SNOW AS A DRIVER OF SOIL BIOGEOCHEMICAL CYCLING IN THE SEMIARID DRYLAND CEREAL PRODUCTION SYSTEMS OF THE NORTHERN GREAT PLAINS

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EXTENDED ABSTRACT

In the Judith River Watershed (JRW) of the Upper Missouri River Basin in central Montana (Figure 1), extensive non-irrigated cereal crop production occurs on thin, well-drained soils susceptible to water loss and nitrate leaching[1,2]. This landscape consists of fluvial terraces and alluvial fans with shallow, unconfined aquifers that are vulnerable to accumulating nitrate leached from overlying soils and thus commonly host groundwater concentrations twice the EPA drinking water standard of 10 mg N L^{-1}. In these non-irrigated agricultural systems of the Northern Great Plains, snow provides a vital source of winter and spring water for crop production [3,4], yet the role of snow as a driver of nitrate dynamics in these soils is less understood[5]. Additionally, the distribution of snow across these relatively flat cultivated areas is highly variable, with wind patterns and the character of crop stubble dictating when and where snow accumulates, melts, and infiltrates – ultimately contributing water to soil storage[4].

The isotopic compositions of the hydrogen and oxygen atoms that make up the water molecules in snow vary due to heavier isotopes (atoms with additional neutrons; ^{2}H compared to ^{1}H and ^{18}O compared to ^{16}O) leading to heavier water molecules[6]. For quantitative comparisons of the relatively small number of heavier atoms, the ratio of the heavier to the lighter isotope in the sample (R_{sample}) is commonly normalized to the ratio found in the global standard for water ($R_{standard}$, Vienna Standard Mean Ocean Water, VSMOW) to quantify a relative metric of isotope abundance denoted by δ (in units of per mil (‰))[6].

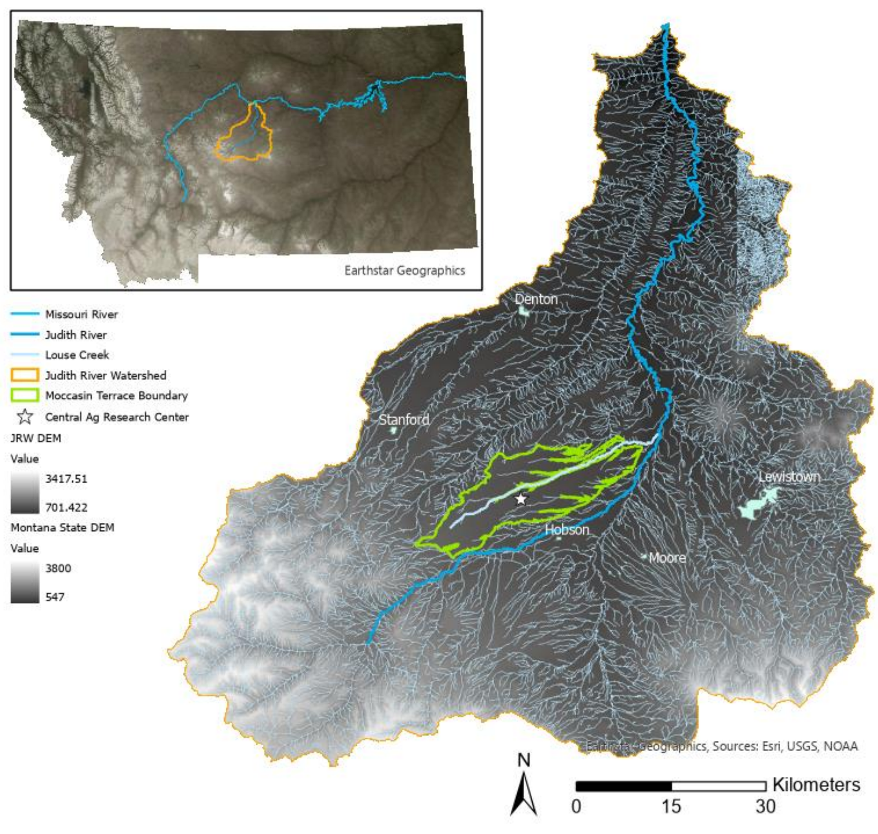

Figure 1. .The Judith River Watershed (JRW) is part of the Missouri River Basin and located in central Montana. The Moccasin terrace (green) sits in the center of the JRW, geographically isolated from mountain snowpack. Louse Creek traverses the terrace and was sampled for main channel water isotope analysis in this study.

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Equation 1: $$\delta = \left(\frac{R_{sample}}{R_{standard}} - 1\right) \text{x } 1000$$

Differences between the isotopic composition of typically lighter snow (lower $\delta^{18}O$ and $\delta^{2}H$ values) versus typically heavier rain (higher $\delta^{18}O$ and $\delta^{2}H$ values) can signal the origin of water in soil profiles[7,8]. These contrasting isotopic signals illuminate the character and timing of precipitation that may influence critical periods of biogeochemical cycling within soils during the winter and into the next growing season. In addition, remotely-sensed imagery can quantify spatial distributions of snow deposition and accumulation patterns across landforms[9], identifying areas receiving increased snow water. These wetter areas would hypothetically have increased rates of water driven nutrient processing, ultimately linking snow accumulation to both soil hydrology and biogeochemistry. In this preliminary research, we use on-going analyses of water isotope values in conjunction with high resolution surface models derived from LiDAR data to develop the conceptual basis for a soil water transport model that will address the question: *How does the relationship between soil architecture and storage of snowmelt influence nitrate fate and transport in non-irrigated agricultural soils?* Through our work thus far, we begin to quantify snowmelt contributions to soil and groundwaters, unravelling the link between prairie snow and biogeochemical cycling in these lower-elevation, lower-relief regions.

METHODS

The shallow, unconfined Moccasin terrace aquifers, located in the center of the JRW (Figure 1), are topographically isolated from recharge sourced by mountain snowmelt. Thus, these aquifers recharge exclusively from local precipitation and present an unconfounded setting for measuring direct effects of snow water as it travels through soil, groundwater, and emergent streams. Water samples were collected from 2012 to 2021 and analyzed for oxygen and hydrogen isotopic composition at the Montana State University Environmental Analytical Laboratory (EAL) using a Los Gatos Research (LGR) laser spectrometer. Repeated measurements of the EAL working standard over last five years (n = 80) had a standard deviation of 0.6 ‰ for $\delta^{18}O$ and 0.9 ‰ for $\delta^{2}H$, providing an estimate of total uncertainty in our samples.

Snow depth measurements were made along transects established at Montana State University's Central Agricultural Research Center (CARC) located near the center of the Moccasin terrace (Figure 1). Snow samples were collected at 3- to 10-m intervals along the transect, measured for snow density, and analyzed for water isotopic values on the LGR laser instrument (Los Gatos Research Liquid Water Isotope Analyzer) at the MSU EAL. Transect data were paired with remotely sensed imagery of a 1-km^2 area of the CARC using LiDAR obtained from an Uncrewed Aerial Vehicle (UAV) to measure snow depth (Figure 2). Continuous observations of snow and rain dynamics at the CARC were made using a Global Network of Isotopes in Precipitation (GNIP) collector (Palmex Rain Sampler 1B) along with a snow scale (Sommer SSG-2) and sonic depth sensor (Sommer USH-9) measuring snow water equivalent and snow depth respectively. Additional sensors operated by the Montana Climate Office measured soil moisture and temperature at depths of 10, 20, 50, and 90 cm, as well as air temperature, wind speed, and wind direction (https://mco.cfc.umt.edu/mesonet_data/).

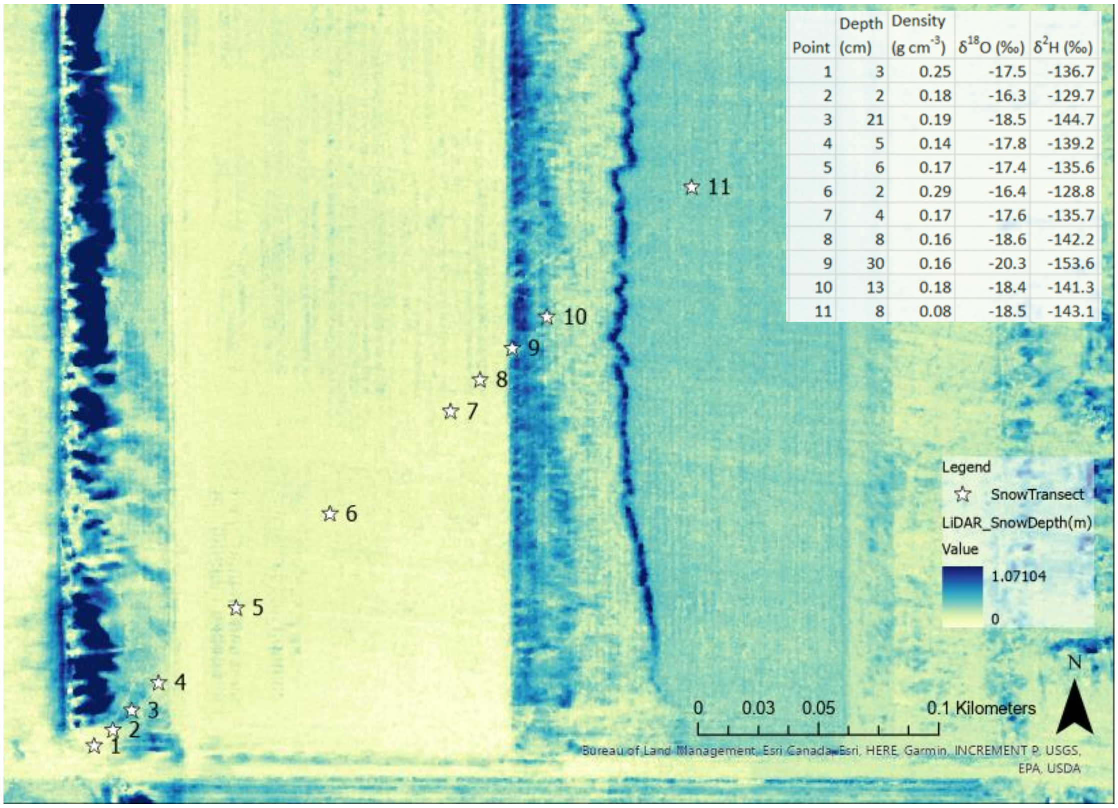

Figure 2. LiDAR image taken of snowpack Jan. 20, 2021. Points indicate sample locations along transect taken the same day. Inset displays snow depth, density, $\delta^{18}O$, and $\delta^{2}H$ result values associated with each sample location.

RESULTS

Variation in snow depths and densities of the samples collected on 20 January along the established transect at the CARC range from 2 to 30 cm and 0.08 to 0.29 g cm^{-3}, respectively. A local meteoric water line (LMWL) determined by linear regression of $\delta^{18}O$ and $\delta^{2}H$ values measured in these samples and previously collected JRW precipitation samples resulted in a slope of 7.17 and y-intercept of 10.49, similar to other regional LMWLs[7,10] (Figure 3). We used a Monte Carlo analysis to propagate analytical uncertainty in isotope measurements of precipitation samples to uncertainty in derivation of the LMWL. A total of 5000 Monte Carlo realizations of the regression of the LMWL were generated by repeated random sampling from the dataset assumed to be influenced by normally distributed analytical error in $\delta^{18}O$ and $\delta^{2}H$. Based on the 2.5% and 97.5% quantiles of this Monte Carlo ensemble and including the uncertainty of residual error (Figure 3, dashed lines), we establish prediction intervals around the LMWL to allow

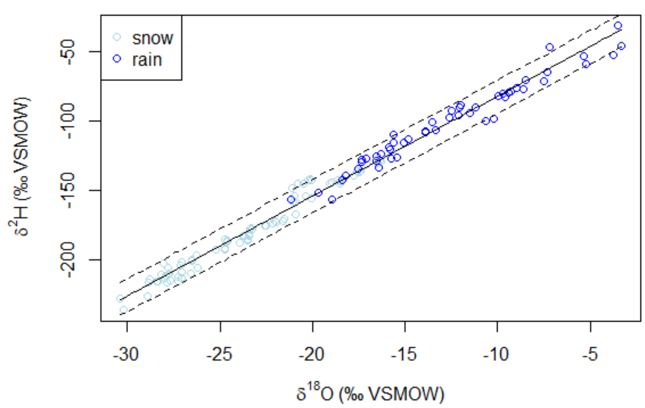

Figure 3. Moccasin terrace precipitation sample results (2012-2021) informing our conceptualization of timing and distribution of nutrients conveyed by water movement through soils. Linear fit is the local meteoric water line (LMWL) derived from linear regression of precipitation sample isotopic values and has slope = 7.17 and y-intercept = 10.49. Dashed lines indicate the prediction interval based on a Monte Carlo ensemble of 5000 randomly generated realizations.

visualization of whether the difference between a precipitation isotope value and the LMWL is meaningful within analytical uncertainty. The isotopic composition of snow varied from -30.4 to -12.0 ‰ in $\delta^{18}O$ and -235.2 to -104.0 ‰ in $\delta^{2}H$, and was predominantly lower than that of rain, which varied from -21.2 to -3.3 ‰ in $\delta^{18}O$ and -156.7 to -31.7 ‰ in $\delta^{2}H$ (Figure 3). Variation in isotopic composition of surface water, soil water and groundwater samples was more limited, spanning a combined range of -21.5 to -4.6 ‰ in $\delta^{18}O$ and -167.0 to -66.3 ‰ in $\delta^{2}H$.

DISCUSSION

The lower isotopic composition of snow compared to rain reflects fractionation processes in the atmosphere resulting from seasonal weather patterns. Variation in the isotopic composition of precipitation indicates temporal patterns of water entering soil (Fig. 3). Compared to precipitation, more limited variation in water isotopic values for surface water, soil water, and groundwater samples indicates mixing of snow and rain in these reservoirs (Figure 4). Sample values within the confidence interval of the LMWL suggest limited influence of evaporation or other fractionating transformation such as sublimation of snow[5], though slight variation away from the line in the spring and surface water samples suggests evaporation influence and merits further refinement of the LMWL. Soil water isotopic values located lower (down and to the left) on the LMWL reflect greater contributions from snowmelt water to soil relative to surface ("main channel") waters at certain times of year.

IMPLICATIONS AND NEXT STEPS

The isotopic composition of soil water suggests that snow-derived water drives initial plant growth and nutrient cycling during the spring melt period and may drive N loss to leaching and denitrification during this period[11]. Areas of the landscape where soils receive and hold more water create a positive feedback supporting increased plant growth and consequently increased soil organic matter inputs. Ongoing field sampling coupled with remote sensing, water isotope analyses, nutrient analyses, and modeling will allow us to understand both the variability in snowmelt water delivered to soils, and its effects on N dynamics. These preliminary results suggest that snowmelt influence on crop production and nutrient cycling is not only a function of soil storage capacity, but also reflects management practices that drive snow retention throughout the winter.
Moving forward, we will use ~~r~~emotely-sensed imagery to extrapolate field measurements across the landscape and inform a multi-layer bucket model, in which each "bucket" is a soil depth interval (Figure 5). Each bucket in this model is defined by soil depths and associated field capacity (i.e., ability to hold water). The model allows us to simulate water movement through soil and associated processes over time.

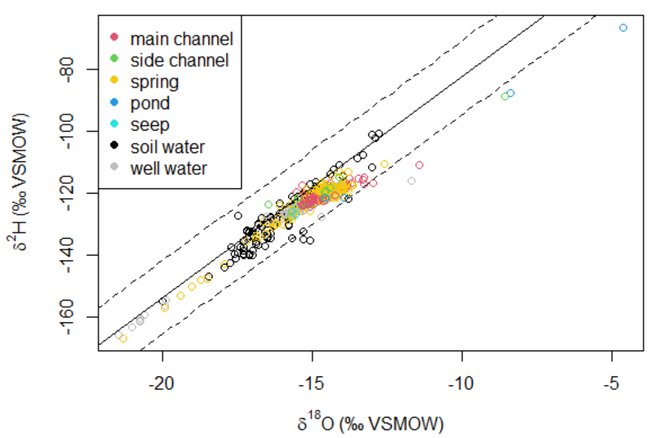

Figure 4. Surface, soil, and ground water results (2012-2021). The relation between non-precipitation water samples along the LMWL and the associated prediction interval (solid and dashed lines, respectively, established by precipitation samples, Fig. 3) shows mixture, transformation, and degree of fractionation of source waters through different process domains.

Through investigating the variation of snow accumulation and contribution to soil water across these lower-elevation, lower-relief regions, we begin to unravel the extent to which snowmelt water drives biogeochemical processes such as those involved in nitrogen cycling. Understanding the role snow plays in producing bioavailable nitrogen and reducing leachable nitrates provides an opportunity for precision agriculture approaches to the application of N fertilizer. Optimizing nutrient inputs benefits the producer economically and ultimately improves soil health and water quality in these agricultural systems. **(**KEYWORDS: prairie snow, water isotope, nitrate, soils)

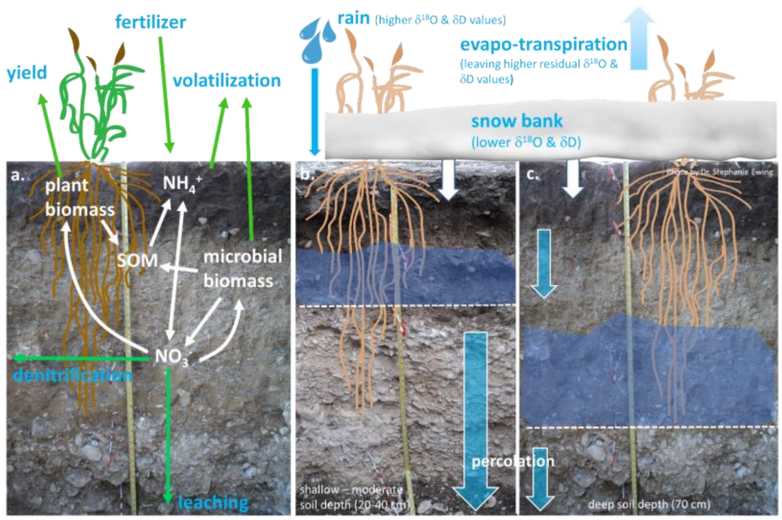

Figure 5**.** A conceptualization of nutrient cycling in soils and working bucket model approach to hydrologic processes. *(a)* Key components of nitrogen cycling in non-irrigated cereal crop production. Synthetic fertilizer provides ample nitrogen for the plant. Excess N is converted to soluble nitrate that is either taken up by the plant, processed by microbes, or leached out of the soil. Nitrate can be both derived from and contribute to soil organic matter. Water infiltrates fine soil material to the textural contrast with gravel and fills the fine textured zone according to its thickness *(b, c).* As water is held in the fines, water is taken up by roots or held in aggregate pores. Remaining water percolates to a groundwater reservoir. Size of arrow indicates degree of deep percolation that leaches nitrate from the soil.

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