fire and Postfire Grazing Utilization. Rangeland Ecology & Management 67:52–60. https://doi.org/10.2111/REM-D-13-00007.1

Vermeire LT, Strong DJ, Waterman RC (2018) Grazing History Effects on Rangeland Biomass, Cover and Diversity Responses to Fire and Grazing Utilization. Rangeland Ecology & Management 71:770–775. https://doi.org/10.1016/j.rama.2018.05.001

Wakimoto RH, Willard EE, Reid B (2004) Historic Fire Regimes and Changes Since European Settlement on the Northern Mixed Prairie: Effect on Ecosystem Function and Fire Behavior. University of Montana

Wiesmeier M, Urbanski L, Hobley E, et al (2019) Soil organic carbon storage as a key function of soils - A review of drivers and indicators at various scales. Geoderma 333:149–162. https://doi.org/10.1016/j.geoderma.2018.07.026

Williams A (2020) Evaluating grazing and defoliation effects on Ponderosa Pine grassland following the Lodgepole complex wildfire. Thesis - Open Access, Montana State University

CHAPTER THREE

CONCLUSIONS

Research results on rest periods from grazing after fire are variable across ecosystems and primarily focus on vegetation response. The Lodgepole Complex wildfire provided us with insight on how soil health on ponderosa pine grasslands in the northern Great Plains (NGP) respond to grazing two out of three years following a wildfire. Previous studies on rest periods in the NGP have shown that the system is resilient to grazing first year post fire. However, the adoption of this practice is not widespread due to conflicting research from other areas noting one to two years of rest is necessary for ecosystem recovery.

Chapter Two adds depth to these previous studies by demonstrating that grazing post fire has seemingly minimal impact on soil health in NGP ponderosa pine savannas. From the soil metrics measured, soil organic matter was lower in grazed plots compared to exclosures. With SOM differences between grazing treatments detected, long term monitoring is necessary to observe if this trend continues. Plant community changes due to SOM and associated factors would lead to a less resilient system to the next wildfire. Nutrient concentration, water infiltration and soil stability were not different between resting and grazing two out of the three years. This study indicates that rest periods are not necessary for soil health recovery, which is important for long-term grazing system sustainability.

Wildfires are getting larger in size and affecting more hectares in the west every year. When producers must rest land from grazing after fire in the NGP it has a significant impact on their operations. This study, as well as companion studies done in this area have shown that the commonly recommended rest periods are not as necessary for this ecosystem. This new

information will help inform land managers on post-fire grazing management practices when the next wildfire occurs in this ecosystem.

REFERENCES CITED

Allan, Deborah L., and Randy Killorn. 1996. “Assessing Soil Nitrogen, Phosphorus, and Potassium for Crop Nutrition and Environmental Risk.” In *Methods for Assessing Soil Quality*, 187–201. John Wiley & Sons, Ltd. https://doi.org/10.2136/sssaspecpub49.c11.

Anderson, Roger C. 2006. “Evolution and Origin of the Central Grassland of North America: Climate, Fire, and Mammalian Grazers.” *The Journal of the Torrey Botanical Society* 133 (4): 626–47.

Augustin, Christopher, and Larry J. Cihacek. 2016. “Relationships Between Soil Carbon and Soil Texture in the Northern Great Plains:” *Soil Science* 181 (8): 386–92. https://doi.org/10.1097/SS.0000000000000173.

Augustine, David J., and Samuel J. McNaughton. 2006. “Interactive Effects of Ungulate Herbivores, Soil Fertility, and Variable Rainfall on Ecosystem Processes in a Semi-Arid Savanna.” *Ecosystems* 9 (8): 1242–56. https://doi.org/10.1007/s10021-005-0020-y.

Ball, D. F. 1964. “Loss-on-Ignition as an Estimate of Organic Matter and Organic Carbon in Non-Calcareous Soils.” *Journal of Soil Science* 15 (1): 84–92. https://doi.org/10.1111/j.1365-2389.1964.tb00247.x.

Bardgett, Richard D., and David A. Wardle. 2003. “Herbivore-Mediated Linkages Between Aboveground and Belowground Communities.” *Ecology* 84 (9): 2258–68. https://doi.org/10.1890/02-0274.

Bates, Douglas, Martin Mächler, Ben Bolker, and Steve Walker. 2015. “Fitting Linear Mixed-Effects Models Using Lme4” 67 (1): 1–48. https://doi.org/10.18637/jss.v067.i01.

Biondini, Mario E., Bob D. Patton, and Paul E. Nyren. 1998. “Grazing Intensity and Ecosystem Processes in a Northern Mixed-Grass Prairie, Usa.” *Ecological Applications* 8 (2): 469–79. https://doi.org/10.1890/1051-0761(1998)008[0469:GIAEPI]2.0.CO;2.

Blackburn, W. H. 1984. “Impacts of Grazing Intensity and Specialized Grazing Systems on Watershed Characteristics and Responses.” In *Developing Strategies for Rangeland Management*, 927–83. Boulder, CO, USA: Westview Press. https://agris.fao.org/agris-search/search.do?recordID=US8618876.

Briske, D. D., and J. H. Richards. 1995. “Plant Responses to Defoliation: A Physiological, Morphological and Demographic Evaluation.” In *Wildland Plants: Physiological Ecology and Developmental Morphology*. Denver, CO: Society for Range Management.

Briske, David D, Justin D Derner, Daniel G Milchunas, and Ken W Tate. 2011. “An Evidence-Based Assessment of Prescribed Grazing Practices.” In *In Conservation Benefits of Rangeland Practices: Assessment, Recommendations, and Knowledge Gaps*, 22–74.

Washington, DC: United States Department of Agriculture, Natural Resource Conservation Service.

Brown, J. R., and J. E. Herrick. 2016. “Making Soil Health a Part of Rangeland Management.” *Journal of Soil and Water Conservation* 71 (3): 55A-60A. https://doi.org/10.2489/jswc.71.3.55A.

Brown, Peter M., and Carolyn H. Sieg. 1999. “Historical Variability in Fire at the Ponderosa Pine - Northern Great Plains Prairie Ecotone, Southeastern Black Hills, South Dakota.” *Écoscience* 6 (4): 539–47. https://doi.org/10.1080/11956860.1999.11682563.

Busse, Matt D., Steven A. Simon, and Gregg M. Riegel. 2000. “Tree-Growth and Understory Responses to Low-Severity Prescribed Burning in Thinned Pinus Ponderosa Forests of Central Oregon.” *Forest Science* 46 (2): 258–68. https://doi.org/10.1093/forestscience/46.2.258.

Certini, Giacomo. 2005. “Effects of Fire on Properties of Forest Soils: A Review.” *Oecologia* 143 (1): 1–10. https://doi.org/10.1007/s00442-004-1788-8.

Chen, Wenqing, Ding Huang, Nan Liu, Yingjun Zhang, Warwick B. Badgery, Xiaoya Wang, and Yue Shen. 2015. “Improved Grazing Management May Increase Soil Carbon Sequestration in Temperate Steppe.” *Scientific Reports* 5 (1): 10892. https://doi.org/10.1038/srep10892.

Comer, Jacob. 2019. “Effects of Grazing and Fire on Soil Microbial Communities and Hydrological Processes in the Northern Great Plains Grassland.” Thesis - Open Access, South Dakota State University.

Covington, W. Wallace, and S. S. Sackett. 1992. “Soil Mineral Nitrogen Changes Following Prescribed Burning in Ponderosa Pine.” *Forest Ecology and Management* 54 (1): 175–91. https://doi.org/10.1016/0378-1127(92)90011-W.

DeBano, L. F. 2000. “The Role of Fire and Soil Heating on Water Repellency in Wildland Environments: A Review.” *Journal of Hydrology* 231–232 (May): 195–206. https://doi.org/10.1016/S0022-1694(00)00194-3.

DeBano, L. F., P. H. Dunn, and C. E. Conrad. 1977. *Proceedings of the Symposium on the Environmental Consequences of Fire and Fuel Management in Mediterranean Ecosystems, August 1-5, 1977, Palo Alto, California*. Forest Service, U.S. Department of Agriculture.

Derner, Justin D., Alexander J. Smart, Theodore P. Toombs, Dana Larsen, Rebecca L. McCulley, Jeff Goodwin, Scott Sims, and Leslie M. Roche. 2018. “Soil Health as a Transformational Change Agent for US Grazing Lands Management.” *Rangeland Ecology & Management* 71 (4): 403–8. https://doi.org/10.1016/j.rama.2018.03.007.

Doran, John W., and Michael R. Zeiss. 2000. “Soil Health and Sustainability: Managing the Biotic Component of Soil Quality.” *Applied Soil Ecology* 15 (1): 3–11. https://doi.org/10.1016/S0929-1393(00)00067-6.

Dormaar, J. F., S. Smoliak, and W. D. Willms. 1990. “Distribution of Nitrogen Fractions in Grazed and Ungrazed Fescue Grassland Ah Horizons.” *Rangeland Ecology & Management / Journal of Range Management Archives* 43 (1): 6–9.

Ebel, Brian A., and Deborah A. Martin. 2017. “Meta-Analysis of Field-Saturated Hydraulic Conductivity Recovery Following Wildland Fire: Applications for Hydrologic Model Parameterization and Resilience Assessment.” *Hydrological Processes* 31 (21): 3682–96. https://doi.org/10.1002/hyp.11288.

Evans, R. Dave, Richard A. Gill, Valerie T. Eviner, and Vanessa Bailey. 2017. “Soil and Belowground Processes.” In *Rangeland Systems: Processes, Management and Challenges*, edited by David D. Briske, 131–68. Springer Series on Environmental Management. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-46709-2_4.

Fernández-Ugalde, Oihane, Iñigo Virto, Pierre Barré, Marcos Apesteguía, Alberto Enrique, María J. Imaz, and Paloma Bescansa. 2014. “Mechanisms of Macroaggregate Stabilisation by Carbonates: Implications for Organic Matter Protection in Semi-Arid Calcareous Soils.” *Soil Research* 52 (2): 180–92. https://doi.org/10.1071/SR13234.

Fox, D. M., F. Darboux, and P. Carrega. 2007. “Effects of Fire-Induced Water Repellency on Soil Aggregate Stability, Splash Erosion, and Saturated Hydraulic Conductivity for Different Size Fractions.” *Hydrological Processes* 21 (17): 2377–84. https://doi.org/10.1002/hyp.6758.

Fox, John, and Sanford Weisberg. 2019. *An R Companion to Applied Regression*. Third. Thousands Oaks, CA: Sage. https://socialsciences.mcmaster.ca/jfox/Books/Companion/.

Frank, A. B, M. A Liebig, and J. D Hanson. 2002. “Soil Carbon Dioxide Fluxes in Northern Semiarid Grasslands.” *Soil Biology and Biochemistry* 34 (9): 1235–41. https://doi.org/10.1016/S0038-0717(02)00062-7.

Fuhlendorf, Samuel D., David M. Engle, Jay Kerby, and Robert Hamilton. 2009. “Pyric Herbivory: Rewilding Landscapes through the Recoupling of Fire and Grazing.” *Conservation Biology* 23 (3): 588–98. https://doi.org/10.1111/j.1523-1739.2008.01139.x.

Ganjegunte, Girisha K., George F. Vance, Caroline M. Preston, Gerald E. Schuman, Lachlan J. Ingram, Peter D. Stahl, and Jeffrey M. Welker. 2005. “Soil Organic Carbon Composition in a Northern Mixed-Grass Prairie.” *Soil Science Society of America Journal* 69 (6): 1746–56. https://doi.org/10.2136/sssaj2005.0020.

Gates, Emily A., Lance T. Vermeire, Clayton B. Marlow, and Richard C. Waterman. 2017. "Reconsidering Rest Following Fire: Northern Mixed-Grass Prairie Is Resilient to Grazing Following Spring Wildfire." *Agriculture, Ecosystems & Environment* 237 (January): 258–64. https://doi.org/10.1016/j.agee.2017.01.001.

Gifford, Gerald F., and Richard H. Hawkins. 1978. "Hydrologic Impact of Grazing on Infiltration: A Critical Review." *Water Resources Research* 14 (2): 305–13. https://doi.org/10.1029/WR014i002p00305.

González-Pérez, José A., Francisco J. González-Vila, Gonzalo Almendros, and Heike Knicker. 2004. "The Effect of Fire on Soil Organic Matter—a Review." *Environment International* 30 (6): 855–70. https://doi.org/10.1016/j.envint.2004.02.003.

Helalia, Awad M. 1993. "The Relation between Soil Infiltration and Effective Porosity in Different Soils." *Agricultural Water Management* 24 (1): 39–47. https://doi.org/10.1016/0378-3774(93)90060-N.

Herrick, J. E, W. G Whitford, A. G de Soyza, J. W Van Zee, K. M Havstad, C. A Seybold, and M Walton. 2001. "Field Soil Aggregate Stability Kit for Soil Quality and Rangeland Health Evaluations." *CATENA*, Soil aggregation in arid and semi-arid environments, 44 (1): 27–35. https://doi.org/10.1016/S0341-8162(00)00173-9.

Karl, Jason W., Jeffrey E. Herrick, and David A. Pyke. 2017. "Monitoring Protocols: Options, Approaches, Implementation, Benefits." In , 527–67. Springer. https://pubs.er.usgs.gov/publication/70187414.

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.

Keeley, Jon E. 2009. "Fire Intensity, Fire Severity and Burn Severity: A Brief Review and Suggested Usage." *International Journal of Wildland Fire* 18 (1): 116. https://doi.org/10.1071/WF07049.

Kennard, D. K., and H. L. Gholz. 2001. "Effects of High- and Low-Intensity Fires on Soil Properties and Plant Growth in a Bolivian Dry Forest." *Plant and Soil* 234 (1): 119–29. https://doi.org/10.1023/A:1010507414994.

Kirkham, M. B. 2004. *Principles of Soil and Plant Water Relations*. Burlington, UNITED STATES: Elsevier Science & Technology. http://ebookcentral.proquest.com/lib/montana/detail.action?docID=294662.

Kitchen, Duane J., John M. Blair, and Mac A. Callaham. 2009. "Annual Fire and Mowing Alter Biomass, Depth Distribution, and C and N Content of Roots and Soil in Tallgrass Prairie." *Plant and Soil* 323 (1–2): 235–47. https://doi.org/10.1007/s11104-009-9931-2.

Kral, Katherine Claire-Ann. 2014. “Impact of Wildfire and Targeted Grazing Effects on Northern Great Plains Range and Pasture Lands.” Thesis - Open Access, North Dakota State University.

Kutiel, P., and Z. Naveh. 1987. “The Effect of Fire on Nutrients in a Pine Forest Soil.” *Plant and Soil* 104 (2): 269–74. https://doi.org/10.1007/BF02372541.

Lenth, Russell V. 2021. *Emmeans: Estimated Marginal Means, Aka Least-Squares Means*. https://CRAN.R-project.org/package=emmeans.

Lentile, Leigh B., Penelope Morgan, Andrew T. Hudak, Michael J. Bobbitt, Sarah A. Lewis, Alistair M. S. Smith, and Peter R. Robichaud. 2007. “Post-Fire Burn Severity and Vegetation Response Following Eight Large Wildfires Across the Western United States.” *Fire Ecology* 3 (1): 91–108. https://doi.org/10.4996/fireecology.0301091.

Lewis, Sarah A., Joan Q. Wu, and Peter R. Robichaud. 2006. “Assessing Burn Severity and Comparing Soil Water Repellency, Hayman Fire, Colorado.” *Hydrological Processes* 20 (1): 1–16. https://doi.org/10.1002/hyp.5880.

Limb, Ryan F., Samuel D. Fuhlendorf, David M. Engle, and Richard F. Miller. 2016. “Synthesis Paper: Assessment of Research on Rangeland Fire as a Management Practice.” *Rangeland Ecology & Management* 69 (6): 415–22. https://doi.org/10.1016/j.rama.2016.07.013.

Martin, Deborah A., and John A. Moody. 2001. “Comparison of Soil Infiltration Rates in Burned and Unburned Mountainous Watersheds.” *Hydrological Processes* 15 (15): 2893–2903. https://doi.org/10.1002/hyp.380.

Mataix-Solera, J., A. Cerdà, V. Arcenegui, A. Jordán, and L. M. Zavala. 2011. “Fire Effects on Soil Aggregation: A Review.” *Earth-Science Reviews* 109 (1): 44–60. https://doi.org/10.1016/j.earscirev.2011.08.002.

Neary, Daniel G, Carole C Klopatek, Leonard F DeBano, and Peter F Ffolliott. 1999. “Fire Effects on Belowground Sustainability: A Review and Synthesis.” *Forest Ecology and Management* 122 (1): 51–71. https://doi.org/10.1016/S0378-1127(99)00032-8.

Oades, J. M. 1984. “Soil Organic Matter and Structural Stability: Mechanisms and Implications for Management.” In *Biological Processes and Soil Fertility*, edited by J. Tinsley and J. F. Darbyshire, 319–37. Developments in Plant and Soil Sciences. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-009-6101-2_28.

Oldfield, Emily E., Stephen A. Wood, and Mark A. Bradford. 2020. “Direct Evidence Using a Controlled Greenhouse Study for Threshold Effects of Soil Organic Matter on Crop Growth.” *Ecological Applications* 30 (4): e02073. https://doi.org/10.1002/eap.2073.

Pei, Shifang, Hua Fu, and Changgui Wan. 2008. “Changes in Soil Properties and Vegetation Following Exclosure and Grazing in Degraded Alxa Desert Steppe of Inner Mongolia, China.” *Agriculture, Ecosystems & Environment*, Special Section: Problems and Prospects of Grassland Agroecosystems in Western China, 124 (1): 33–39. https://doi.org/10.1016/j.agee.2007.08.008.

Plaza-Álvarez, P. A., M. E. Lucas-Borja, J. Sagra, D. A. Zema, J. González-Romero, D. Moya, and J. De las Heras. 2019. “Changes in Soil Hydraulic Conductivity after Prescribed Fires in Mediterranean Pine Forests.” *Journal of Environmental Management* 232 (February): 1021–27. https://doi.org/10.1016/j.jenvman.2018.12.012.

Powell, Jacob, Brian Martin, Victoria J. Dreitz, and Brady W. Allred. 2018. “Grazing Preferences and Vegetation Feedbacks of the Fire-Grazing Interaction in the Northern Great Plains.” *Rangeland Ecology & Management* 71 (1): 45–52. https://doi.org/10.1016/j.rama.2017.09.003.

Printz, Jeffrey L., David Toledo, and Stanley C. Boltz. 2014. “Rangeland Health Assessment: The Key to Understanding and Assessing Rangeland Soil Health in the Northern Great Plains.” *Journal of Soil and Water Conservation* 69 (3): 73A-77A. https://doi.org/10.2489/jswc.69.3.73A.

PRISM Climate Group. n.d. “PRISM Climate Group.” Accessed November 2, 2020. http://prism.oregonstate.edu.

R Core Team. 2021. *R: A Language and Environment for Statistical Computing*. Vienna, Austria: R Foundation for Statistical Computing. https://www.R-project.org/.

Reeder, J. D, and G. E Schuman. 2002. “Influence of Livestock Grazing on C Sequestration in Semi-Arid Mixed-Grass and Short-Grass Rangelands.” *Environmental Pollution* 116 (3): 457–63. https://doi.org/10.1016/S0269-7491(01)00223-8.

Reinhart, Kurt O., & Sadikshya R. Dangi, and Lance T. Vermeire. 2016. “The Effect of Fire Intensity, Nutrients, Soil Microbes, and Spatial Distance on Grassland Productivity.” *Plant Soil* 409: 203–16. https://doi.org/10.1007/s11104-016-2957-3.

Reinhart, Kurt O., Matthew J. Rinella, Richard C. Waterman, Mark K. Petersen, and Lance T. Vermeire. 2019. “Testing Rangeland Health Theory in the Northern Great Plains.” *Journal of Applied Ecology* 56 (2): 319–29. https://doi.org/10.1111/1365-2664.13273.

Robichaud, Peter R., Joseph W. Wagenbrenner, Fredrick B. Pierson, Kenneth E. Spaeth, Louise E. Ashmun, and Corey A. Moffet. 2016. “Infiltration and Interrill Erosion Rates after a Wildfire in Western Montana, USA.” *CATENA* 142 (July): 77–88. https://doi.org/10.1016/j.catena.2016.01.027.

Ryle, G. J. A., and C. E. Powell. 1975. “Defoliation and Regrowth in the Graminaceous Plant: The Role of Current Assimilate.” *Annals of Botany* 39 (2): 297–310. https://doi.org/10.1093/oxfordjournals.aob.a084943.

Santos, G. L., and M. J. Trlica. 1978. “Clipping Effects on Production and Carbohydrate Reserves of Blue Grama and Western Wheatgrass,” no. 31: 384–86.

Sarkar, Reshmi, Vanessa Corriher-Olson, Charles Long, and Anil Somenahally. 2020. “Challenges and Potentials for Soil Organic Carbon Sequestration in Forage and Grazing Systems.” *Rangeland Ecology & Management*, Special Section: Weed-Suppressive Bacteria, 73 (6): 786–95. https://doi.org/10.1016/j.rama.2020.04.002.

Savadogo, Patrice, Louis Sawadogo, and Daniel Tiveau. 2007. “Effects of Grazing Intensity and Prescribed Fire on Soil Physical and Hydrological Properties and Pasture Yield in the Savanna Woodlands of Burkina Faso.” *Agriculture, Ecosystems & Environment* 118 (1): 80–92. https://doi.org/10.1016/j.agee.2006.05.002.

Shakesby, R.A., and S.H. Doerr. 2006. “Wildfire as a Hydrological and Geomorphological Agent.” *Earth-Science Reviews* 74 (3–4): 269–307. https://doi.org/10.1016/j.earscirev.2005.10.006.

Sheikh Leiveci, Kobra, Gholam Abbas Kazemi, and Noorali Damough. 2016. “Measuring Infiltration Rate and Hydraulic Conductivity in a Dry Well in a Thin Overburden” 6 (1): 63–73.

Sikora, Lawrence J., and D. E. Stott. 1996. “Soil Organic Carbon and Nitrogen.” In *Methods for Assessing Soil Quality*, 157–67. John Wiley & Sons, Ltd. https://doi.org/10.2136/sssaspecpub49.c9.

Smith, Jeffrey L., and John W. Doran. 1996. “Measurement and Use of PH and Electrical Conductivity for Soil Quality Analysis.” In *Methods for Assessing Soil Quality*, 169–85. John Wiley & Sons, Ltd. https://doi.org/10.2136/sssaspecpub49.c10.

Snedecor, G. W., and W. G. Cochran. 1991. *Statistical Methods, 8th Edition | Wiley*. Eighth. https://www.wiley.com/en-us/Statistical+Methods%2C+8th+Edition-p-9780813815619.

Sousa, W P. 1984. “The Role of Disturbance in Natural Communities.” *Annual Review of Ecology and Systematics* 15 (1): 353–91. https://doi.org/10.1146/annurev.es.15.110184.002033.

Stavi, Ilan, Daniel Barkai, Yaakov M. Knoll, and Eli Zaady. 2016. “Livestock Grazing Impact on Soil Wettability and Erosion Risk in Post-Fire Agricultural Lands.” *Science of The Total Environment* 573 (December): 1203–8. https://doi.org/10.1016/j.scitotenv.2016.03.126.

Switzer, Joshua M., Graeme D. Hope, Sue J. Grayston, and Cindy E. Prescott. 2012. “Changes in Soil Chemical and Biological Properties after Thinning and Prescribed Fire for

Ecosystem Restoration in a Rocky Mountain Douglas-Fir Forest." *Forest Ecology and Management* 275 (July): 1–13. https://doi.org/10.1016/j.foreco.2012.02.025.

Tiessen, H., E. Cuevas, and P. Chacon. 1994. "The Role of Soil Organic Matter in Sustaining Soil Fertility." *Nature* 371 (6500): 783–85. https://doi.org/10.1038/371783a0.

Vermeire, Lance T., Jessica L. Crowder, and David B. Wester. 2014. "Semiarid Rangeland Is Resilient to Summer Fire and Postfire Grazing Utilization." *Rangeland Ecology & Management* 67 (1): 52–60. https://doi.org/10.2111/REM-D-13-00007.1.

Wakimoto, Ronald H., E. Earl Willard, and Bruce Reid. 2004. "Historic Fire Regimes and Changes Since European Settlement on the Northern Mixed Prairie: Effect on Ecosystem Function and Fire Behavior." University of Montana. https://www.firescience.gov/JFSP_advanced_search_results_detail.cfm?jdbid=%23%26JO%3B%0A.

Wiesmeier, Martin, Livia Urbanski, Eleanor Hobley, Birgit Lang, Margit von Lützow, Erika Marin-Spiotta, Bas van Wesemael, et al. 2019. "Soil Organic Carbon Storage as a Key Function of Soils - A Review of Drivers and Indicators at Various Scales." *Geoderma* 333 (January): 149–62. https://doi.org/10.1016/j.geoderma.2018.07.026.

Williams, Amanda. 2020. "Evaluating Grazing and Defoliation Effects on Ponderosa Pine Grassland Following the Lodgepole Complex Wildfire." Thesis - Open Access, Montana State University.