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# Regional Plant Community Differences in the Nebraska Sandhills

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REGIONAL PLANT COMMUNITY DIFFERENCES IN THE NEBRASKA SANDHILLS

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REGIONAL PLANT COMMUNITY DIFFERENCES IN THE

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The Nebraska Sandhills is very valuable to the state of Nebraska, representing one of the most in-tact and largest grassland ecosystems in temperate regions in the world. Rangeland managers must understand plant community dynamics across the Sandhills to better inform management decisions. The first objective of this study was to evaluate plant community variability on upland Sands ecological sites across different precipitation zones in the Nebraska Sandhills. The second objective of our study was to utilize the Rangeland Analysis Platform (RAP) to examine spatial and temporal variability in biomass production and cover on pastures of ranches analyzed in the first objective across different regional precipitation zones. Frequency of occurrence, dry-weight rank (DWR), and cover point data were collected on 14 working ranches across low precipitation (LPZ), moderate precipitation (MPZ), and high precipitation (HPZ) from 2019 to 2021. Regional differences were found in species frequency and DWR across all years, establishing two distinct plant communities. The LPZ plant community was characterized by prairie sandreed (*Calamovilfa longifolia* (Hook) Scribn.), sand bluestem (*Andropogon gerardii spp. hallii* (Hack.) Wipiff), and sand dropseed (*Sporobolus cryptandrus* (Torr.) A. Gray); whereas plant communities in the MPZ and HPZ were characterized by little bluestem (*Schizachyrium scoparium* (Michx.) Nash), Scribner's rosette grass (*Dichanthelium oligosanthes var. scribnerianum* (Nash) Gould)., and western ragweed (*Ambrosia psilostachya* D.C.). Remote sensing data collected from the RAP on the same 14 ranches was used to compare biomass and cover across precipitation zones from 1984-2019. Regional differences were found in mean biomass, bare ground, and perennial forbs and grasses cover, as well as in the response of these variables to annual precipitation. Biomass production was lowest in the LPZ and highest in the HPZ. Bare ground was higher and perennial forbs and grasses cover was lower in the LPZ than the MPZ or HPZ. Bare ground and perennial forbs and grasses cover in the LPZ had a greater response to annual precipitation than the MPZ or HPZ, where cover in the HPZ did not demonstrate large responses to these variables. This research highlights the regional variability that exists on upland plant communities in the Sandhills.

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# Chapter 1: LITERATURE REVIEW

## Nebraska Sandhills Ecoregion

The Nebraska Sandhills is an ecoregion in the Great Plains located in north central Nebraska. This vast region, covering approximately 49,987 $km.^2$, represents one of the largest intact grasslands left on Earth (Scholtz and Twidwell 2022). The annual precipitation of the Sandhills ranges from 431.8-533.4 mm (17-23 in.), generally increasing from west to east, with approximately 70-75% of this precipitation falling from April to September (Burzlaff 1962; Whitcomb 1989; Bleed and Flowerday 1990). This precipitation gradient is the result of the interior location of the region, the Rocky Mountain rain shadow, and the distance from the Gulf of Mexico (Bleed and Flowerday 1990). The climate of the Sandhills is described as a typical continental climate with fairly harsh winters and warm summers (Burzlaff 1962). The average annual temperature in the Sandhills ranges from 9.4º C (49º F) in the east to 8.9º C (48º F) in the west, with mean temperatures in the summer around 21.1º C (70º F) and mean temperature in the winter around 0º C (32º F) (Bleed and Flowerday 1990). The elevation of the Sandhills ranges from 1,220 m (4,003 ft) in the west to 610 m (2,001 ft) in the east (Whitcomb 1989).

This region hosts a suite of ecosystems, ranging from xeric dune tops to mesic wetlands, however dune formations comprise approximately 90% of the land area (Schacht et al. 2000). The dune formations found in the Sandhills present a heterogeneous landscape of rolling slopes, dunetops, and interdune swales (Stephenson et al. 2019). The formation of the Sandhills developed from a combination of sediments deposited by ancient oceans, sediments deposited by streams, and wind movement of sand that created dune formations typically oriented from east to west (Burzlaff 1962; Bleed and Flowerday 1990). This wind action formed large dunes of eolian sand which sit on top of solid tertiary materials (Burzlaff 1962; Whitcomb 1989; Bleed and Flowerday 1990). Evidence suggests that the Sandhills region is relatively young, forming within the past 10,000 years (Whitcomb 1989). Periods of drought which created blowout formations, however, modified dune structures as recently as 1,500 years ago. One characteristic that is often featured in the Sandhills are "blowouts", or pockets of open sand where the vegetation has been removed by repeated fires or a concentration of grazing animals, leaving the soil vulnerable to wind erosion (Stubbendieck et al. 1989).

Soils in the Sandhills are grouped into 7 soil associations: Els-Valentine-Ipage, Elsmere-Ipage-Loup, Valentine, Valentine Hilly, Valentine-Els-Wildhorse, Valentine-Else-Tyron, and Valentine Thurman (Bleed and Flowerday 1990). These soils are generally described as being of a loamy fine sand, sand, or fine sandy loam texture. While many ecological sites are present in the Sandhills ecosystem, one of the most common ecological sites is described as a Sands ecological site (USDA NRCS). These sites are typically represented as upland locations on the slopes and dune tops of rolling Sandhills with a sandy loam texture (USDA NRCS). The vegetation for this site is described as a warm season mid-grass plant community with a native shrub component (USDA NRCS). The state-and-transition model for this ecological site describes a Sand Bluestem [*Andropogon gerardii spp. hallii* (Hack.) Wipiff] / Prairie Sandreed [*Calamovilfa longifolia* (Hook) Scribn.] reference plant community in the low precipitation zone in the Sandhills and a Bluestem/ Prairie Sandreed/ Needlegrass (*Stipa*

L. spp.) reference plant community in the moderate and high precipitation zones (USDA NRCS).

The vegetation of the Sandhills ecoregion is a mixed grass prairie, hosting species native to tallgrass and shortgrass prairies alike (Barnes et al. 1984; Whitcomb 1989; Bleed and Flowerday 1990; Schact et al. 2000). There are approximately 720 species of plants known in the Sandhills region, with only around 50 of these being introduced (Whitcomb 1989; Bleed and Flowerday 1990). Despite the large number of species, the only species endemic to the Sandhills is blowout penstemon [*Penstemon haydenii* (S. Watson)] (Whitcomb 1989; Bleed and Flowerday 1990).

**Botanical Surveys of the Nebraska Sandhills**

One of the earliest detailed surveys of the vegetation in the Nebraska Sandhills was completed by Raymond Pool, a University of Nebraska-Lincoln botanist, in 1914 (Pool 1914). Numerous plant associations were assembled and described in this survey, including a bunchgrass association, which was the most common plant community association observed on Sandhills uplands. This association included little bluestem [*Schizachyrium scoparium* (Michx.) Nash] as the dominant plant, with sand bluestem mentioned as a co-dominant species. Pool described little bluestem as being the plant species with the “widest distribution and of most frequent controlling influence” in the Sandhills (Pool 1914). Other species important in this association included prairie sandreed, needlegrasses, and prairie junegrass [*Koeleria macrantha* (Ledeb) Schult.].

In the mid-20$^{th}$ century, Frolik and Shepherd (1940) completed a vegetation survey of the Sandhills in Cherry County, Nebraska. In this survey ocular estimations of vegetation plots 50 feet in diameter were used to estimate vegetation density and composition. The researchers found that prairie sandreed (41.2%), sand dropseed [*Sporobolus cryptandrus* (Torr.) A. Gray] (23.2%), and hairy grama (*Bouteloua hirsuta* Lag.) (10.1%) were the dominant species on uplands in terms of percent total productivity. Using stem counts in quadrates to estimate plant density, Tolstead (1942) also found that prairie sandreed was the most characteristic grass on uplands in Cherry County, with hairy grama, blue grama [*Bouteloua gracilis* (Kunth) Lag. ex Griffiths], and needlegrasses being co-dominants depending on soil texture and degree of grazing.

The lack of little bluestem mentioned in the reports reviewed above is notable considering that Pool (1914) described it as being so dominant in his earlier evaluation. One potential explanation for the absence of little bluestem during this time period is the occurrence of severe drought between 1934-1937 (Weaver and Albertson 1939; Frolik and Shepherd 1940; Weaver 1965; Stubbendieck and Tunnel 2008). While the most important species near the beginning of the 20$^{th}$ century were little bluestem, sand bluestem, prairie sandreed, and needle-and-thread, losses of little bluestem during the 1933-1940 drought were reported to be approximately 90-100% (Weaver 1965). This loss in little bluestem was then followed by a greater abundance of prairie sandreed and sand bluestem. By 1965, Weaver (1965) noted that a bunch grass community was the most characteristic vegetation of the Sandhills. The return of little bluestem in Sandhills plant communities in the later botanical surveys conducted in Arthur County (Keeler 1980; Barnes 1984), Brown County (Schacht et al. 2000), Cherry County (Bragg 1998), and Thomas County (Stubbendieck and Tunnel 2008) suggests that the species recovered from the drought mentioned by Weaver and Albertson (1939), Weaver (1965), and Frolik and Shepherd (1940).

Other botanical surveys in the Sandhills include those conducted by Burzlaff (1962) and Bragg (1998) who focused on composition of Sandhills plant communities on uplands. Burzlaff (1962) conducted a botanical survey on 24 different ranches across the Sandhills. In this study, 8 counties within the Sandhills were randomly selected, within which 3 ranches were selected with assistance from extension agents and technicians of the Soil Conservation Service. Each ranch was required to have three representative range sites, being the dry valley, choppy sandhills, and rolling sands sites, and each site needed to be categorized within the "excellent" to "high good" range. Through surveying using the point-frequency frame technique, Burzlaff (1962) found that prairie sandreed was the most frequent species on uplands (71.5%) along with sand dropseed (35.8%), sand bluestem (35.7%), little bluestem (12.1%), needle-and-thread [*Hesperostipa comata* (Trin. & Rupr.) Barkworth] (15.7%), and blue grama (21.7%). While prairie sandreed was described as the "most important and abundant component of the flora", sand bluestem and little bluestem were also mentioned as major contributors to the plant community as they were often seen dominating the sites where they could be found. Burzlaff (1962) noted that the high percent composition of sand dropseed (20.7%) that was noted by Frolik and Shepherd (1940) in their study did not agree with the percent composition of this species in his study (6.11%).

Bragg (1998) conducted a botanical survey investigating the percent canopy cover on Sandhills uplands at the Valentine Migratory Waterfowl Refuge in Cherry County, Nebraska. Data collected in this survey involved a modified sampling method which combined the ocular reconnaissance method with the square-foot density method to determine the percent canopy cover of species in given 50 ft. diameter plots within a described vegetation type. A dune sand vegetation type was the dominant plant community in this study, making up 63.6% of the study area. Bragg (1998) found that the dominant species in terms of percent canopy cover on uplands were sand bluestem (~34%), sedge (*Carex* spp.) (~32%), little bluestem (~31.3%), western ragweed (*Ambrosia psilostachya* D.C.*)* (~23.3%), prairie sandreed (~19.3%), and sand lovegrass [*Eragrostis trichodes* (Nutt.) Alph. Wsood] (~11%). The importance displayed by the cover of sedge species is significant, as sedge isn't listed as a dominant species in most other plant community associations.

The influence of topographic position on upland Sandhills plant community composition was also a focus in the literature. Keeler et al. (1980) completed a thorough survey of the vegetation of the Arapaho Prairie in Arthur County, Nebraska in reference to topographic position. In this survey they found that the dominant species in terms of percent canopy cover on the "slope" topographic position were blue grama (27%), prairie sandreed (22%), and hairy grama (13%). The dominant species on the "ridge" topographic position were hairy grama (20%), prairie sandreed (13%), and little bluestem (10%).

Barnes et al. (1984) conducted a study of how topography (ridge, slope, and valley) influenced cover of Sandhills vegetation in Arthur County, Nebraska. The slope category was described as characteristic of mid-slopes and lower elevation rolling dunes. Ridges were described as those upper elevation dune slopes and exposed ridges. On slopes, which comprised 61% of the study area, dominant species in terms of percent frequency included prairie sandreed (100%), blue grama (90%), and hairy grama (77%). Sub-dominant species included needle-and-thread (85%), sand bluestem (82%), and prairie junegrass (62%). Dune ridges and upper slopes were dominated by hairy grama (98%), needle-and-thread (60%), little bluestem (68%), and prairie sandreed (84%).

Over the past century, several botanical surveys have evaluated the upland plant communities in the Sandhills ecosystem. Throughout these surveys, the reported composition of the dominant plant communities on upland rolling hills conflicted between reports. Early surveys conducted by Pool (1914) reported a bunchgrass plant community dominated by little bluestem as the most common on Sandhills uplands. Surveys in the mid-20th century reported prairie sandreed and sand bluestem as the most dominant species in the plant community (Frolik and Shepherd 1940; Tolstead 1942, Burzlaff 1960). More recent botanical surveys conducted in the Sandhills have presented the return of a bunchgrass plant community as one of the most common associations across the Sandhills (Keeler 1980; Barnes 1984; Bragg 1998; Schact et al. 2000). While drought was thought to explain the absence of little bluestem in the mid-20th century (Weaver and Albertson 1939; Weaver 1965), Bleed and Flowerday (1990) suggested that precipitation variability across the Sandhills has not been evaluated as a major driver of plant community dynamics. In addition, topography and precipitation have been identified as key components in explaining the variability of the plant community composition of the Sandhills (Schacht et al. 2000; Stephenson et al. 2019).

Schacht et al. (2000) conducted a study investigating the effect of topographic position on plant community composition at the University of Nebraska Barta Brothers Ranch in Rock County and Brown County, Nebraska. Schacht et al. (2000) found that species such as bluegrasses (*Poa* L. spp.), switchgrass (*Panicum virgatum L.*), and white sage (*Artemisia ludoviciana* Nutt.) were more frequently observed in interdunal valleys compared to upland slopes and dune tops of the Sandhills, 72%, 65.9%, and 10.9% frequency of occurrence respectively. Needlegrasses (43.9%), little bluestem (40.1%), and prairie junegrass (15.2%) tend to be more frequently observed on north-facing slopes, whereas prairie sandreed (23%) and sand bluestem (15.4%) were more frequently found on south-facing slopes (Schact et al. 2000). One significant difference in this study compared to Keeler et al. (1980) and Barnes et al. (1984) was that blue grama tended to be most frequent in interdune areas rather than on uplands.

Stephenson et al. (2019) investigated the effect of topographic position on Sandhills plant community composition and production at the UNL Barta Brothers Ranch. This study utilized plant production data collected from grazing exclosures in mid-June and mid-August from 2001-2017. This study found that cool season grasses were more abundant on interdune sites, whereas warm season grasses were more abundant on south-facing slopes and dunetops compared to interdunes and north-facing slopes. Stephenson et al. (2019) also found differences in Precipitation Use Efficiency (PUE) and Precipitation Marginal Response (PMR) among plant functional group and topographic positions in this study. Cool-season grasses had a greater response to increasing precipitation in interdune sites compared to dune sites. Production was also greater on interdune sites compared to dune sites, however the response of warm-season grass production to precipitation was similar among all topographic positions.

**Monitoring Grassland Plant Communities**

Monitoring vegetation is an important component of rangeland management. Establishing monitoring sites and collecting monitoring data provides rangeland managers with the ability to identify and track changes in vegetation over time (Despain et al. 1997). In addition, data collected through rangeland monitoring aids in evaluating management practices and making management decisions to meet the goals of an operation. The purpose of the following section is to provide an overview of common monitoring methods that are used to evaluate grassland plant communities (Colloudon et al. 1999). These methods include frequency of occurrence, dry-weight rank, ground cover estimation, photographs, and remote sensing.

**Methods of Monitoring Grassland Plant Communities: Frequency of Occurrence**

Frequency of occurrence is often described as one of the simplest and quickest ways of monitoring vegetation, as it describes the abundance and distribution of species. It is also commonly used to monitor changes in plant communities over time (Colloudon et al. 1999). Frequency, generally expressed as a percentage, is defined as how often a species is present in a sample of quadrats of the same size which were repeatedly placed across a landscape (Daubenmire 1968; Mueller-Dombois and Ellenberg 1974; Greig-Smith 1983; Despain et al. 1997). This method is useful when monitoring vegetation at the same locations over time to track changes in plant community abundance and composition (Despain et al. 1997). Using frequency alone as an indicator of range trend, however, is not recommended as other parameters (e.g. ground cover and biomass) provide more insight than simple presence or absence of plant species.

Common methodologies in collecting plant frequency data include the pace frequency, quadrat frequency, and nested frequency methods (Collouden et al. 1999). All these methods involve reading quadrats placed along transects, with these quadrats placed at specific intervals along the transect. Pace frequency techniques, such as step point, Parker 3-step, and point frames have been used in the past to collect plant community frequency data (Despain et al. 1997). While many methods of collecting frequency of occurrence data exist, the point sampling method has several disadvantages including the need for a large number of sample points on a site because many placements of the point do not encounter a plant. In addition, point sampling is difficult to repeat because of how a point is read and where a point is placed between observers without bias.

The quadrat method of collecting frequency data simply involves recording the presence or absence of species within the designated quadrat area (Curtis and McIntosh 1950; Collouden et al. 1999). Quadrats are generally in the shape of a circle or square and quadrat size is determined based on the characteristics of the plant community to be sampled (Despain et al. 1997; Collouden et al. 1999). Using one quadrat, however, often results in frequency values falling outside of the optimum frequency range for important species in the plant community (Collouden et al. 1999).

It is important to note that the size of the quadrat used has a large influence on the frequency data collected, as the size of the quadrat determines the probability of each species presence or absence within the quadrat (Hyder et al. 1963; Hyder et al. 1965; Despain et al. 1997; Collouden et al. 1999). The optimum frequency range for species of interest is described as greater than 20% to less than 80%. Due to the dilemma of determining a proper quadrat size, using a nested-frequency method may present a better option. A nested-frequency plot involves smaller quadrats nested within a larger quadrat, allowing for frequency of occurrence data to be collected using multiple quadrat sizes (Hyder et al. 1965; Despain et al. 1997; Coullouden et al. 1999). When recording data using this method, species found in smaller plots are also included in the successively larger plots (Coullouden et al. 1999). This method increases the probability that the correct size of quadrat is used for multiple species.

Advantages of collecting frequency of occurrence data include its objectivity, rapidity, and simplicity as well as its low sensitivity to periodic fluctuations and ability to detect changes in plant distribution and abundance (Despain et al. 1997; Coullouden et al. 1999). Minimum training is generally needed when collecting frequency data, as long as examiners are able to identify the plant species present in the plant community (Coullouden et al. 1999). Disadvantages of collecting frequency of occurrence data include that the data is non-absolute, frequency values depend on quadrat size, and this method is not suited to larger shrubs (Despain et al. 1997). The sensitivity of frequency data to density and dispersion characteristics may also be viewed as a disadvantage because of the difficulty in determining which characteristic is causing changes observed in the data, however this problem mostly occurs when comparing two plant communities in different locations rather than when observing one plant community over time.

**Methods of Monitoring Grassland Plant Communities: Dry Weight Rank**

Plant community composition by biomass weight is one of the best ways to measure the importance of different species within a monitoring site (Smith and Despain 1997). Hand-sorting harvested plant samples or ocular estimates are often used to measure composition by weight, however these methods were labor intensive and/or unreliable due to bias among samplers (Neuteboom et al. 1998). One method that is useful for the analysis of botanical composition of pastures is the dry weight rank (DWR) method developed by Mannetje and Haydock (1963). This method quickly and accurately estimates the species composition to total plant production of grasslands on a dry weight basis by assigning visually observed rankings to individual plant species. This eliminates the need for clipping and sorting species to estimate contributions of different species to total standing crop production (Dowhower et al. 2001). The DWR method has been tested thoroughly as a viable method of estimating species weight contributions to total production in rangelands across the world including Oklahoma, USA, Africa, and Australia (Gillen and Smith 1986; Kelley and McNeill 1980; Friedel et al. 1988). These trials all found DWR to be a reasonably accurate and useful tool for monitoring species contribution to total production on rangelands. In a trial evaluating this method in Oklahoma, Gillen and Smith (1986) found the DWR method to be comparable in accuracy to hand clipping, however the DWR method did tend to have slightly higher standard deviations than hand clipping.

The DWR method is performed by simply ranking the top three species which contribute the most to the dry weight biomass in the quadrat (Mannetje and Haydock 1963). Collecting DWR data in the field can be done quickly and easily because this method does not require ranking every species found within the quadrat (Smith and Despain 1997). The size of the quadrat used must fit the plant community the sampling is taking place in, however the DWR method is commonly performed in conjunction with other quadrat-based methods such as frequency and cover, where the quadrat size has often already been determined. When collecting data in the field, observers assign species with the highest contribution to dry weight a rank of 1, the next 2, and the third highest 3 (Mannetje and Haydock 1963). If there are fewer than three species in a given quadrat, the observer may either simply assign a rank to the species present (ex: assign rank 1 and rank 2 if there are 2 species or only rank 1 if there is 1 species) or assign multiple ranks to the species present in the frame (Smith and Despain 1997; Coulloudon et al. 1999). The DWR method operates on rules of proportion, where rank 1 corresponds to 70% composition, rank 2 corresponds to 20%, and rank 3 corresponds to 10% respectively (Mannetje and Haydock 1963; Smith and Despain 1997; Coulloudon et al. 2000). These original proportions of Mannatje and Haydock (1963) were later modified using additional data sets by Jones and Hargreaves (1979) to 71.4%, 24.7%, and 3.9% respectively, however these modified proportions were not proven to lead to significantly improved results. Actual weight in terms of lbs/acre or kg/ha can be calculated by using the DWR method data in conjunction with the comparative yield method (Smith and Despain 1997).

Minimal training is needed for observers to successfully collect data using the DWR method. Smith and Despain (1997) explain that getting a feel for estimating dry weight in the field is the only key skill that is needed in this method. This skill can be developed by clipping and weighing dry plant material in the field. In addition, this method tends to be forgiving of errors resulting from inaccurate ranking of species because the quantity of samples normally taken in the field generally produces accurate results.

While the DWR method is a rapid and useful tool for monitoring rangelands, using this method does have certain constraints and problems. Jones and Hargreaves (1979) highlight that, due to the proportions under which the DWR method operates, a single species can never exceed a value of approximately 70%. However, this problem can be solved by simply assigning the first and second rank to the species that occupies those proportions of the dry weight rank, giving that species a new proportion of 90%.

Another problem arises when there is a constant relationship between species dominance and quadrat yield. Neuteboom et al. (1997) explain that this relationship can cause issues if one specific species is always ranked first in high yielding quadrats and another specific species is always ranked first in low yielding quadrats. In this scenario, the dominant species in the high yielding quadrats will be underestimated and the dominant species in the low yielding quadrat will be overestimated. This problem can be solved by applying a yield correction through assigning a weighting factor which is derived from the yields of species in their respective quadrats (Jones and Hargreaves 1979). These weighting factors are then used to calculate the DWR of the sampled species more accurately across a site.

**Methods of Monitoring Grassland Plant Communities: Ground Cover Estimation**

Ground cover in plant communities represents an extremely important attribute, as it is often used to determine the state of soil and hydrologic functions at a site (Coulloudon et al. 1999). Booth and Tueller (2003) note that measuring the effectiveness of land management practices to improve soil stability can be successfully completed using accurate cover and bare ground measurements. Cover is generally expressed as the proportion of the ground surface which is covered by vegetation. While this is true, there are several different kinds of cover that are recognized, including vegetation cover, foliar cover, canopy cover, basal cover, and ground cover. Foliar cover is the ground area which is covered by a vertical projection of the aerial portions of a given plant, where the small gaps and interspecific overlap between plants are excluded. Canopy cover is different than foliar cover, where this cover type takes into account the ground area which is covered by the vertical projection of the perimeter of the foliage of a plant. Both foliar and canopy cover involve vertical projections, where ground cover refers only to cover on the ground surface. In this report, basal and ground cover will be highlighted. Basal cover is often referred to as the proportion of the ground which is covered by the basal portion of plants, where ground cover is the proportion of plants, litter, rocks, and gravel across a site. Common methods used to collect ground cover and basal cover data include point frame (Levy and Madden 1933), line intercept, and step point (Coulloudon et al. 1999).

The point frame method (sometimes referred to as the steel-point frame), was originally developed by Levy and Madden (1933). This device consists of an upright frame with 1 to 10 pins that are lowered until they contact (or "hit") a plant, litter, rock, or bare ground (Levy and Madden 1933; Brun and Box 1963; Booth et al. 2006). After data collection using this method is complete, percent cover for each cover category is calculated (Brun and Box 1963; Booth et al. 2006). While this data can be collected quickly, many data points may be needed to accurately compare sites (Goodall 1952; Owensby 1973). In addition, point frames often overestimate the percent cover of larger plants (such as shrubs or bunchgrasses) because the same plant is recorded by different points on the same frame (Bonham 1989).

The line intercept method is a method of collecting cover data by recording horizontal, linear measurements of the intercepts of different plant species along a tape (Coulloudon et al. 1999), with application of its use in rangelands being explored in the mid-20$^{th}$ century by Canfield (1941). This method allows for collecting both foliar and basal cover and is similar to the point frame, however the pin that is used to read the points is placed along a transect (Brun and Box 1963; Coulloudon et al. 1999; Booth et al. 2006). One limitation to the line intercept method is that it is best used in places where the boundaries of the vegetation present are easy to determine, such as shrublands (Coulloudon et al. 1999). Coulloudon et al. (1999) also share that this method does not fit well in estimating cover of single-stemmed species, dense grasslands, and litter. Due to these limitations, other methods for collecting ground cover data in ecoregions such as the Nebraska Sandhills may be more desirable, such as the step-point method.

Brun and Box (1963) compared the point frame and line intercept methods in sagebrush-grass and sagebrush-shadscale plant communities. In their research, Brun and Box (1963) found that the point frame was 5.67 times faster at estimating ground cover than the line intercept method as well as being approximately 5 times more efficient. The point frame and line intercept methods were similar in accurately estimating botanical composition in both plant communities mentioned as well.

Another simple method of collecting ground and basal cover data is through the step point method. The step point method was reviewed in depth by Evans and Love (1957) who share that this method was derived from the point quadrat method developed by Levy and Madden (1933). This method uses a single pin, instead of a group of pins on a frame, and the observer simply places the pin perpendicular to the ground to record what was hit for every "step" along a transect (Evans and Love 1957; Coulloudon et al. 1999). Owensby (1973) recommended a modified step point system to estimate basal cover. In his recommendation, Ownensby (1973) shared that a modified step point frame consisting of multiple points, where the observer places one leg of the frame at the end of their boot and reads the hit off a point extending from the frame, would limit subconscious bias and reduce the number of points needed for comparable accuracy.

Using this method, a large amount of data can be collected in a short time (Goodall 1952; Coulloudon et al. 1999).

**Methods of Monitoring Grassland Plant Communities: Photographs**

Documenting change over time in plant communities using photographs can be a useful tool when making management decisions (McGinty and White 1998; Coulloudon et al. 1999; Hall 2002). Because of the ease of doing so, Coulloudon et al. (1999) suggest taking pictures at all study sites. The repeatability of this method allows for comparison of a site over a period of years, making changes in plant communities or soil characteristics visually evident. Several approaches can be taken when documenting an area with photographs including close-up, general view, and photo point methods.

Close-up pictures are usually used to document soil surface characteristics and ground cover (McGinty and White 1998; Coulloudon et al. 1999). These pictures are taken at permanently located photo plots and pointed directly over a frame on the ground surface. It is recommended that close-up pictures are taken toward the northern edge of the study site so that no shadow is casted over the area of interest. General view pictures are used to display a larger view of the landscape, making relocation of study sites easier.

Photopoints are one of the more popular methods of photographic monitoring due to the simple, rapid, and inexpensive nature of the method (O'Connor and Bond 2007). Photopoints are described as being a method of recording change in a natural environment by taking a series of images of a fixed area over time. The process of documenting photopoints is relatively simple. Once a permanent reference point on the study site is selected, a photograph is taken to visually portray the vegetation in the area. It is important, however, that all photos are labeled with the location, site name, photograph number, and date so that the site of the photograph can be found when future photographs are to be taken and photographs from the same site can be compared. Some reference point in the photograph is often recommended, such as a fence post or notable feature on the horizon. Another important aspect is when the photographs are taken. Hall (2002) shares that, if vegetation is the focus, that a fixed date or dates be established so that the state of the vegetation can be observed at the same time of year every year. After the photographs have been taken and comparison is taking place, it is important to look for any significant changes between photos such as changes in the abundance of desirable plant species, amount of visible bare ground, or the formation of erosion features such as gullies.

There are many benefits that make photopoints an attractive monitoring technique. O'Connor and Bond (2007) share that photopoints provide an accurate and long-lasting record of visible detail, as well as a simple, fast, and inexpensive means of monitoring vegetation. Photopoints also have a low impact on the study area, require little skill, and can be a useful tool in supporting other monitoring data (Coulloudon et al. 1999; Hall 2002; O'Connor and Bond 2007).

While there are many benefits that accompany the photopoint method, limitations must also be considered. Photopoints are an easy monitoring method, however they should only be employed when the objectives of the study require visually observing change (Hall 2002). Photopoints are only capable of displaying change that is large enough to see from the view of the camera (O'Connor and Bond 2007). Therefore, if subtle changes are of interest, then photopoints may not be the monitoring method of choice. In addition, interpreting photopoints alone without additional data may lead to faulty conclusions.

**Methods of Monitoring Grassland Plant Communities: Remote Sensing**

Remote sensing is a modern tool available to rangeland managers that can be used to evaluate grazing management, biomass, wildlife habitat, and soils (Tueller 1989). Booth and Tueller (2003) describe remote sensing as one of the most effective ways of acquiring information over large areas in short time periods, especially on sites that are remote and hard to access on the ground. Where traditional ways of monitoring are always accompanied by some degree of human error, remote sensing allows for a less subjective form of monitoring rangeland landscapes (Booth and Tueller 2003; Jones et al. 2020). In its simplest description, Tueller (1989) describes remote sensing as the collection of data relating to an object or event without the use of physical contact. Through the knowledge and expertise of professionals in remote sensing, this method has risen to the forefront of innovative rangeland monitoring (Robinson et al. 2018).

Historically, interpretation of aerial photography was the extent of remote sensing technology (Tueller 1989). At the time of his paper, Tueller (1989) credited aerial photographs with providing the highest resolution over any other procedure. However, the launching of Landsat 1 in 1972 set the stage for what would become a new era of digital analysis of multispectral and multitemporal data (Tueller 1989; Booth and Tueller 2003). This new era was realized when several spacecrafts were launched in the 1980s with remote sensing capabilities including the Landsat Multispectral Scanner (MMS), the Landsat Thermal Mapper (TM), the System Pour l'Observation de la Terre (SPOT), and the Advanced Very High Resolution Radiometer (AVHRR) (Tueller 1989). These spacecraft capture information from multiple levels of the electromagnetic spectrum and represent them as image pixels, where a pixel is the minimum feature size represented by the spectral data. Another important characteristic of remote sensing data is the resolution, which has to do with pixel dimensions and image detail (Colwell 1983). Simply put, the higher (i.e., finer) the image resolution, the higher its precision (i.e., detail).

Rangeland managers tend to be interested in ground cover when monitoring rangelands (Booth and Tueller 2003; Hunt et al. 2003). Ground cover is of particular interest primarily because this characteristic influences soil stability and watershed function (Hunt et al. 2003; Boswell et al. 2017). Reflectance of live green vegetation plays a large part in making prediction of ground cover type with remote sensing possible (Hunt et al. 2003). Live green vegetation displays a wide array of reflectance and absorption of electromagnetic radiation for visible wavelengths compared to wavelengths in the infrared spectrum. These differences have led to the development of several multispectral band ratios and vegetation indices that involve both the red/infrared differences and coefficients derived from several bands (Huete et al. 1985; Huete 1988; Qi et al. 1994; Qi et al. 2000). These indices make it possible for remote sensing technology to recognize differences in plant cover types and make predictions in cover amounts. However, there were significant limitations with early remote sensing technology. Tueller (1989) shares that the background and shadows often influenced the signal received by remote sensing devices, causing complications and uncertainty regarding accuracy. In addition, remote sensing has traditionally not provided rangeland managers with more detailed information than overall cover classifications which limits the conclusions and decisions that can be made using this monitoring method (Hunt et al. 2003). While there are certainly limitations to monitoring using remote sensing, ground cover is one characteristic of rangelands that can be accurately estimated with remote sensing (Booth and Tueller 2003; Afinowicz et al. 2005; Booth et al. 2005; Bozwell et al. 2017). For example, a study conducted by Boswell et al. (2017) found no significant difference found in accuracy of ground cover estimations for canopy cover between remote sensing and field-based techniques. More modern satellite sensors such as the Landsat 7, Indian Remote Sensing, IKONOS, Hyperion, Moderate Resolution Imaging Sectroradiometer (MODIS), and National Aerial Photography Program (NAPP) may have contributed to this accuracy (Booth and Tueller 2003).

A relatively new decision support tool available to land managers to estimate fractional ground cover is the Rangeland Analysis Platform (RAP) (Jones et al. 2018). The RAP is the first of its kind, combining machine learning and cloud-based computing with historical remote sensing and field data to estimate vegetation cover and biomass for the entire western United States. Using the Landsat satellite record, canopy cover data was made available at a 30 m. resolution from 1984-2017 and included functional group cover classifications for annual forbs and grasses, perennial forbs and grasses, shrubs, and bare ground for the entire western United States. This work was recently improved upon by Allred et al. (2021), where average mean absolute error was 6.3% and the root mean squared error was 9.6% when vegetation cover estimates were compared to 5,780 on-the-ground vegetation plots. The datasets produced by the RAP are updated annually and biomass estimates are now available at a 16-day interval. Using this information managers can effectively and efficiently respond to the challenges that threaten the biodiversity and ecosystem services that rangelands offer.

Estimating biomass production is another capability of remote sensing. Hunt et al. (2003) share that biomass production can be estimated using Landsat or AVHRR data when using models of gross primary production based on the radiation efficiency. One metric that was commonly used to estimate production before the development of other models and approaches was the Normalized Difference Vegetation Index (NDVI) (Svoray et al. 2013). More recently, the MODIS MOD17 algorithm has been used to estimate gross primary production and net primary production (Robinson et al. 2018). This model, combined with medium resolution land cover classifications and meteorological data for the United States, allowed Robinson et al. (2018) to produce a product that provides 16-day gross primary production and annual net primary production estimates at a 30 m. resolution in a time series of 1986-2017 for the western United States. This data was also made available through the RAP and is updated on an annual basis (Robinson et al. 2018; Jones et al. 2021).

With the advancements of modern technology, the barriers that previously limited remote sensing are being removed (Allred et al. 2021). For example, Uden et al. (2019) were able to use RAP data to screen for spatial signals of erosion and desertification, woody encroachment, and annual exotic grass invasion using remote sensing technology. Jones et al. (2020) utilized RAP data to analyze trends in rangeland vegetation cover over the past 20 years across the western United States, finding increases in annual grass, tree, and shrub cover. Remote sensing provides a way to accurately monitor large areas of land without the labor and error associated with on-the-ground monitoring techniques (Booth and Tueller 2003; Svoray et al. 2013). While remote sensing provides valuable data that rangeland managers can use, there is also skill that must be possessed to use the full potential of the technology. Tueller (1989) referred to remote sensing as both a science and an art, with the science being provided by the experts whose abilities made remote sensing possible and the art being in understanding the ecology and relationships that exist in landscapes. It is imperative that users of innovative data products, such as the RAP, have a working knowledge of ecological principals and local areas so that the potential of this technology can be realized.

**Grazing Management Strategy Impact on Rangeland Plant Communities**

Grazing management and its impact on rangeland plant communities has been the focus of much research in the field of rangeland management. Grazing management is defined by Vallentine (2001) as the manipulation of livestock grazing to reach desirable outcomes based on animal, plant, land, and economic feedbacks. Vallentine (2001) also shares that the immediate goal of grazing management is to ensure an adequate supply of forage on the landscape to satisfy the needs and production potential of grazing animals. Grazing management strategies are determined with consideration of the vegetation, livestock, and economics of an operation, and the manager must make decisions on when a pasture should be stocked, the stocking rate to be used, as well as when and where the livestock should be moved (Bement 1969). The general goal of grazing management in the mid-20$^{th}$ century was to increase production on the landscape through key plant species securing enough resources (such as light, water, and nutrients) to enhance their growth, while also aiming to increase the harvest efficiency of grazing animals (Briske et al. 2008). More modern views of grazing management goals include managing for heterogeneity on the landscape to enhance ecological structure and function (Fuhlendorf and Engle 2001; Briske 2017). Two factors of grazing management strategies that have attracted attention regarding their impact on rangeland plant communities are stocking rate and grazing system (Briske et al. 2008; Wilmer et al. 2018).

Stocking rate has been a principal component of grazing management strategies since the early 1900's (Holecheck 1988). Stocking rate is of particular importance because it determines the intensity of grazing that is to take place and, in effect, determines the amount of biomass that remains after grazing has taken place. Bement (1969) shares that heavy stocking rates remove a large amount of leaf tissue, leaving a minimal amount of photosynthetic material that is used for vegetative production. Light stocking rates often remove considerably less leaf tissue, leaving more photosynthetic material for plant growth (Bement 1969). These findings are reiterated by Briske et al. (2008) who explain that the loss in leaf area prevents plants from absorbing solar energy and converting it to chemical energy. Klipple and Costello (1960) found that heavy grazing on vegetation reduced herbage yield in subsequent years. However, this loss in herbage yield could be restored using lighter stocking rates (Klipple and Bement 1961). O'Reagain and Scanlan (2013) found that stocking at long-term carrying capacity was more profitable and maintained land condition compared to heavy stocking.

Plant species composition on a landscape may also be influenced by stocking rate. Lighter stocking rates allow grazing animals to behave more selectively when grazing, putting some species at a competitive disadvantage (Anderson and Briske 1995). This idea of plant species' response to grazing was first brought to light by Dyksterhuis (1949) who introduced the principle of increaser, decreaser, and invader species in response to grazing. Characteristics of plants that indicate which category they might fit in include the plant height and number/location of meristems (Briske et al. 2008). In a study on how plants respond to defoliation, Briske and Richards (1995) found that the height of a given plant at different stages of development characterize whether that plant will be grazed and how intensely that plant will be grazed.

Stocking rate also influences plant community composition by determining the heterogeneity of grazing patterns. Heterogeneous grazing patterns induced by lighter stocking rates and increased selectivity has been shown to modify plant community composition over space and time (Willms et al. 1988; O'Connor 1992; Bailey et al. 1996; McIvor et al. 2005). Allowing selectivity in grazing animals results in areas of preferential use in pastures which receive a disproportionate amount of grazing pressure, increasing the stocking rate on those preferred patches compared to the whole pasture (Fuhlendorf and Engle 2001). This increased grazing pressure can result in altered species composition throughout the pasture in both preferred patches with relatively heavy grazing pressure and avoided patches with relatively low grazing pressure. It is worth noting, however, that stocking rate is not the only determining factor for heterogeneity in a pasture. Coughenour (1991) shares that grazing patterns are influenced by the spatial distribution of topography, water, cover, minerals, and inter- and intraspecific animal interactions. Over time, heterogeneous use of rangelands can change the spatial and temporal variability of primary production and intensify grazing impact on preferred patches (Fuls 1992; Kellner and Bosch 1992; Illius and O'Connor 1999, Teague and Barnes 2017).

Much debate exists in the literature on which grazing system is superior. A grazing system is often described as a practice in grazing management where reoccurring periods of grazing, rest, and deferment are used in two or more pastures (Heitschmidt and Taylor 1991). Many grazing systems have been introduced over time including simple deferred grazing (Sampson 1913), sophisticated rotational systems (Vallentine 1967), intensive short duration systems (Savory 1978), and adaptive multi-paddock strategies (Teague and Barnes 2017; Augustine et al. 2020). Continuous (season-long grazing) has also been utilized by ranchers as a viable grazing management strategy with appropriate stocking rates (Briske et al. 2008). However, despite clear evidence that rotational systems are not superior to continuous systems over the past 60 years, rotational systems continue to be promoted as a superior system (Briske et al. 2008). Briske et al. (2008) found that 17 of 19 studies (89%) comparing rotational and continuous grazing systems with similar stocking rates found no differences in plant production between the two systems. Teague and Barnes (2017) argue, however, that the studies cited by Briske et al. (2008) were largely reductionist in nature, ignored the critical factor of scale, and were too short-term to see the benefits that can come from multi-paddock grazing. In addition, Teague and Barnes (2017) argue that multi-paddock grazing has been used successfully by many ranchers to increase soil and ecosystem community biodiversity and promote the most productive plant species.

Several studies have investigated the effect of grazing systems and grazing intensity on plant community dynamics within diverse plant communities and climate regions. One recent study investigated the effect of diverse management strategies on plant communities in eastern Colorado and eastern Wyoming (Wilmer et al. 2018). In this study, vegetation monitoring data were collected on 17 different ranches. The ranches were grouped based on similar management and the ecological monitoring data were statistically compared across the different groups of ranches. Wilmer et al. (2018) concluded that the grazing management strategy of the ranches in their study did not influence vegetation composition when grazing intensity was not considered. When ranches were grouped by grazing intensity, using Non-Metric Multidimensional Scaling (NMDS) analysis, distinct clusters of ranches with different plant species composition formed. This research suggests that grazing intensity is a primary driver of rangeland plant community composition. Augustine et al. (2020) conducted a study comparing the vegetation and livestock performance effects of adaptive, multipaddock, rotational grazing to traditional season-long continuous grazing in Colorado. Despite the difference in management, this study found that the adaptive rotational grazing did not increase total forage production or shift the vegetation composition of the study sites. The limited differences observed in this study was thought to be a result of the use of similar stocking rates among the different grazing systems. Porensky et al. (2021) also found that a collaborative adaptive management framework did not differ significantly in its effect on plant community species composition independent of stocking rate. These studies highlight the importance of stocking rate as a driving factor in plant community composition.

Many studies have investigated the effects of stocking rate on plant community composition. Porensky et al. (2016) conducted a study investigating the long-term effects of light (15.7 AUD/ha$^{-1}$), moderate (32.6 AUD/ha$^{-1}$), and heavy (43.4 AUD/ha$^{-1}$) stocking rates on vegetation characteristics at the High Plains Grasslands Research Station in

Cheyenne, Wyoming. Each stocking rate was implemented using a continuous season-long grazing management style, and vegetation response to the grazing treatments was evaluated using Daubenmire basal and foliar cover estimates. In this study, heavier stocking rates decreased cover of the dominant cool-season grasses on their study sites and increased cover of blue grama. This is similar to research conducted by Hart (2001) who found that blue grama was the dominant plant species in a shortgrass steppe under heavy grazing and Manley et al. (1997) who found that western wheatgrass (a cool-season grass) decreased under heavy grazing in a mixed-grass prairie. Poresnky et al. (2016) also investigated the effect of reversing stocking rates from heavy grazing to light or no grazing for 8 years following the heavy grazing treatment. In this trial, the cool-season grass cover that was reduced by heavy grazing was restored, however cover of blue grama did not change following the change in stocking rate. These results differ from Gillen et al. (2000) and Vermeire et al. (2008), who found that altering stocking rates produced little changes in the plant community composition in mixed-grass prairies.

**Summary**

The Sandhills ecoregion is an important resource for the state of Nebraska, serving as one of the last remaining contiguous native grassland ecosystems in temperate regions of the world. The vegetation of this ecosystem has been extensively studied over the past century, with dominant plant associations changing over time. Many traditional vegetation monitoring methods have been used to collect plant community data in this landscape over the years, including frequency of occurrence, dry weight rank, ground cover estimation, biomass, and photopoints. Newer monitoring methods of collecting environmental data include remote sensing methods, which along with field data, inform estimates in the RAP and related decision support tools, which have greatly expanded the ability of rangeland managers to monitor ecological changes at larger spatial and temporal scales. The effects of grazing management on rangeland plant communities have been a focus of the rangeland literature for decades, with superiority of management types (i.e., rotational or continuous grazing) being unclear and stocking rate providing the best explanation of vegetation response to management. Little research exists comparing plant communities of ranches with diverse management at a large scale in the Sandhills.

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# Chapter 2: REGIONAL DIFFERENCES IN PLANT SPECIES COMPOSITION IN THE NEBRASKA SANDHILLS

## Introduction

The Nebraska Sandhills ecoregion is one of the most intact and largest contiguous grasslands in temperate regions of the world, providing many ecosystem services as well as prime grazing land for cattle (Scholtz and Twidwell 2022). Because of this, the Sandhills serves as an important source of biodiversity and a vital resource for conservation concerns such as habitat for grassland bird populations (Sliwinski et al. 2019), preservation of endangered species (Stubbendieck et al. 1989), and carbon sequestration (Conant 2010). Plant community composition and annual plant production in the Sandhills are heavily influenced at small scales spatially by the variability in the topographic positions of the dunes and temporally by the amount and timing of precipitation (Adler and Levine 2007; Schacht et al. 2000; Stephenson et al. 2019). At broader spatial scales in the Sandhills, understanding how regional climate influences plant community composition can provide rangeland managers with valuable information for making decisions on how to manage plant communities in their respective precipitation regimes.

Over the past century, several botanical surveys have evaluated the upland plant community composition in the Sandhills. Throughout these surveys, the reported composition of the dominant plant communities on upland rolling hills has conflicted between reports. Early surveys conducted by Pound and Clements (1900) and Pool (1914) reported a bunchgrass plant community dominated by little bluestem (*Schizachyrium scoparium* (Michx.) Nash) as the most common on Sandhills uplands.

Other surveys conducted in the mid-20th century reported the rhizomatous prairie sandreed (*Calamovilfa longifolia* (Hook) Scribn.) as the most abundant species in the plant community on upland Sandhills rangelands (Frolik and Shepherd 1940; Tolstead 1942; Burzlaff 1962).

Few recent studies exist in the literature which examine plant community composition across working ranches in the Sandhills. One of the last studies to undergo this kind of research was conducted by Burzlaff (1962). In his study, Burzlaff (1962) conducted botanical surveys on 24 different ranches distributed across 8 different counties in the Sandhills. Prairie sandreed was the most frequently observed species on uplands rolling sands monitoring sites, with little bluestem and sand bluestem (*Andropogon gerardii spp. hallii* (Hack.) Wipiff) described as subdominant species.

More recently, however, botanical surveys conducted in the Sandhills have presented the bunchgrass plant community as one of the most common plant associations across the Sandhills (Keeler 1980; Barnes 1984; Bragg 1998; Schact et al. 2000). While severe drought in the 1930s has been suggested as a causal factor in the reduction of little bluestem for plant communities in the mid-20th century (Weaver and Albertson 1939; Weaver 1965; Stubbendieck and Tunnel 2008), Bleed and Flowerday (1990) suggested that precipitation variability from the western region to the eastern region of the Sandhills has not been evaluated as a major driver of plant species composition across the Sandhills. Large-scale plant community assessments, such as the work done by Burzlaff (1962) and found within ecological site descriptions (EDIT 2022), are valuable as they aid in capturing the inherent variability that exists across rangeland landscapes. Conducting further large-scale assessments is necessary to follow up on this work and provide a more up-to-date view of the plant communities that exist on working landscapes in the Nebraska Sandhills.

The influence of management, such as stocking rate or grazing strategy, on plant community composition has been extensively investigated throughout the scientific literature, however few studies exist which successfully prove one strategy as being superior on native rangelands (Briske et al. 2008). While some research has identified benefits for multi-paddock rotational grazing (Teague et al. 2008; Teague et al. 2013; Teague and Barnes 2017), these results do not provide clear evidence that this grazing system is a panacea for all rangelands. Additional research has found that stocking rate is a key factor in determining the composition of the plant community on rangelands (Manley et al. 1997; Hart et al. 2001; Porensky et al. 2016; Wilmer et al. 2018). Studying grazing strategies is difficult because plant shifts are often long-term, real world rangeland management situations are difficult to replicate in a research setting, and the scale of the study is important (Barnes and Hild 2013, Teague et al. 2011; Teague et al. 2013; Teague and Barnes 2017). Wilmer et al. (2018) conducted a study investigating the effects of diverse management strategies on vegetation composition in the western Great Plains. This study concluded that grazing management strategies did not influence vegetation composition on rangelands independent of grazing intensity in the western Great Plains. Studies comparing vegetation composition on working ranches and rangeland landscapes with longer-term and diverse management strategies provides valuable information that can be used by rangeland managers to implement strategies that support the goals of their operation.

The objective of our study was to evaluate plant community variability on upland Sands ecological sites on rangeland landscapes across the different precipitation zones in the Nebraska Sandhills. Ranch managers must understand what plant communities occupy their ranches to make important management decisions such as timing of grazing events and stocking rates. Understanding what plant communities are present across the Sandhills, and the drivers that influence these plant communities provides important baseline data to inform management decisions in this ecosystem.

## Materials and Methods

### Study Area

This study was conducted across the Nebraska Sandhills, which encompasses 49,987 $km.^2$ of contiguous mixed grass prairie in the north-central portion of the state (Bleed and Flowerday 1990). The Sandhills is composed of a heterogeneous landscape of rolling slopes, dunetops, interdune swales, and subirrigated meadows (Stephenson et al. 2019). While this ecosystem is made up of many ecological sites, one of the most common ecological sites is the Sands ecological site (EDIT 2022). Sands ecological sites are mostly found on uplands, having a Sandy Loam soil texture with gently rolling terrain and 3-24% slopes. The major soil series associated with Sands ecological sites include Valent and Valentine, with the McKelvie series also found within the description. The common vegetation in this ecological site is a warm season mid-grass community with a native shrub component, with prairie sandreed, sand bluestem (*Andropogon gerardii spp. hallii* (Hack.) Wipiff), and little bluestem composing the dominant species. Secondary grasses in this ecological site include needlegrasses (*Hesperostipa spp.*), sand dropseed (*Sporobolus cryptandrus* (Torr.) A. Gray), and switchgrass (*Panicum virgatum* L.). The annual precipitation in the Sandhills generally ranges from 17-23 in. (431.8-533.4 mm), increasing from west to east, with approximately 70-75% of this precipitation falling from April to September (Burzlaff 1962; Whitcomb 1989; Bleed and Flowerday 1990).

Ranches included in this study were selected based on discussion with cooperating grazing managers, differences in grazing management strategies, and location of the ranches across the different precipitation zones in the Sandhills. In total, fourteen working ranches were selected for this study which included a diverse array of management strategies (Table 2.1). Data were collected across 3 years (2019, 2020, and 2021). While the study ended with 14 ranches, ranches were added in each year of data collection (7 total ranches in 2019, 8 total ranches in 2020, 14 total ranches in 2021). Because of this, the ranches that began the study in 2019 were monitored for three years, the one ranch added in 2020 was monitored for two years, and the six ranches added in 2021 were monitored for one year. Due to the COVID-19 pandemic, our resources only allowed one additional ranch to be added to the study in 2020. These ranches were distributed throughout three precipitation zones across the Sandhills that are found within the NRCS MLRA 65 description and classified by the Nebraska NRCS (Fig. 2.1; EDIT 2022; Personal communication with NRCS State Range Conservationist, Jeff Nichols). Following this description, the low precipitation zone, located on the western side of the Sandhills, is classified as receiving 355.6-431.8 mm. (14-17 in.) of precipitation annually. The moderate precipitation zone, located in the central Sandhills, receives 431.8-558.8 mm. (17-22 in.) of precipitation annually. Finally, the high precipitation zone, on the eastern side of the Sandhills, receives 558.8-635.0 mm. (22-25 in). of precipitation annually. Guided by these established precipitation zones, we used the most recent 30-

year average (1991-2020) annual precipitation data to define annual precipitation at each of the ranches in the study using the PRISM Climate Group (PRISM 2022). Through this process, we determined ranches had higher mean annual precipitation metrics compared to the established values. Within the low precipitation zone (LPZ), ranches received 450-500 mm (17.7-19.7 in.) of annual precipitation, ranches in the moderate precipitation zone (MPZ) received 500-600 mm. (19.7-23.6 in.) of annual precipitation, and ranches in the high precipitation zone (HPZ) received >600 mm. (>23.6 in.) of precipitation (Fig. 2.1). Ranch LPZ2 is located on the boundary between the low and moderate precipitation zone. The 30-year average annual precipitation received by this ranch (474 mm.) was more similar to the other ranches in the low precipitation zone compared to the moderate precipitation zone and this ranch was classified as being within the low precipitation zone.

**Site Selection and Establishment**

Once ranches were selected within the different precipitation zones, study sites were established within three pastures on each ranch which represented the typical management on the ranch as determined by the grazing manager (e.g. summer grazing as part of their management plan). Three study sites were established within each pasture. Across all the ranches, a total of 126 monitoring sites were selected and monitored during the final year of the study in 2021 (Appendix 2.A). Monitoring sites were located on uplands, within Sands ecological sites (R065XY012NE; R065XY033NE; R065XY055NE) across each precipitation zone. Sandy, Choppy Sands, and subirrigated wet meadow ecological sites are important components of the Nebraska sandhills ecosystem but were omitted from monitoring consideration for time and consistency so that sites could be compared similarly across the different ranches. Attempts were made to distribute monitoring sites across different topographical positions within each pasture (e.g., north facing slope, south facing slope, and dune top). In the field, study sites in each pasture were established by reviewing ecological site maps, visually selecting representative sites in the field, and assessing sites and slopes based on the description of a Sands ecological site by the NRCS. Study sites were also located at least 241 m. (0.15 miles) from a water source. At each site, a GPS reading was recorded at the middle point so that sites could be revisited. Transects were established in three different directions (generally 340°, 240°, and 140°) extending away from the middle point.

**Vegetation Data Collection**

Study sites were typically visited and monitored from early-July and ending in early-August of each year to assess the growing season plant community at each ranch. A quadrat step method with the placement of a 40 x 40 cm. monitoring frame was employed to measure ground cover, frequency of occurrence, and dry-weight rank (DWR) of each upland plant community (Hall et al. 2018). A 40 x 40 cm. frame was selected with the objective that important species in the plant community would be sampled within the optimum range (i.e., >20% to <80% frequency) for statistical analysis (Despain et al. 1997; Collouden et al. 1999). However, this was not possible for all species, especially those species that were not frequently observed. Along each transect, moving away from the center of the monitoring site, a frame was placed every pace and vegetation was monitored for 11 readings per transect. Thirty-three frames were measured for each monitoring site and 99 frames for each pasture. This allowed for a total of 297 quadrat frame placements within 3 pastures and 9 monitoring sites on each ranch. All data collected were recorded using the Vegetation GIS Data System (VGS 2021).

At each quadrat placement, ground cover was quantified by identifying what was directly underneath the tip of the cover-point (a wood screw) located on the monitoring frame. Litter, bare ground, or basal live vegetation was identified and recorded. If basal live vegetation was hit, the species was recorded. From these observations, percent cover was calculated by dividing the number of hits from each respective cover type by the total number of observations (Coulloudon et al. 1999). Frequency of occurrence for individual plant species was recorded for all species rooted within the 40 x 40 cm. frame (Despain et al. 1997; Coulloudon et al. 1999). To estimate species composition in terms of production by dry weight, we used a dry-weight rank estimating procedure within each of the quadrat placements (Mannetje and Haydock 1963). Dry-weight rank (DWR) has been shown to be a reasonably accurate and useful tool to monitor species contribution to total production in different ecosystems (Gillen and Smith 1986; Kelley and McNeill 1980; Friedel et al. 1988). Observers would first visually estimate the top three species within the 40 x 40 cm. frame in terms of the greatest yield from that current growing season’s growth based on dry matter. The observer then assigned a rank of first, second, or third to these species. Using this method, a first-rank corresponds to 70% of the total biomass composition, second to 20%, and third to 10% (Mannetje and Haydock 1963; Smith and Despain 1997; Coulloudon et al. 1999). The mean across the quadrat placements was calculated to estimate the contribution of each species to total biomass.

Following data collection along the transects, an observer systematically walked across the site and recorded additional species that were present but did not appear in the frames along the transect. The record of all species observed at each site was used to calculate total species richness at each of the monitoring sites. The DWR data were used in calculations of similarity index based on NRCS descriptions by comparing the species percent contribution to the biomass in each study pasture to the acceptable range of percent biomass contribution for the reference plant community for a Sands ecological site in each respective precipitation zone (USDA 2006). In this calculation, the contribution of each species to the total biomass cannot exceed the allowable production of each respective species in the reference plant community. The percent contribution to the biomass of each species in the ecological site description is then summed to express the percent similarity of each pasture to the reference plant community.

Management information from each ranch was collected by conducting personal interviews and sending surveys to each ranch manager. From this survey, ownership, grazing animal type, average pasture size, number of grazing events during the growing and dormant season, rest following grazing, and average annual stocking rate were collected and summarized (Table 2.1). We calculated the stocking rate ($AUM \cdot ha.^{-1}$) for each ranch by using information collected from managers on the number of cattle in a pasture, the length of grazing in a pasture, the size of the pasture, and the average weight of the grazing animals. While there are clearly defined grazing strategies in the literature, ranch managers often deviate from these strategies so to meet the individual goals of their operation (Byrnes et al. 2018; Sliwinski et al. 2019). For this reason, the categories we defined that encompass the grazing management of each ranch is our best classification for the management that occurs on the upland pastures of these ranches in a given year.

**Data Analysis**

To assess important drivers in plant community variability across ranches, a principal component analysis (PCA) was conducted using the R Studio packages factoextra and FactoMineR for the frequency of occurrence and DWR of all plant species across the monitoring sites in each year (R 4.1.1). Following the PCA analysis a mixed model of variance was conducted in SAS 9.4 using the PROC GLIMMIX statement to evaluate significant differences among common species with precipitation zone and plant species as fixed effects. The most frequently observed 15 plant species across all regions were used for comparative analysis. These species included little bluestem, prairie sandreed, sand dropseed, blue grama (*Bouteloua gracilis* (Kunth) Lag. ex Griffiths), sand bluestem (*Andropogon gerardii spp. hallii* (Hack.) Wipiff), sedges (*Carex* spp.), needlegrasses, hairy grama (*Bouteloua hirsuta* Lag.), prairie junegrass (*Koeleria macrantha* (Ledeb) Schult.), wild rose (*Rosa arkansana* Porter), switchgrass, Wilcox rosette grass (*Dichanthelium wilcoxianum* (Vasey) Freckmann), stiff sunflower (*Helianthus pauciflorus* Nutt.), western ragweed (*Ambrosia psilostachya* D.C.), and Scribner’s rosette grass (*Dichanthelium oligosanthes var. scribnerianum* (Nash) Gould). These same 15 species were used for the DWR analysis, as these species provided at least 85% of the total contribution of biomass across all sites. Ground cover, similarity index, and total species richness were also analyzed using the PROC GLIMMIX procedure with a fixed effect of precipitation zone. Residual and quantile-quantile (qq)-plots were used to assess the normality assumption. When differences were observed at a significance level $P \leq 0.05$, means between species and precipitation zones were separated using Tukey-Kramer adjustment to account for multiple comparisons. To account for the different number of ranches in each year, the data for each year was analyzed separately.

## Results

### Frequency of Occurrence

The first two axes of the principal component analysis used the plant community diversity derived from the frequency of occurrence data to explain 45-53% of the variability in plant communities on upland Sandhills rangelands from 2019-2021 (Fig. 2.2). The separation in ranches located within the low precipitation zone (LPZ) compared to the moderate (MPZ) and high precipitation zones (HPZ) that occurs along the x-axis in the principal component analysis indicates that climatic variability in terms of annual precipitation may be a key variable in explaining plant frequency of occurrence in the Sandhills. In all years, plant communities were shown to be regionally unique and segregated between the LPZ compared to the MPZ and HPZ. These distinct clusters of ranches described by regionally unique plant communities indicates that a gradient in plant frequency of occurrence exists across different precipitation zones in the Sandhills.

Significant frequency of occurrence differences ($P \leq 0.05$) were found among several species across precipitation zones in all years (Fig. 2.3). Species observed more frequently in the LPZ than the MPZ or HPZ included prairie sandreed, sand dropseed, and blue grama (Fig. 2.2; Fig. 2.3). Species observed more frequently in the MPZ and HPZ compared to the LPZ included little bluestem, Scribner’s rosette grass, Wilcox rosette grass, western ragweed, switchgrass, and wild rose (Fig. 2.2; Fig. 2.3). Stiff sunflower was more frequently observed in the MPZ than the LPZ in 2019 and 2020, and more than the LPZ and HPZ in 2021.

Some species were observed almost exclusively in the MPZ and HPZ. These species included little bluestem, Scribner's rosette grass, stiff sunflower, Wilcox rosette grass, and wild rose. Little bluestem was a consistently dominant component of the upland plant community in the MPZ and HPZ, having a frequency of occurrence above 70% in all years across these regions. This contrasted with the LPZ, where little bluestem had a frequency of occurrence typically less than 5% (Fig. 2.3). Another species that was found exclusively in the MPZ and HPZ was Scribner's rosette grass. This species was the second most frequently observed species in the MPZ and HPZ, having a frequency of occurrence of at least 50% in all years across these regions. In our observations, Scribner's rosette grass was completely absent on uplands in the LPZ. Prairie sandreed was the most frequently observed grass species in the LPZ, averaging over 70% frequency of occurrence across all years. Prairie sandreed was present in the MPZ and HPZ, however this grass was approximately 23-34 percentage points higher in frequency of occurrence on sites in the LPZ than the MPZ or HPZ. Sand dropseed was another species that was frequently observed in the LPZ, averaging over 45% frequency of occurrence across all years. Frequency of sand dropseed was approximately 2.5-5 times greater in the LPZ compared to the MPZ and HPZ. Sand bluestem was significantly higher in the LPZ than the MPZ or HPZ in 2020, but this grass was not different among regions in 2019 or 2021. However, sand bluestem was trending higher in the LPZ ($P \leq 0.1$) than the MPZ in 2019.

**Dry Weight Rank (DWR)**

The first two axes of the principal component analysis used the DWR data to explain 64-68% of the variability in plant communities on upland Sandhills rangelands from 2019-

2021 (Fig. 2.4). Similar to the frequency of occurrence data, this analysis demonstrated a separation among ranches within the different precipitation zones. A few plant species were influential in defining DWR among ranches. Sand bluestem and prairie sandreed were defining species of DWR on ranches in the LPZ, whereas little bluestem was the primary species defining DWR on ranches in the MPZ and HPZ. Distinct differences in the clustering of ranches within the principal component analysis between ranches within the LPZ from the MPZ and HPZ indicates that the species that contribute the most to the total biomass on uplands shifts across the different precipitation zones in the Sandhills.

Significant differences ($P \leq 0.05$) were found between several species in terms of species percent contribution to total biomass between precipitation zones in all years (Fig. 2.5). Species with significantly higher percent contribution to total biomass in the LPZ compared to the MPZ or HPZ included prairie sandreed, sand bluestem, sand dropseed, and sedges, while species with significantly higher percent contribution to total biomass in the MPZ than the LPZ in 2019, 2020, and 2021 included little bluestem, stiff sunflower, switchgrass, and Scribner's rosette grass. Stiff sunflower percent contribution to biomass was significantly higher ($P \leq 0.05$) in the MPZ than all other regions in 2021. Needlegrasses percent contribution to biomass was significantly lower ($P \leq 0.05$) in the MPZ in 2021 than all other regions.

Little bluestem was the dominant component of the percent contribution to biomass in the MPZ in 2019 and 2020, and the MPZ and HPZ in 2021. Little bluestem's percent contribution to biomass in the MPZ and HPZ ranged from 33% to 39%. This contribution of little bluestem to the total biomass sharply contrasts with the LPZ, where little bluestem accounted for only 1-2% of the total biomass. Stiff sunflower was a characteristic species in terms of contribution to biomass in the MPZ, making up approximately 7-13% of the biomass. Stiff sunflower rarely attributed much biomass production to the other precipitation zones across all years of study, where the highest contribution recorded was 2% in the HPZ in 2021.

Prairie sandreed and sand bluestem were the highest contributors to the total biomass in the LPZ in all years. Prairie sandreed contributed significantly more to the total biomass in the LPZ than the MPZ or HPZ, ranging from 24-30% in the LPZ. This contrasted with the MPZ and HPZ where prairie sandreed accounted for only 5-10% of the total biomass. Sand bluestem was also a major contributor to the total biomass in the LPZ, composing 22-28% of the total biomass across all years. However, sand bluestem was only a minor factor for the total biomass in the MPZ and HPZ, making up only 5-8% of the biomass in these regions across all years.

**Ground Cover, Similarity Index, and Total Species Richness**

No significant differences ($P > 0.05$) were found in bare ground, litter, or basal vegetation ground cover among precipitation zones in 2019, 2020, or 2021 (Fig. 2.6). Across all years and regions, bare ground accounted for approximately $20.6 \pm 3.8\%$ of the ground cover, litter accounted for approximately $64.7 \pm 3.6\%$ of the ground cover, and basal vegetation accounted for approximately $14.7 \pm 1.7\%$ of the ground cover. While bare ground in the LPZ had consistently higher means, variability in the data resulted in no statistical differences.

Significant differences ($P \leq 0.04$) were found between similarity index values among precipitation zones in 2019, 2020, and 2021 (Fig. 2.7). In all years, the LPZ had higher similarity indexes than the MPZ or HPZ when comparing observed DWR contributions to the total biomass with Sands ecological site description reference plant communities. On average, the similarity index for ranches in the LPZ was 10 percentage points higher than ranches in the MPZ or HPZ when compared to their respective reference plant communities.

A total of 118 plant species were found across all precipitation zones, including 26 grass species, 84 forb species, and 8 shrub species. Significant differences ($P \leq 0.02$) were found between total species richness among precipitation zones (Fig. 2.7). Species richness was higher in the MPZ and HPZ, averaging approximately 30 ± 1.2 species per site compared to 23 ± 1.1 species per site in the LPZ. The difference in species richness between the MPZ and HPZ compared to the LPZ was generally the result of a greater number of grass species richness across all years.

## Discussion

Climatic variability within distinct precipitation zones influenced the plant species frequency and contribution to biomass on Nebraska Sandhills uplands across ranches with diverse management strategies. Our data established the existence of two distinct plant communities among precipitation zones in the Sandhills, with the LPZ plant community being characterized by prairie sandreed, sand bluestem, and sand dropseed and plant communities in the MPZ and HPZ being characterized by little bluestem Scribner’s rosette grass, and western ragweed. These results identify plant communities in the Sandhills that are influenced by precipitation zones, which has previously not been documented in the literature (Bleed and Flowerday 1990).

The dominance of little bluestem on uplands in the Sandhills is similar to some early botanical surveys conducted by Pound and Clements (1900) and Pool (1914), who reported a bunchgrass community dominated by little bluestem as being the most common plant community in the Sandhills. More recent botanical surveys have also documented a bunchgrass community to be the most common association on uplands in the Sandhills (Keeler 1980; Barnes 1984; Bragg 1998; Schact et al. 2000). In plant communities where little bluestem was the most frequently observed species, this species also was clearly dominant in terms of species contribution to total biomass. In the MPZ and HPZ, little bluestem contributed over two times more to the total biomass than any other species. Derner et al. (2011) found that little bluestem was especially resilient to rainout treatments in the southern Great Plains, concluding that a disproportionate share of the available resources is collected by little bluestem allowing it to consistently produce more biomass than other species in the plant community. Polley et al. (2007) also found that the variability in biomass production of plant communities with a high abundance of little bluestem was largely influenced by the production of this grass species, and that the response of these plant communities to variables such as precipitation depends largely on the traits of the dominant species in the ecosystem. One species that appeared to demonstrate increased contribution to total biomass in the absence of little bluestem was sand bluestem. This species, while displaying limited differences in frequency of occurrence across all precipitation zones, had significantly higher contributions to the total biomass in the LPZ compared to the other precipitation zones. One reason for this may have been that increased resource uptake by little bluestem limited sand bluestem biomass production in the MPZ and HPZ (Polley et al. 2007; Derner et al. 2011).

Our results identifying a prairie sandreed and sand bluestem dominated plant community in the LPZ were similar to results from botanical surveys in the mid-20th century that identified prairie sandreed as the dominant species on upland plant communities in the Sandhills (Frolik and Shepherd 1940; Tolstead 1942). The data from these studies was only collected in Cherry County, however, which is part of the MPZ. The limited amount of data collected from the LPZ and HPZ in previous suverys of the Sandhills suggests that further variability in the upland plant communities in these regions may exist. Our results indicate that prairie sandreed, sand dropseed, and sand bluestem are characteristic grasses of the LPZ in terms of frequency of occurrence and species contribution to biomass, where only trace amounts of little bluestem were found. This suggests that these species may be better suited to a dryer environment than the little bluestem plant community because of the gradient in annual precipitation that is seen from the LPZ to the HPZ.

Limited research has investigated the drought tolerance of native warm season grasses found in the Sandhills. Awada et al. (2002) found that the stomatal characteristics of prairie sandreed, in terms of stomatal distribution and leaf folding patterns, allowed this species to retain 35% of its water content after a dry-down process, compared to only 9% water retention in little bluestem. This characterstic may allow prairie sandreed to conserve more water throughout the dry conditions that occur in the LPZ in the Sandhills. In addition, the severe drought during the 1930s documented by Weaver and Albertson (1939) and Weaver (1965) was shown to dramatically decrease little blustem populations in the Sandhills. Stubbendieck and Tunnel (2008) also document large decreases in the frequency of occurrence of little bluestem during the drought period from the 1930s to

1940 in Thomas County. The transects were not read from 1948 to 1979, but by 1979 little bluestem had returned to pre-drought levels (Stubbendieck and Tunnel 2008). These results suggest that little bluestem may be sensitive to extreme drought in the Sandhills, which could explain why little bluestem is limited in the western part of the Sandhills and why other research did not report little bluestem as a dominant plant species in the Sandhills during the mid-20$^{th}$ century.

Our data reported a higher similarity to the reference plant community in the LPZ compared to the similarity index of the MPZ on Sands ecological sites. This difference in similarity index between the LPZ compared to the MPZ appears to be caused by the dominance of little bluestem and the lack of sand bluestem or prairie sandreed contribution to the biomass in the MPZ. The reference plant community for the MPZ is a Bluestem/ Prairie Sandreed/ Needlegrass community (EDIT 2022). In this plant community, little bluestem is allowed 15-25% composition of the total biomass. The average percent contribution to the biomass of little bluestem in the MPZ was 36-39% across all years in our study. This theme is also reflected in the reference plant community for the HPZ, where little bluestem was commonly recorded at values over 30% in this precipitation zone. In addition the reference plant community in the MPZ and HPZ allows for 25-40% contribution to the biomass of sand bluestem and 15-25% for prairie sandreed. The average percent contribution for these species across ranches in the MPZ and HPZ in our study was only 5-9%. The large scale dominance of little bluestem, in terms of frequency of occurrence and percent contribution to biomass, across multiple ranches of different management strategies in the MPZ and HPZ may validate the need to develop a new stable state in the state-and-transition model for Sands ecological sites on uplands in these regions that includes little bluestem as a more dominant component of the plant community.

Differences in species richness were also reported in our data, with the MPZ and HPZ having higher average total species richness than the LPZ. These results indicate that species richness increases with increasing annual precipitation in the Sandhills. This is consistent with research by Adler and Levine (2007) who found that plant species richness increased significificiantly with mean annual precipitation across grasslands in the Great Plains. Additionally, species richness differences in our data were mainly driven by the presence of grasses such as switchgrass, Scribner's rosette grass, and Wilcox rosette grass in the MPZ and HPZ.

## Management Implications

It is important for grassland managers to have a clear understanding of the plant communities that occupy their pastures so that management decisions can be made to support plant communities in the goals of the operation. This research highlighted that regional precipitaiton zones influence the plant communities that are present on Sands ecological sites throughout the Nebraska Sandhills. Managers can use the data collected in this study to aid in making informed decisions on how to manage the plant communities based on the precipitation zones where they are located. These data can also be used to outline the baseline plant communities that exist on uplands in the Sandhills ecosystem by the agencies that manage this resource. Further research is needed to better understand the influence of specific management practices on ranches within the different precipitation zones on the regional variability of upland Sandhills plant community dynamics based on long-term management practices.

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## Tables

**Table 2.1.** Grazing management strategies for ranches in the low precipitation zone (LPZ), moderate precipitation zone (MPZ), and high precipitation zone (HPZ). GS indicates the number of grazing events in the growing season. DS indicates the number of grazing events in the dormant season. An asterisk (*) represents grazing events that occur occassionaly, but not every year.

| Ranch ID | Ownership | Animal Type | Pasture Size (ha.) | Number of Grazing Events | Length of Grazing | Time Between Grazing Events | Stocking Rate (AUM·ha.$^{-1}$) |
|---|---|---|---|---|---|---|---|
| LPZ1 | Private | Cow-Calf | 253 | 3-4 GS | 1-1.5 mo. | 1-3 mo. | ~ 1.25 |
| LPZ2 | Private | Bison | 1,214 | 1 GS; 1 DS* | 1-2 mo. | >9 mo. | ~ 1.0-1.5 |
| LPZ3 | Federal | Cow-Calf | 340 | 1 GS | 1-1.5 mo. | >9 mo. | ~ 0.5 |
| LPZ4 | Private | Cow-Calf; Yearlings | 263 | 1 GS; 1 DS | 1-2 wk. | 6-9 mo. | ~ 1.5-2.5 |
| LPZ5 | Private | Cow-Calf; Yearlings | 202 | 1-2 GS; 1 DS | 1-2 wk. | 1-3 mo. | ~ 1.5-2.5 |
| MPZ1 | Private | Cow-Calf; Yearlings | 324 | 1-2 GS; 1 DS | >2 mo. | 3-9 mo. | ~ 1.5-1.75 |
| MPZ3 | University | Cow-Calf | 405 | 1 GS; 1-3 DS | >2 mo. | 6-9 mo. | ~ 1.0-1.5 |
| MPZ4 | Private | Cow-Calf | 129 | 1 GS | 2-4 wk. | >9 mo. | ~ 2.0 |
| MPZ5 | Private | Cow-Calf | 243 | 1 GS; 1-2 DS | 1-2 wk. | 3-6 mo. | ~ 1.5-2.5 |
| MPZ6 | Private | Bison | 1,113 | 1-2 GS | 1-2 wk. | 6-9 mo. | ~ 1.0-1.5 |
| HPZ1 | University | Cow-Calf | 161 | 1 GS | 1-1.5 mo. | >9 mo. | ~ 1.75-2.0 |
| HPZ2 | Private | Cow-Calf; Yearlings | 89 | 1-2 GS; 1 DS | 1-2 wk. | 1-3 mo. | ~ 1.63 |
| HPZ3 | Private | Yearlings | 162 | 1 GS | 2-4 wk. | 6-9 mo. | ~ 1.75 |
| HPZ4 | Federal | Cow-Calf | 364 | 1 GS; 1 DS* | 1-1.5 mo. | 6-9 mo. | ~ 0.75-1.0 |

# Figures

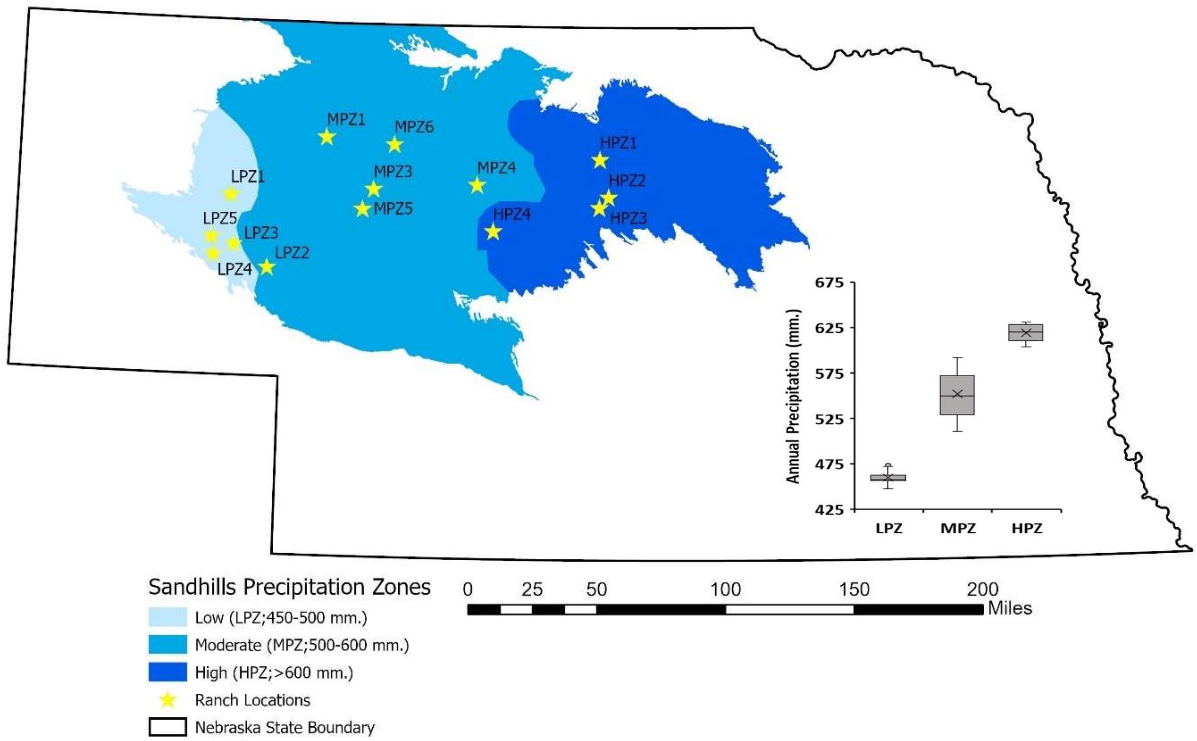


**Fig. 2.1.** Locations of study sites within 3 Sandhills precipitation zones in Nebraska defined by the NRCS MLRA 65 description. LPZ# represents ranches within the low precipitation zone. MPZ# represents ranches within the moderate precipitation zone. HPZ# represents ranches within the high precipitation zone. The inset box and whisker plot displays the actual estimated 30-year (1991-2020) average annual precipitation (mm.) (PRISM 2022) amounts across monitoring sites.

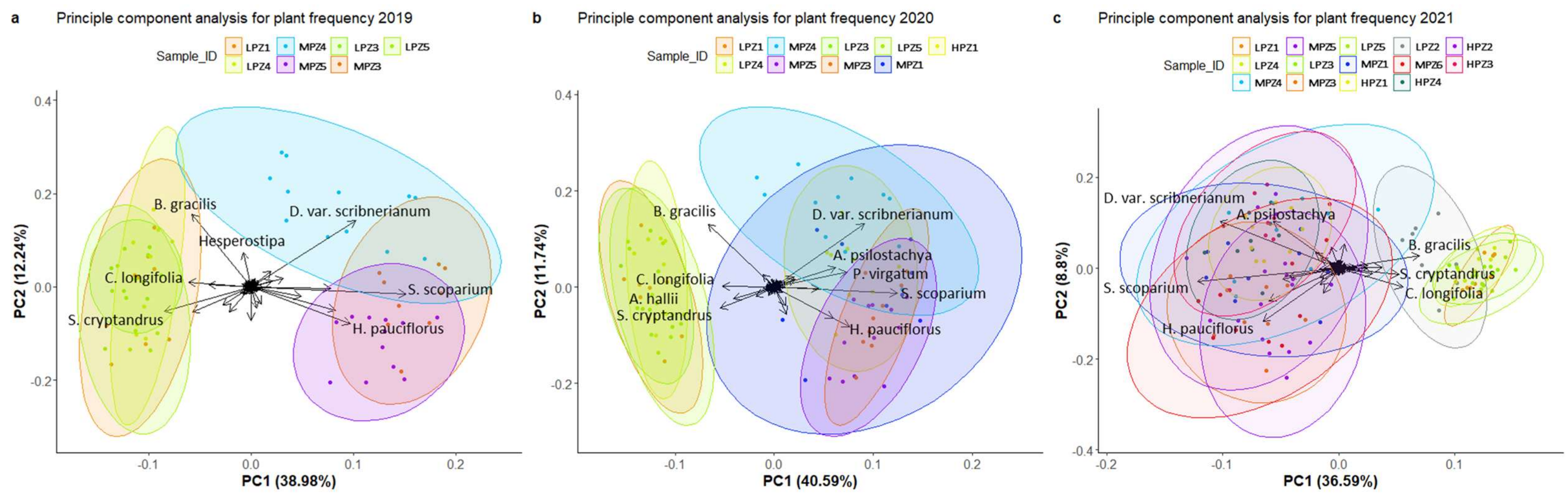


**Fig. 2.2.** Principal component analysis for plant frequency in a) 2019, b) 2020, and c) 2021. Each colored polygon represents the plant community defined across monitoring sites on each ranch. LPZ# represents ranches within the low precipitation zone, MPZ# represents ranches within the moderate precipitation zone, and HPZ# represents ranches within the high precipitation zone. Arrows extending from the middle of each figure represent species defining plant community associations among sites. Major defining species are labeled.

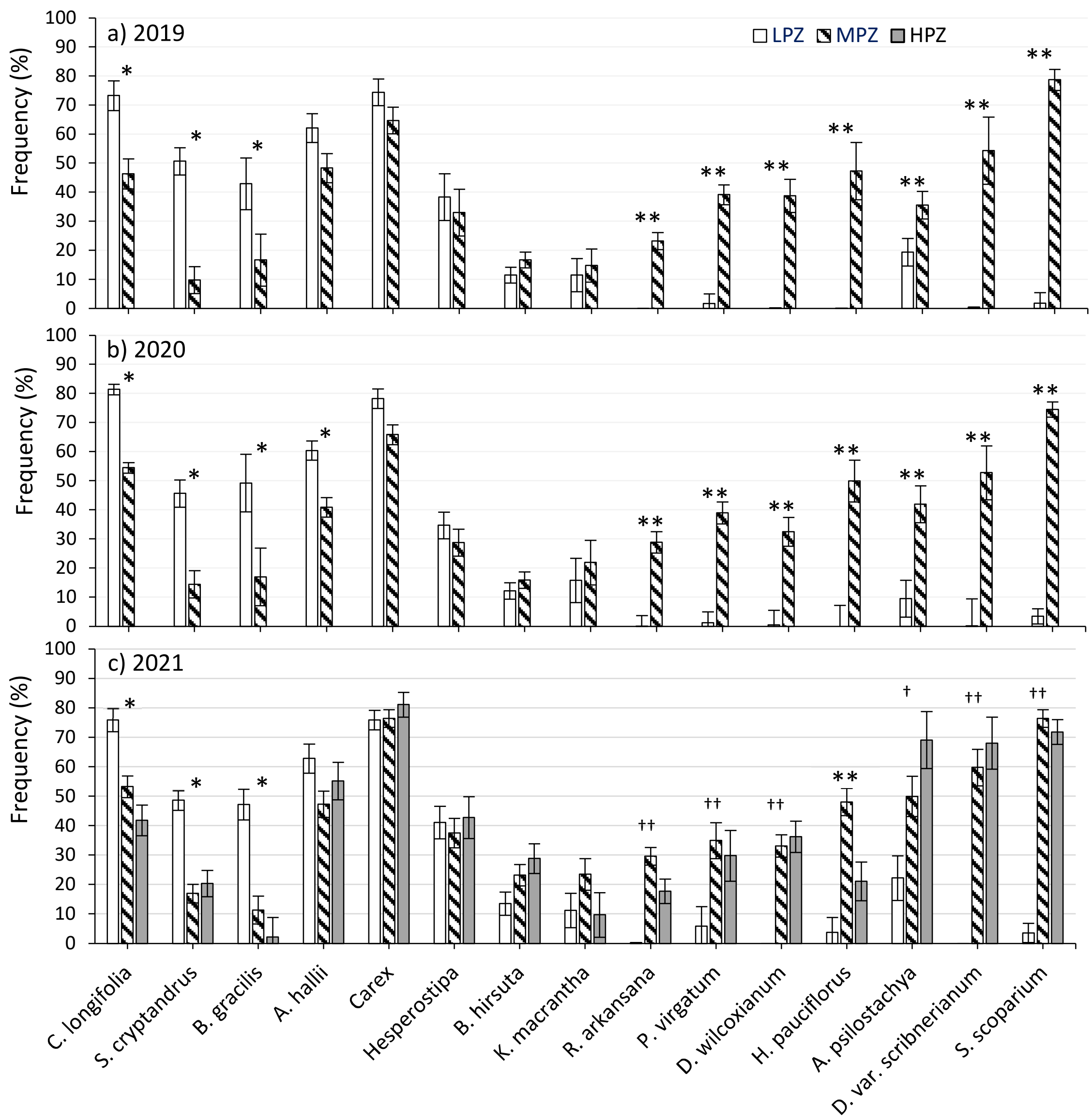


**Fig. 2.3.** Percent frequency of occurrence for ranches in the low precipitation zone (LPZ), moderate precipitation zone (MPZ), and high precipitation zone (HPZ) in a) 2019, b) 2020, and c) 2021. All symbols indicate significant differences (P≤ 0.05). (*) species that are higher in the LPZ compared to other zones, (**) species that are higher in the MPZ compared to other zones, ( †† ) species that are higher in the MPZ and HPZ compared to the LPZ, and ( † ) species that are different across all precipitation zones.

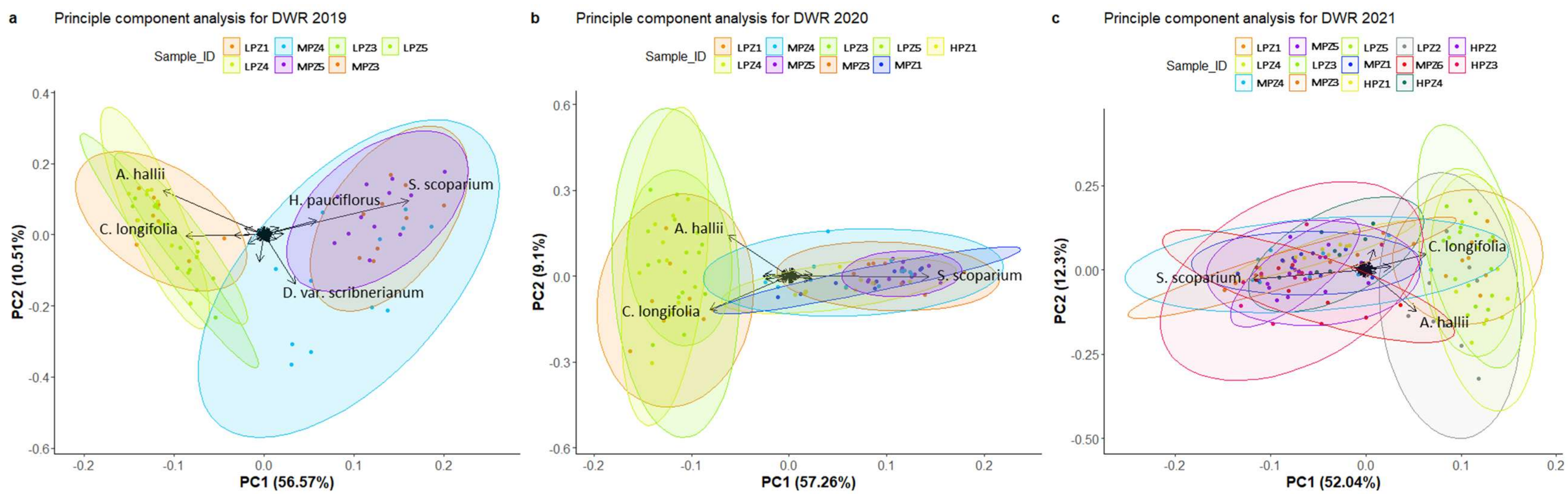


**Fig. 2.4.** Principal component analysis for plant DWR in a) 2019, b) 2020, and c) 2021. Each colored polygon represents the plant community defined by monitoring sites on each ranch. LPZ# represents ranches within the low precipitation zone, MPZ# represents ranches within the moderate precipitation zone, and HPZ# represents ranches within the high precipitation zone. Arrows extending from the middle of each figure represent species defining plant community associations among sites. Major defining species are labeled.

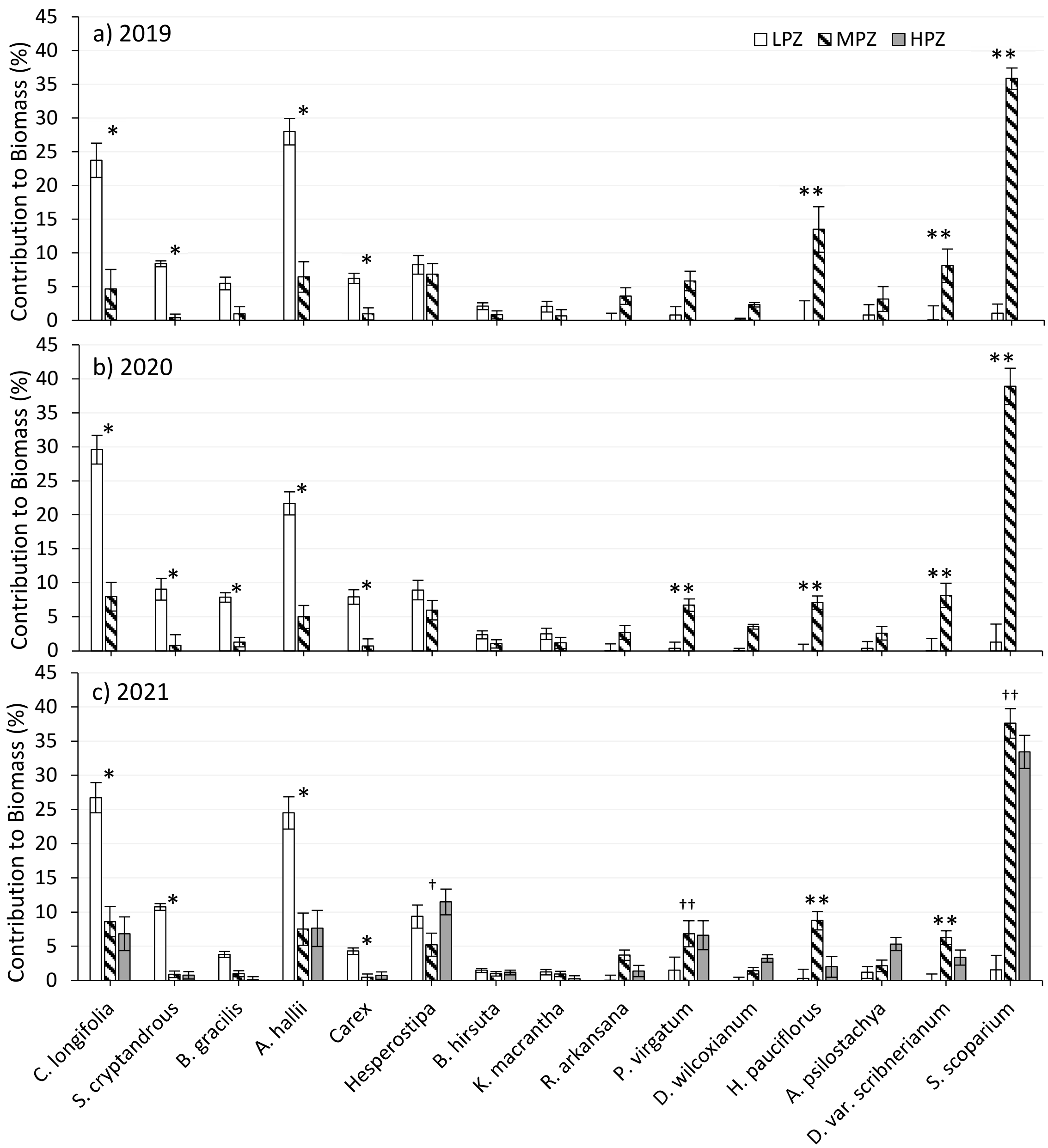


**Fig. 2.5.** Species percent contribution to biomass estimated by Dry Weight Rank (DWR) for ranches in the low precipitation zone (LPZ), moderate precipitation zone (MPZ), and high precipitation zone (HPZ) in a) 2019, b) 2020, and c) 2021. All symbols indicate significant differences (P≤ 0.05). (*) species that are higher in the LPZ compared to other zones, (**) species that are higher in the MPZ compared to other zones, ( †† ) species that are higher in the MPZ and HPZ compared to the LPZ, and ( † ) species that are lower in the MPZ compared to other zones.

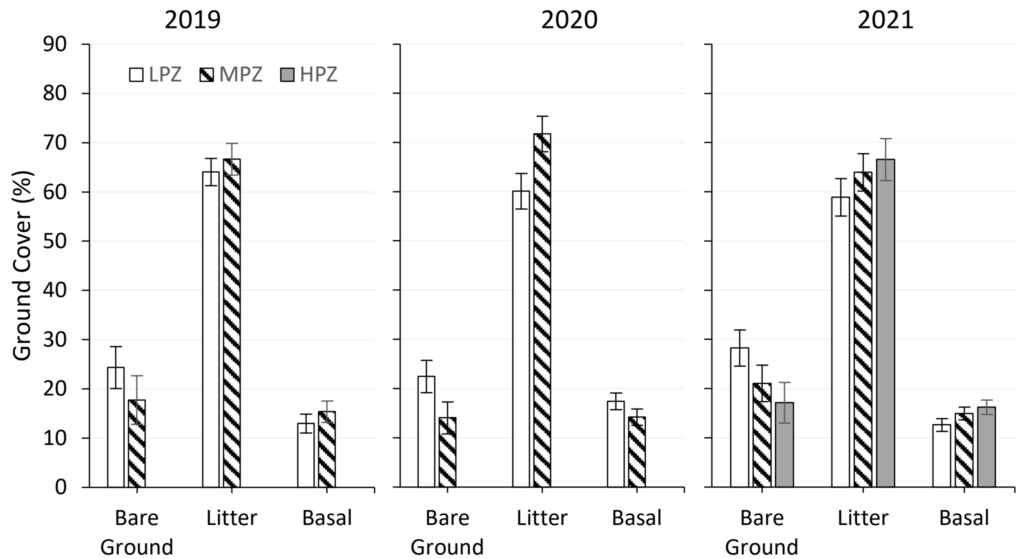


**Fig. 2.6.** Percent ground cover for ranches in the low precipitation zone (LPZ), moderate precipitation zone (MPZ), and high precipitation zone (HPZ) in 2019, 2020, and 2021.

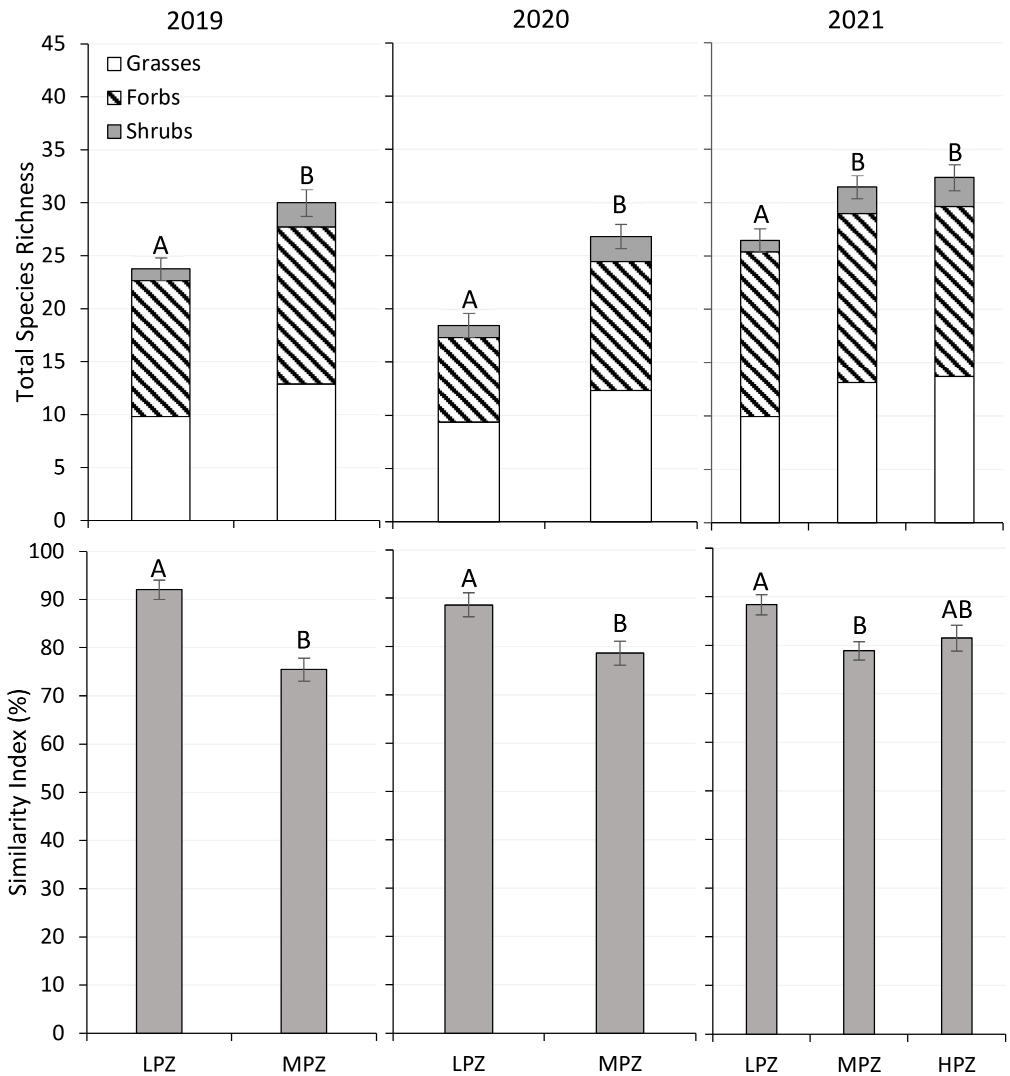


**Fig. 2.7.** Total species richness and similarity index calculations for ranches in the low precipitation zone (LPZ), moderate precipitation zone (MPZ), and high precipitation zone (HPZ) in 2019, 2020, and 2021. Different letters indicate significant differences (P≤ 0.05) in total species richness or similarity index.

# Appendix

**Appendix 2.A.** Study Site Information

| Study Site | Ecological Site | Elevation (ft) | Slope (%) | Aspect (º) | Latitude | Longitude |
|---|---|---|---|---|---|---|
| LPZ1 01 | Sands Low P.Z. | 1197.6 | 5.7 | N 15 | 42.01843 | -102.456 |
| LPZ1 02 | Sands Low P.Z. | 1208.4 | 5 | SW 238 | 42.02141 | -102.449 |
| LPZ1 03 | Sands Low P.Z. | 1204.2 | 8.8 | NW 336 | 42.01944 | -102.447 |
| LPZ1 04 | Sands Low P.Z. | 1198.6 | 9.4 | N 359 | 42.01848 | -102.444 |
| LPZ1 05 | Sands Low P.Z. | 1201 | 4.4 | W 202 | 42.01204 | -102.441 |
| LPZ1 06 | Sands Low P.Z. | 1194.4 | 3.7 | SE 108 | 42.00991 | -102.446 |
| LPZ1 07 | Sands Low P.Z. | 1198.5 | 10.1 | NE 34 | 42.01269 | -102.435 |
| LPZ1 08 | Sands Low P.Z. | 1185.4 | 9.1 | NE 47 | 42.02104 | -102.46 |
| LPZ1 09 | Sands Low P.Z. | 1192.8 | 8.6 | S 190 | 42.01905 | -102.461 |
| LPZ2 01 | Sands Low P.Z. | 1178.5 | 10.9 | 0.35 | 41.63524 | -102.152 |
| LPZ2 02 | Sands Low P.Z. | 1188.3 | 1.5 | 162 | 41.62907 | -102.158 |
| LPZ2 03 | Sands Low P.Z. | 1169.8 | 8.7 | 288 | 41.62215 | -102.154 |
| LPZ2 04 | Sands Low P.Z. | 1163.9 | 13.8 | 265 | 41.60973 | -102.151 |
| LPZ2 05 | Sands Low P.Z. | 1157.7 | 19.5 | 19 | 41.60077 | -102.168 |
| LPZ2 06 | Sands Low P.Z. | 1164.9 | 7 | 193 | 41.59574 | -102.17 |
| LPZ2 07 | Sands Low P.Z. | 1158.1 | 4.4 | 11 | 41.5835 | -102.182 |
| LPZ2 08 | Sands Low P.Z. | 1155.7 | 3.5 | 214 | 41.5846 | -102.187 |
| LPZ2 09 | Sands Low P.Z. | 1151 | 0.5 | 158 | 41.57691 | -102.205 |
| LPZ3 01 | Sands Low P.Z. | 1205.7 | 9.7 | E 76 | 41.75287 | -102.396 |
| LPZ3 02 | Sands Low P.Z. | 1190.5 | 15 | S 187 | 41.75367 | -102.398 |
| LPZ3 03 | Sands Low P.Z. | 1174.6 | 4.3 | N 13 | 41.74841 | -102.401 |
| LPZ3 04 | Sands Low P.Z. | 1175.8 | 4 | N 351 | 41.74653 | -102.414 |
| LPZ3 05 | Sands Low P.Z. | 1193.4 | 2.1 | S 196 | 41.73728 | -102.415 |
| LPZ3 06 | Sands Low P.Z. | 1192.8 | 7.1 | S 177 | 41.73859 | -102.415 |
| LPZ3 07 | Sands Low P.Z. | 1173.6 | 4.7 | N 340 | 41.73602 | -102.421 |
| LPZ3 08 | Sands Low P.Z. | 1172.1 | 3.6 | N 346 | 41.72997 | -102.408 |
| LPZ3 09 | Sands Low P.Z. | 1178.1 | 1 | NW 326 | 41.72657 | -102.405 |
| LPZ4 01 | Sands Low P.Z. | 1198.4 | 3.5 | N 0 | 41.67735 | -102.55 |
| LPZ4 02 | Sands Low P.Z. | 1206.5 | 7.2 | S 191 | 41.68048 | -102.551 |
| LPZ4 03 | Sands Low P.Z. | 1190.5 | 2.1 | SW 223 | 41.67514 | -102.553 |
| LPZ4 04 | Sands Low P.Z. | 1197.4 | 5.8 | SW 241 | 41.6769 | -102.559 |
| LPZ4 05 | Sands Low P.Z. | 1200.9 | 1.1 | NE 51 | 41.67593 | -102.564 |
| LPZ4 06 | Sands Low P.Z. | 1193.2 | 7 | SW 220 | 41.68193 | -102.574 |
| LPZ4 07 | Sands Low P.Z. | 1191.5 | 3.1 | SW 238 | 41.66638 | -102.588 |
| LPZ4 08 | Sands Low P.Z. | 1193.5 | 5.9 | SW 233 | 41.66292 | -102.584 |
| LPZ4 09 | Sands Low P.Z. | 1184.2 | 3.5 | NE 64 | 41.65782 | -102.583 |
| LPZ5 01 | Sands Low P.Z. | 1186.4 | 2.4 | SW 206 | 41.79852 | -102.585 |

| | | | | | | |
|---|---|---|---|---|---|---|
| LPZ5 02 | Sands Low P.Z. | 1183.3 | 2.1 | S 161 | 41.8008 | -102.591 |
| LPZ5 03 | Sands Low P.Z. | 1193.4 | 19.6 | NE 34 | 41.79909 | -102.592 |
| LPZ5 04 | Sands Low P.Z. | 1189.5 | 3 | NW 332 | 41.78197 | -102.587 |
| LPZ5 05 | Sands Low P.Z. | 1190.9 | 6.3 | SW 230 | 41.77796 | -102.587 |
| LPZ5 06 | Sands Low P.Z. | 1196.6 | 6.8 | NE 56 | 41.78285 | -102.594 |
| LPZ5 07 | Sands Low P.Z. | 1187.1 | 0 | NE 57 | 41.77615 | -102.575 |
| LPZ5 08 | Sands Low P.Z. | 1196.7 | 12.1 | NW 336 | 41.77756 | -102.579 |
| LPZ5 09 | Sands Low P.Z. | 1192.7 | 6.5 | SW 226 | 41.77868 | -102.579 |
| MPZ1 01 | Sands Medium P.Z. | 1146.5383 | 19 | N 7 | 42.36688 | -101.74 |
| MPZ1 02 | Sands Medium P.Z. | 1156.804 | 4 | SW 205 | 42.36435 | -101.747 |
| MPZ1 03 | Sands Medium P.Z. | 1156.3409 | 17 | S 177 | 42.3634 | -101.748 |
| MPZ1 04 | Sands Medium P.Z. | 1156.0283 | 25 | N 358 | 42.34488 | -101.772 |
| MPZ1 05 | Sands Medium P.Z. | 1181.3853 | 3 | E 95 | 42.34348 | -101.79 |
| MPZ1 06 | Sands Medium P.Z. | 1161.6165 | 15 | S 175 | 42.3401 | -101.782 |
| MPZ1 07 | Sands Medium P.Z. | 1154.9437 | 11 | S 193 | 42.32598 | -101.722 |
| MPZ1 08 | Sands Medium P.Z. | 1149.0963 | 4 | E 73 | 42.3275 | -101.713 |
| MPZ1 09 | Sands Medium P.Z. | 1144.3015 | 21 | NE 26 | 42.33016 | -101.717 |
| MPZ3 01 | Sands Medium P.Z. | 1076.1 | 3 | NW 296 | 42.06483 | -101.33 |
| MPZ3 02 | Sands Medium P.Z. | 1097.3 | 2.8 | N 345 | 42.06134 | -101.33 |
| MPZ3 03 | Sands Medium P.Z. | 1071.4 | 10.3 | SW 229 | 42.07123 | 101.3384 |
| MPZ3 04 | Sands Medium P.Z. | 1077.1 | 6.6 | SW 216 | 42.06666 | -101.37 |
| MPZ3 05 | Sands Medium P.Z. | 1087 | 12 | N 6 | 42.08586 | -101.366 |
| MPZ3 06 | Sands Medium P.Z. | 1091.6 | 8.1 | NW 337 | 42.07747 | -101.388 |
| MPZ3 07 | Sands Medium P.Z. | 1093 | 4.8 | NW 325 | 42.05121 | -101.379 |
| MPZ3 08 | Sands Medium P.Z. | 1088.8 | 7.8 | N 343 | 42.05578 | -101.378 |
| MPZ3 09 | Sands Medium P.Z. | 1076.6 | 1 | SW 233 | 42.066 | -101.387 |
| MPZ4 01 | Sands Medium P.Z. | 917.6 | 19.5 | SW 205 | 42.10435 | -100.566 |
| MPZ4 02 | Sands Medium P.Z. | 917.8 | 23.12 | NE 29 | 42.10734 | -100.577 |
| MPZ4 03 | Sands Medium P.Z. | 925.2 | 7.2 | NE 28 | 42.10798 | -100.564 |
| MPZ4 04 | Sands Medium P.Z. | 897.6 | 12.6 | S 189 | 42.08939 | -100.525 |
| MPZ4 05 | Sands Medium P.Z. | 907.6 | 5.3 | SW 227 | 42.09026 | -100.532 |
| MPZ4 06 | Sands Medium P.Z. | 900.7 | 11.9 | N 17 | 42.08801 | -100.534 |
| MPZ4 07 | Sands Medium P.Z. | 921.1 | 10.81 | S 187 | 42.10806 | -100.602 |
| MPZ4 08 | Sands Medium P.Z. | 919.9 | 15.9 | N 13 | 42.11256 | -100.6 |
| MPZ4 09 | Sands Medium P.Z. | 927.7 | 2.19 | N 6 | 42.10908 | -100.597 |
| MPZ5 03 | Sands Medium P.Z. | 1101.9 | 7.6 | N 4 | 41.96495 | -101.471 |
| MPZ5 04 | Sands Medium P.Z. | 1104 | 8.2 | NW 324 | 41.96085 | -101.466 |
| MPZ5 05 | Sands Medium P.Z. | 1103.3 | 7 | NW 326 | 41.95784 | -101.468 |
| MPZ5 09 | Sands Medium P.Z. | 1015.6 | 5.6 | E 104 | 42.01043 | -101.334 |
| MPZ5 10 | Sands Medium P.Z. | 1050.4 | 8.5 | S 186 | 42.00711 | -101.328 |
| MPZ5 11 | Sands Medium P.Z. | 1057.7 | 7.8 | NE 37 | 42.00734 | 101.3305 |
| MPZ5 12 | Sands Medium P.Z. | 1079.3 | 1.8 | N 21 | 42.02435 | 101.396 |
| MPZ5 13 | Sands Medium P.Z. | 1080.7 | 20 | N 11 | 42.0236 | -101.393 |

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|---|---|---|---|---|---|---|
| MPZ5 14 | Sands Medium P.Z. | 1085.3 | 21.6 | S 185 | 42.02414 | -101.392 |
| MPZ6 01 | Sands Medium P.Z. | 1042.3 | 22.6 | 193 | 42.33333 | -101.21 |
| MPZ6 02 | Sands Medium P.Z. | 1047.7 | 1.7 | 75 | 42.33126 | -101.199 |
| MPZ6 03 | Sands Medium P.Z. | 1067.4 | 25.7 | 354 | 42.33581 | -101.226 |
| MPZ6 04 | Sands Medium P.Z. | 1066.7 | 9.4 | 186 | 42.31742 | -101.223 |
| MPZ6 05 | Sands Medium P.Z. | 1044.4 | 6.2 | 35 | 42.29174 | -101.196 |
| MPZ6 06 | Sands Medium P.Z. | 1047.7 | 23.8 | 206 | 42.30565 | -101.2 |
| MPZ6 07 | Sands Medium P.Z. | 1052.4 | 14.9 | 29 | 42.32281 | -101.233 |
| MPZ6 08 | Sands Medium P.Z. | 1059.6 | 20.8 | 182 | 42.32999 | -101.235 |
| MPZ6 09 | Sands Medium P.Z. | 1043.1 | 4 | 33 | 42.34662 | -101.24 |
| HPZ1 01 | Sands High P.Z. | 785.7525 | 20 | N 16 | 42.25641 | -99.671 |
| HPZ1 02 | Sands High P.Z. | 1143.105 | 3 | NE 62 | 42.25597 | -99.6652 |
| HPZ1 03 | Sands High P.Z. | 800.12708 | 15 | S 184 | 42.25441 | -99.668 |
| HPZ1 04 | Sands High P.Z. | 794.41315 | 4 | SW 207 | 42.26295 | -99.6653 |
| HPZ1 05 | Sands High P.Z. | 804.50043 | 16 | SW 211 | 42.26926 | -99.6684 |
| HPZ1 06 | Sands High P.Z. | 784.05335 | 15 | N 10 | 42.26522 | -99.6678 |
| HPZ1 07 | Sands High P.Z. | 1152.1536 | 1 | SE 149 | 42.24603 | -99.6576 |
| HPZ1 08 | Sands High P.Z. | 791.79199 | 13 | SW 220 | 42.25174 | -99.6532 |
| HPZ1 09 | Sands High P.Z. | 788.71179 | 15 | N 6 | 42.25135 | -99.6594 |
| HPZ2 01 | Sands High P.Z. | 800.8 | 28.5 | 171 | 42.02532 | -99.5801 |
| HPZ2 02 | Sands High P.Z. | 764.3 | 18.2 | 24 | 42.02882 | -99.5865 |
| HPZ2 03 | Sands High P.Z. | 752.2 | 2.5 | 301 | 42.03033 | -99.5796 |
| HPZ2 04 | Sands High P.Z. | 752.7 | 16 | 18 | 42.04095 | -99.6045 |
| HPZ2 05 | Sands High P.Z. | 755.8 | 22.3 | 186 | 42.04141 | -99.6084 |
| HPZ2 06 | Sands High P.Z. | 759.1 | 2.4 | 239 | 42.03878 | -99.5958 |
| HPZ2 07 | Sands High P.Z. | 752.6 | 29.2 | 3 | 42.0468 | -99.5961 |
| HPZ2 08 | Sands High P.Z. | 755.1 | 22.3 | 180 | 42.04447 | -99.5968 |
| HPZ2 09 | Sands High P.Z. | 753.1 | 2.8 | 179 | 42.04404 | -99.5931 |
| HPZ3 01 | Sands High P.Z. | 775.2 | 3 | 221 | 41.98568 | -99.6505 |
| HPZ3 02 | Sands High P.Z. | 765.1 | 18.3 | 187 | 41.98695 | -99.6545 |
| HPZ3 03 | Sands High P.Z. | 776.6 | 21 | 40 | 41.98301 | -99.6659 |
| HPZ3 04 | Sands High P.Z. | 779.3 | 20 | 191 | 41.98531 | -99.6696 |
| HPZ3 05 | Sands High P.Z. | 772.5 | 5.2 | 19 | 41.98847 | -99.6826 |
| HPZ3 06 | Sands High P.Z. | 771.2 | 11 | 339 | 41.98715 | -99.6737 |
| HPZ3 07 | Sands High P.Z. | 772.7 | 14.7 | 185 | 41.99502 | -99.6746 |
| HPZ3 08 | Sands High P.Z. | 791.2 | 5.4 | 200 | 41.99174 | -99.669 |
| HPZ3 09 | Sands High P.Z. | 774.3 | 17 | 25 | 41.99959 | -99.6801 |
| HPZ4 01 | Sands Medium P.Z. | 900.3 | 5 | 273 | 41.89213 | -100.471 |
| HPZ4 02 | Sands Medium P.Z. | 885.5 | 17.4 | 359 | 41.88237 | -100.468 |
| HPZ4 03 | Sands Medium P.Z. | 882.5 | 18.2 | 198 | 41.8795 | -100.467 |
| HPZ4 04 | Sands Medium P.Z. | 877.6 | 9.5 | 183 | 41.84225 | -100.391 |
| HPZ4 05 | Sands Medium P.Z. | 879.8 | 13.9 | 340 | 41.83251 | -100.393 |
| HPZ4 06 | Sands Medium P.Z. | 872.9 | 19.2 | 189 | 41.83302 | -100.395 |

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|---|---|---|---|---|---|---|
| HPZ4 07 | Sands Medium P.Z. | 888.5 | 26.5 | 215 | 41.83936 | -100.463 |
| HPZ4 08 | Sands Medium P.Z. | 885.3 | 6.7 | 207 | 41.85173 | -100.463 |
| HPZ4 09 | Sands Medium P.Z. | 893.4 | 4.4 | 19 | 41.8488 | -100.459 |

**Appendix 2.B.** Frequency of Occurrence by Precipitation Zone

2019

| | LPZ | MPZ | HPZ |
|---|---|---|---|
| C. longifolia | 73% | 46% | - |
| S. cryptandrus | 51% | 10% | - |
| B. gracilis | 43% | 17% | - |
| A. hallii | 62% | 48% | - |
| Carex | 74% | 65% | - |
| Hesperostipa | 38% | 33% | - |
| B. hirsuta | 12% | 17% | - |
| K. macrantha | 11% | 15% | - |
| R. arkansana | 0% | 23% | - |
| P. virgatum | 2% | 39% | - |
| D. wilcoxianum | 0% | 39% | - |
| H. pauciflorus | 0% | 47% | - |
| A. psilostachya | 19% | 36% | - |
| D. var. scribnerianum | 0% | 54% | - |
| S. scoparium | 2% | 79% | - |

2020

| | LPZ | MPZ | HPZ |
|---|---|---|---|
| C. longifolia | 81% | 54% | - |
| S. cryptandrus | 46% | 14% | - |
| B. gracilis | 49% | 17% | - |
| A. hallii | 60% | 41% | - |
| Carex | 78% | 66% | - |
| Hesperostipa | 35% | 29% | - |
| B. hirsuta | 12% | 16% | - |
| K. macrantha | 16% | 22% | - |
| R. arkansana | 0% | 29% | - |
| P. virgatum | 1% | 39% | - |
| D. wilcoxianum | 1% | 32% | - |
| H. pauciflorus | 0% | 50% | - |
| A. psilostachya | 10% | 42% | - |
| D. var. scribnerianum | 0% | 53% | - |
| S. scoparium | 3% | 75% | - |

2021

| | LPZ | MPZ | HPZ |
|---|---|---|---|
| C. longifolia | 76% | 53% | 42% |
| S. cryptandrus | 49% | 17% | 20% |
| B. gracilis | 47% | 11% | 2% |
| A. hallii | 63% | 47% | 55% |
| Carex | 76% | 76% | 81% |
| Hesperostipa | 41% | 37% | 43% |
| B. hirsuta | 13% | 23% | 29% |
| K. macrantha | 11% | 23% | 10% |
| R. arkansana | 0% | 30% | 18% |
| P. virgatum | 6% | 35% | 30% |
| D. wilcoxianum | 0% | 33% | 36% |
| H. pauciflorus | 4% | 48% | 21% |
| A. psilostachya | 22% | 50% | 69% |
| D. var. scribnerianum | 0% | 60% | 68% |
| S. scoparium | 4% | 76% | 72% |

**Appendix 2.C.** Species Percent Contribution to Biomass by Precipitation Zone

2019

| | LPZ | MPZ | HPZ |
|---|---|---|---|
| C. longifolia | 24% | 5% | - |
| S. cryptandrous | 8% | 0% | - |
| B. gracilis | 5% | 1% | - |
| A. hallii | 28% | 6% | - |
| Carex | 6% | 1% | - |
| Hesperostipa | 8% | 7% | - |
| B. hirsuta | 2% | 1% | - |
| K. macrantha | 2% | 1% | - |
| R. arkansana | 0% | 4% | - |
| P. virgatum | 1% | 6% | - |
| D. wilcoxianum | 0% | 2% | - |
| H. pauciflorus | 0% | 13% | - |
| A. psilostachya | 1% | 3% | - |
| D. var. scribnerianum | 0% | 8% | - |
| S. scoparium | 1% | 36% | - |

2020

| | LPZ | MPZ | HPZ |
|---|---|---|---|
| C. longifolia | 30% | 8% | - |
| S. cryptandrous | 9% | 1% | - |
| B. gracilis | 8% | 1% | - |
| A. hallii | 22% | 5% | - |
| Carex | 8% | 1% | - |
| Hesperostipa | 9% | 6% | - |
| B. hirsuta | 2% | 1% | - |
| K. macrantha | 3% | 1% | - |
| R. arkansana | 0% | 3% | - |
| P. virgatum | 0% | 7% | - |
| D. wilcoxianum | 0% | 4% | - |
| H. pauciflorus | 0% | 7% | - |
| A. psilostachya | 0% | 3% | - |
| D. var. scribnerianum | 0% | 8% | - |
| S. scoparium | 1% | 39% | - |

2021

| | LPZ | MPZ | HPZ |
|---|---|---|---|
| C. longifolia | 27% | 9% | 7% |
| S. cryptandrous | 11% | 1% | 1% |
| B. gracilis | 4% | 1% | 0% |
| A. hallii | 25% | 8% | 8% |
| Carex | 4% | 0% | 1% |
| Hesperostipa | 9% | 5% | 11% |
| B. hirsuta | 1% | 1% | 1% |
| K. macrantha | 1% | 1% | 0% |
| R. arkansana | 0% | 4% | 1% |
| P. virgatum | 2% | 7% | 7% |
| D. wilcoxianum | 0% | 1% | 3% |
| H. pauciflorus | 0% | 9% | 2% |
| A. psilostachya | 1% | 2% | 5% |
| D. var. scribnerianum | 0% | 6% | 3% |
| S. scoparium | 2% | 38% | 33% |

# Chapter 3: REGIONAL DIFFERNECES IN REMOTELY SENSED BIOMASS AND COVER IN THE NEBRASKA SANDHILLS

## Introduction

The Nebraska Sandhills ecoregion is an ecologically unique and valuable region in the central Great Plains, as it represents one of the largest remaining in-tact native grasslands in North America (Scholtz and Twidwell 2022). This ecosystem provides many important services to the state of Nebraska, including an abundance of land for cattle production. Cattle producers are distributed throughout the Sandhills (Clark and Wilson 2004), and each producer has a unique set of goals which are used to shape the management of their operation (Sliwinski et al. 2018). Understanding the ecological impacts of diverse management strategies on a large scale allows producers opportunities to make informed decisions on how to meet the goals of their operation while also managing their natural resources in a sustainable manner. However, the precipitation gradient that exists across the Sandhills may also be an important factor in determining the plant community composition of this ecoregion (see Chapter II). Therefore, understanding how climatic factors, such as precipitation, impact plant communities in the Sandhills provides valuable information that can be used to better inform management decisions in this ecoregion.

While plant species composition is an important factor in determining management strategies, ground cover and herbaceous biomass production are also important metrics that must be considered. Ground cover is often used as a key indicator of the hydrologic function of a site, and measurements of ground cover can be used to evaluate practices aimed at improving soil stability (Coulloudon et al. 1999; Booth and

Tueller 2003). Measuring herbaceous biomass production is also important, as it is used by livestock producers to match animal forage demand with forage availability (Derner and Augustine 2016; Stephenson et al. 2019). In the Nebraska Sandhills, little research exists in the literature which examines the impact of climatic variables on rangeland cover and biomass production across diverse management strategies at a large spatial and temporal scale (Vinton and Larson 2022).

The response of biomass production to climatic variability in terms of annual and seasonal precipitation has been the focus of much research in the literature. The precipitation marginal response, or the linear regression of annual biomass production with annual or seasonal precipitation, has been a useful tool to examine the response of plant communities to variable climatic conditions (Briggs and Knapp 1995; Veron et al. 2005; Irisarri et al. 2016; Stephenson et al. 2019). Throughout these investigations, topographic position, seasonal precipitation, and annual precipitation have been identified as key variables in the small-scale spatial variability of biomass production in the Sandhills and other Great Plains ecosystems (Milchunas et al. 1994; Epstein et al. 1997; Lauenroth et al. 2000; Wilcox et al. 2015; Petrie et al. 2018; Stephenson et al. 2019). Future climate models predict higher annual temperatures, more winter precipitation, and greater variability in growing season precipitation in the coming decades (Craine et al. 2012; Polley et al. 2013; Wilcox et al. 2015). Understanding the ecological dynamics between biomass and annual precipitation variability can assist managers with forecasting forage availability in the face of variable climatic conditions, which aids in properly stocking pastures with livestock during the growing season to match the forage supply (Derner and Augustine 2016).

While early limitations in technology hindered the widespread use of this monitoring method, remote sensing has emerged as a new ecological data collection technique that can be used to collect and analyze data at a larger spatial and temporal scale than is practically possible with conventional techniques (Booth and Tueller 2003; Jones et al. 2020). On-the-ground monitoring techniques are useful for evaluating rangeland plant communities at a plot-level, however statistical extrapolations are often needed in order for rangeland managers to apply plot-level findings to decision-scale areas (Jones et al. 2020). These statistical extrapolations often fail to capture the area-wide spatial and temporal variation that exists in rangeland landscapes (Jones et al. 2020). In addition, remote sensing allows for a less subjective form of monitoring rangelands compared to traditional methods (Booth and Tueller 2003). Using new technology, remote sensing in conjunction with field monitoring has been proven to be a reasonably accurate method of estimating ecological metrics such as tree and herbaceous cover, as well as plant biomass production over space and time (Booth and Tueller 2003; Boswell et al. 2017; Jones et al. 2018; Podebradská et al. 2019; Jones et al. 2020; Allred et al. 2021; Vinton and Larsen 2022). These metrics can be useful to identify ecological trends and spatial signals of ecological threats such as erosion, woody encroachment, and annual exotic grass invasion that are often of interest for natural resource managers in rangeland settings (Jones et al. 2020, Uden et al. 2021). One tool that is freely available to ranch managers to monitor rangelands in the western United States using remote sensing is the Rangeland Analysis Platform (Jones et al. 2018; Allred et al. 2021; RAP 2022). The RAP has emerged as a powerful tool that can be used to collect biomass and cover data over large spatial and temporal scales. Using the RAP, rangeland managers have access to robust datasets that allow for the evaluation of changes in biomass and cover types over space and time, which adds to the understanding of how rangeland ecosystems function.

The objective of our study was to expand upon the on-the-ground monitoring research that was summarized in Chapter II by utilizing the Rangeland Analysis Platform (RAP) to examine spatial and temporal variability in biomass production and cover on pastures within ranches located in different regional precipitation zones in the Nebraska Sandhills. Another objective was to use the RAP to evaluate the response of biomass production and cover to annual precipitation (1984-2019) across working ranches located within regional precipitation zones of the Sandhills.

## Materials and Methods

### Study Area

This study was conducted across the Nebraska Sandhills, which encompasses 49,987 $km.^2$ of contiguous mixed grass prairie (Bleed and Flowerday 1990). The Sandhills is composed of a heterogeneous landscape of rolling slopes, dunetops, interdune swales, and subirrigated meadows (Stephenson et al. 2019). While this ecosystem is made up of many ecological sites, two of the most common ecological sites is the Sands and Sands-Choppy Sands Complex ecological sites (EDIT 2022). Sands ecological sites are mostly found on uplands, having a Sandy Loam soil texture with gently rolling terrain and 3-24% slopes. The major soil series associated with Sands ecological sites include Valent and Valentine, with the McKelvie series also found within the description. In addition, a Sands-Choppy Sands Complex is a common ecological site on uplands in the Sandhills (EDIT 2022). These sites have similar soils to Sands sites, however the slope of Sands-

Choppy Sands sites are generally steeper (>24%). The common vegetation within these ecological sites is a warm season mid-grass community with a native shrub component, with prairie sandreed, sand bluestem [*Andropogon gerardii spp. hallii* (Hack.) Wipiff], and little bluestem composing the dominant species. Secondary grasses in this ecological site include needlegrasses (*Hesperostipa spp.*), sand dropseed [*Sporobolus cryptandrus* (Torr.) A. Gray], and switchgrass (*Panicum virgatum* L.). The annual precipitation in the Sandhills ranges from 17-23 in. (431.8-533.4 mm), generally increasing from west to east, with approximately 70-75% of this precipitation falling from April to September (Burzlaff 1962; Whitcomb 1989; Bleed and Flowerday 1990).

Ranches included in this study were selected based on discussion with cooperating grazing managers, differences in grazing management strategies, and location of the ranches across the different precipitation zones. In total, fourteen working ranches were selected for this study which included a diverse array of management strategies (Table 3.1). These fourteen ranches were distributed throughout three precipitation zones across the Sandhills that are found within the NRCS MLRA 65 description and classified by the Nebraska NRCS (Fig. 3.1; EDIT 2022; Personal communication with NRCS State Range Conservationist, Jeff Nichols). Following this description, the low precipitation zone, located on the western side of the Sandhills, is classified as receiving 355.6-431.8 mm. (14-17 in.) of precipitation annually. The moderate precipitation zone, located in the central Sandhills, receives 431.8-558.8 mm. (17-22 in.) of precipitation annually. Finally, the high precipitation zone, on the eastern side of the Sandhills, receives 558.8-635.0 mm. (22-25 in.) of precipitation annually. Guided by these precipitation zones, we used precipitation data from 1984-2019 produced by the RAP to define precipitation zones across the ranches in the study. Through this process, we determined ranches had higher mean annual precipitation metrics compared to the established values. Within the low precipitation zone (LPZ) ranches received 400-500 mm. (15.7-19.7 in.) of annual precipitation, ranches in the moderate precipitation zone (MPZ) received 500-600 mm. (19.7-23.6 in.) of annual precipitation, and ranches in the high precipitation zone (HPZ) received >600 mm. (>23.6 in.) of precipitation (Fig. 3.1). Ranch LPZ2 is located on the boundary between the low and moderate precipitation zone. The 30-year average annual precipitation received by this ranch (479 mm.) is more similar to the other ranches in the low precipitation zone compared to the moderate precipitation zone and this ranch was classified as being within the low precipitation zone.

**Rangeland Analysis Platform (RAP)**

The Rangeland Analysis Platform (RAP) is a relatively new decision support tool that is available for the public to readily observe and collect vegetative biomass and canopy ground cover data (Jones et al. 2018; Allred et al. 2021). The RAP combines machine learning, cloud-based computing, historical remote sensing data, and field data to provide estimates of annual cover and biomass data at a 30 m. resolution for the entire western United States (Jones et al. 2018). With the aid of the Landsat satellite record, ground cover data is available from 1984-2020 and includes functional group cover classifications for annual forbs and grasses, perennial forbs and grasses, shrubs, and bare ground. Allred et al. (2021) found an average mean absolute error of 6.4% and a root mean squared error of 9.6% when comparing values generated by the RAP to on-the-ground vegetation plots.

The RAP also produces estimates of annual biomass. The MODIS MOD17 algorithm, combined with medium resolution land cover classifications and meteorological data for the United States, is used to produce annual net primary production estimates (Robinson et al. 2018; Jones et al. 2021). Biomass estimates (lbs/acre) are produced for annual forbs and grasses, perennial forbs and grasses, and overall herbaceous biomass. These estimates are also available at a 30 m. resolution and are available from 1986-2020.

**Data Collection**

The RAP was used to collect annual herbaceous biomass production estimates from 1986-2019 and bare ground cover and perennial forbs and grasses cover estimates from 1984-2019, along with annual precipitation estimates from 1984-2019 across pastures on each of the 14 ranches. Data was collected from the same 3 pastures on each ranch that were used for analysis in Chapter II. To collect vegetative biomass and ground cover data from the RAP, shapefiles were first developed for the 3 sampled pastures on each ranch in ArcGIS Pro 2.7.0 (Fig. 3.2A). NRCS ecological site shapefiles for each county for which the ranches were located were then downloaded and clipped to each study pasture shapefile (Fig. 3.2B). Each ranch shapefile was then zipped and uploaded to the RAP (Fig. 3.2C). Within the RAP, yearly mean (i.e., average of all 30 m. pixels within each year) annual herbaceous biomass, bare ground cover, and perennial forbs and grasses cover data was then downloaded in comma separated values (.csv) format for the Sands and Sands-Choppy Sands Complex ecological sites that were found within each respective pasture (Fig. 3.2D; Fig. 3.2E). Lowlands, flat plains, Sandy and Choppy Sands ecological sites, and subirrigated wet meadows are important components of the

Nebraska Sandhills ecosystem but were omitted for consistency so that sites could be compared similarly across the different ranches.

Management information from each ranch was collected by conducting personal interviews with the grazing managers and sending surveys to each ranch manager individually. From this survey, ownership, grazing animal type, average pasture size, number of grazing events during the growing and dormant season, rest following grazing, and average annual stocking rate were collected and summarized (Table 3.1). We calculated the stocking rate ($AUM \cdot ha.^{-1}$) for each ranch by using information collected from managers on the number of cattle in a pasture, the length of grazing in a pasture, the size of the pasture, and the average weight of the grazing animals. While there are clearly defined grazing strategies in the literature, ranch managers often deviate from these strategies so to meet the individual goals of their operation (Byrnes et al. 2018; Sliwinski et al. 2019). For this reason, the categories we defined that encompass the grazing management of each ranch is our best classification for the management that occurs on the upland pastures of these ranches in a given year.

**Data Analysis**

In SAS 9.4, PROC GLIMMIX was used to conduct a mixed model analysis of variance to evaluate significant differences in the average biomass, perennial forbs and grasses cover, and bare ground cover on ranches in each precipitation zone with precipitation zone as the fixed effect. Ranch was treated as the experimental unit in these analyses. Residual and quantile-quantile (qq)-plots were used to assess the normality assumption. When differences were observed at a significance level $P \leq 0.05$, means between biomass or cover and precipitation zones were separated using Tukey-Kramer adjustment to account for multiple comparisons.

Using the tidyverse and lsmeans packages in R Studio, we compared how the average biomass production, average bare ground cover, and average perennial forbs and grasses cover were impacted by annual precipitation by region (R 4.1.1). We first fit a linear model including the main effects of biomass and cover as well as an interaction term between the biomass and cover variables and precipitation (see statistical model below). An interaction term was used to indicate that the relationship between the biomass and cover variables and precipitation varies by region. Slopes of the linear models were compared using an analysis of variance to detect differences in the response of biomass or cover to annual precipitation by precipitation zone. Significant differences were reported at a $P \leq 0.05$ level. P values were adjusted for multiple comparisons using the Tukey-Kramer adjustment. Visualizations were constructed using the package ggplot2. To evaluate the effect of annual precipitation on biomass and cover across different regions, we used y ~ region + precipitation + region*precipitation.

## Results

### Annual Biomass Production

Significant differences ($P \leq 0.01$) were found among the average biomass production on ranches within the different precipitation zones (Fig. 3.3a). The LPZ had the lowest average biomass production among the precipitation zones, averaging approximately 1,433.38 ± 30.2 kg $\cdot ha^{-1}$. Average biomass production in the MPZ was higher than the LPZ but lower than the HPZ, averaging approximately 1.2 times higher than the LPZ and 0.12 times lower than the HPZ. The HPZ had the highest average biomass production among precipitation zones, averaging 1.1-1.3 times higher than the LPZ and MPZ. No significant differences were found ($P > 0.3$) in response of annual biomass production to annual precipitation across all precipitation zones in the Sandhills (Fig. 3.4), where the average response to annual precipitation was 1.0-1.3 ± 0.15 kg $\cdot ha^{-1}$ per mm. (Fig. 3.4).

**Bare Ground and Perennial Forbs and Grasses Cover**

Significant differences ($P \leq 0.01$) were also found among the average perennial forbs and grasses cover and bare ground cover on ranches within the different precipitation zones (Fig. 3.3b, Fig. 3.3c). The LPZ had lower perennial forbs and grasses cover than the MPZ and HPZ, averaging approximately 9% less than the MPZ and HPZ (Fig.3.3b). Additionally bare ground cover was approximately 3-4 percentage points higher in the LPZ compared to the MPZ and HPZ (Fig. 3.3c).

Significant differences ($P \leq 0.05$) were found in perennial forbs and grasses cover response to annual precipitation among precipitation zones in the Sandhills (Fig. 3.5). Perennial forbs and grasses cover response to annual precipitation was greatest in the LPZ, where the response was 1.5 times greater than the MPZ and 300 times greater than the HPZ. The MPZ had a 200 times greater response of perennial forbs and grasses cover to annual precipitation than the HPZ. Significant differences ($P \leq 0.03$) were also found in bare ground cover response to annual precipitation (Fig. 3.6) among precipitation zones in the Sandhills. Bare ground cover in the LPZ had the greatest overall response among all regions to annual precipitation, averaging approximately 1.6 times greater than the MPZ and 7 times greater than the HPZ. The HPZ had the lowest overall response to annual precipitation among all regions, averaging only a -0.002% change in bare ground cover for every mm. of annual precipitation (Fig. 3.6). The MPZ had a significantly greater bare ground response to annual precipitation than the HPZ, but not greater than the LPZ.

## Discussion

Climatic variability in terms of annual precipitation among precipitation zones in the Sandhills established differences in average biomass production, perennial forbs and grasses cover, and bare ground cover on uplands using a 35-year remotely sensed dataset produced by the RAP. This data established differences among all precipitation zones in average biomass production and differences between the LPZ compared to the MPZ and HPZ in perennial forbs and grasses cover and bare ground cover. In addition, while no differences were found in the response of biomass to annual precipitation among precipitation zones, significant differences were established between precipitation zones with respect to the response of cover to annual precipitation. These results identify large-scale spatial and temporal variability on uplands across the Sandhills that is largely absent from the literature.

Our data demonstrated that differences in biomass production existed along a gradient across the different precipitation zones in the Sandhills (Fig. 3.3a). However, each precipitation zone responded similarly in their respective responses to annual precipitation, where the average response to annual precipitation was 1.0-1.3 ± 0.15 kg $\cdot ha^{-1}$ per mm. (Fig. 3.4). The gradient in biomass production that was seen from the LPZ to the HPZ was similar to the results of Podebradska et al. (2019) who used remote sensing to predict total growing season biomass in the Sandhills from drought indices and found lower biomass production in the western Sandhills compared to higher biomass production in the eastern Sandhills. However, our results did not find regional differences in the response of biomass to annual precipitation. This contrasts with Wilcox et al. (2015) who found that responses of aboveground net primary production (ANPP) can vary across precipitation regimes in the temperate grasslands of the Great Plains. Additionally, while significantly higher mean average perennial forbs and grasses cover and significantly lower mean bare ground cover were found among the MPZ and HPZ compared to the LPZ, the cover in each precipitation zone responded differently to annual precipitation as well. These results of different average bare ground cover among precipitation zones in the Sandhills adds to research conducted by Vinton and Larsen (2022) who detected higher bare ground cover on xeric uplands compared to mesic subirrigated meadows in the central Sandhills using remote sensing techniques. The LPZ had the largest negative response to bare ground with respect to annual precipitation (Fig. 3.6), indicating that this precipitation zone is more sensitive to precipitation variability than the other precipitation zones in the Sandhills. In contrast, the HPZ did not have a large response in bare ground to annual precipitation (Fig. 3.6). This indicates that bare ground in the HPZ may be largely unaffected by annual differences in precipitation. As was expected, the response of perennial forbs and grasses cover to annual precipitation among the precipitation zones was inversely related to the bare ground response. Similar to the bare ground results, the response of the HPZ was significantly less than the LPZ, which had the greatest positive response of perennial forbs and grasses to annual precipitation (Fig. 3.5). This reiterates how cover in the LPZ seems to be more sensitive to variability in annual precipitation than the HPZ.

Our results indicate that regional variability exists in terms of biomass production and cover on uplands in the Nebraska Sandhills across different precipitation zones.

Many studies that exist in the literature have established models predicting biomass response in grasslands to climatic variables, including variables such as topographical position and drought indices in their prediction models (Briggs and Knapp 1995; Nippert et al. 2011; Podebradska 2019; Stephenson et al. 2019). However, the purpose of our study was not to validate the models produced by the RAP, but to use estimates produced by the RAP to compare ranches across precipitation zones in the Sandhills. Therefore, while models that incorporate other variables may better explain variability in biomass and cover in grassland ecosystems, using data that was freely available to the public from the RAP allowed us to identify differences and responses to these important ecological metrics across precipitation zones in the Sandhills.

This data also aids in expanding upon the plant community data collected through on-the-ground monitoring across these same ranches in Chapter II, which established regional differences in frequency of occurrence and percent contribution to biomass of key species across the Sandhills. Through using the RAP, we were able to collect data on a wider spatial and temporal scale than is possible with conventional methods (Jones et al. 2021). This allowed us to explore more of the large-scale spatial and temporal variability that exists regionally on uplands across the Sandhills. The regional differences in biomass, perennial forbs and grasses cover, and bare ground cover, along with regional differences in cover response to annual precipitation, that we established through this research aids in understanding the large-scale plant community dynamics that exist across precipitation zones in the Nebraska Sandhills. Additionally, our results found differences in bare ground cover among regions that was not documented in our on-the-ground monitoring from Chapter II (Fig. 3.3c). However, the RAP produces estimates of canopy cover rather than basal cover. Because of this, these two datasets must be compared with caution.

## Management Implications

It is important that ranch managers in the Sandhills understand the large-scale spatial and temporal variability in biomass and cover that is present throughout this region. This research established regional differences in biomass production and the cover of bare ground and perennial forbs and grasses on uplands in the Sandhills using a 35-year dataset from a freely available remote sensing tool in the RAP. In addition, the response of bare ground and perennial forbs and grasses cover to annual precipitation was significantly different throughout the precipitation zones in this region. With the uncertainty that is inherent in the future of climatic patterns, understanding how biomass and cover on rangelands respond to variability in annual precipitation provides valuable insight for how these ecosystems will react to future climatic variability. This research provides insight for how uplands in the Sandhills respond to such variability. Future research is needed to better understand the influence of specific management practices on ranches within the different precipitation zones on the regional variability of biomass and cover dynamics based on long-term management practices (Table 3.1) at a large spatial and temporal scale.

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## Tables

**Table 3.1.** Grazing management strategies for ranches in the low precipitation zone (LPZ), moderate precipitation zone (MPZ), and high precipitation zone (HPZ). GS indicates the number of grazing events in the growing season. DS indicates the number of grazing events in the dormant season. An asterisk (*) represents grazing events that occur sometimes, but not every year.

| Ranch ID | Ownership | Animal Type | Pasture Size (ha.) | Number of Grazing Events | Length of Grazing | Time Between Grazing Events | Stocking Rate (AUM·ha.$^{-1}$) |
|---|---|---|---|---|---|---|---|
| LPZ1 | Private | Cow-Calf | 253 | 3-4 GS | 1-1.5 mo. | 1-3 mo. | ~ 1.25 |
| LPZ2 | Private | Bison | 1,214 | 1 GS; 1 DS* | 1-2 mo. | >9 mo. | ~ 1.0-1.5 |
| LPZ3 | Federal | Cow-Calf | 340 | 1 GS | 1-1.5 mo. | >9 mo. | ~ 0.5 |
| LPZ4 | Private | Cow-Calf; Yearlings | 263 | 1 GS; 1 DS | 1-2 wk. | 6-9 mo. | ~ 1.5-2.5 |
| LPZ5 | Private | Cow-Calf; Yearlings | 202 | 1-2 GS; 1 DS | 1-2 wk. | 1-3 mo. | ~ 1.5-2.5 |
| MPZ1 | Private | Cow-Calf; Yearlings | 324 | 1-2 GS; 1 DS | >2 mo. | 3-9 mo. | ~ 1.5-1.75 |
| MPZ3 | University | Cow-Calf | 405 | 1 GS; 1-3 DS | >2 mo. | 6-9 mo. | ~ 1.0-1.5 |
| MPZ4 | Private | Cow-Calf | 129 | 1 GS | 2-4 wk. | >9 mo. | ~ 2.0 |
| MPZ5 | Private | Cow-Calf | 243 | 1 GS; 1-2 DS | 1-2 wk. | 3-6 mo. | ~ 1.5-2.5 |
| MPZ6 | Private | Bison | 1,113 | 1-2 GS | 1-2 wk. | 6-9 mo. | ~ 1.0-1.5 |
| HPZ1 | University | Cow-Calf | 161 | 1 GS | 1-1.5 mo. | >9 mo. | ~ 1.75-2.0 |
| HPZ2 | Private | Cow-Calf; Yearlings | 89 | 1-2 GS; 1 DS | 1-2 wk. | 1-3 mo. | ~ 1.63 |
| HPZ3 | Private | Yearlings | 162 | 1 GS | 2-4 wk. | 6-9 mo. | ~ 1.75 |
| HPZ4 | Federal | Cow-Calf | 364 | 1 GS; 1 DS* | 1-1.5 mo. | 6-9 mo. | ~ 0.75-1.0 |

**Figures**

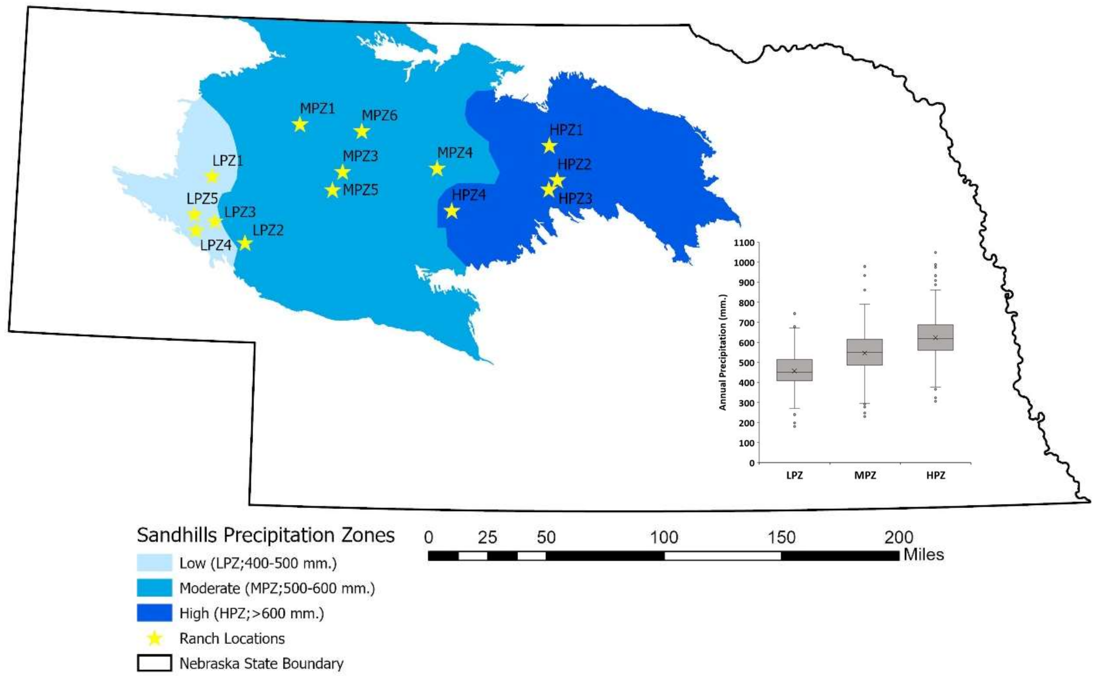


**Fig. 3.1.** Locations of study sites within 3 Sandhills precipitation zones in Nebraska defined by the NRCS MLRA 65 description. LPZ# represents ranches within the low precipitation zone. MPZ# represents ranches within the moderate precipitation zone. HPZ# represents ranches within the high precipitation zone. The inset box and whisker plot displays the average precipitation across ranches within each precipitation zone from 1984-2019 (RAP 2022).

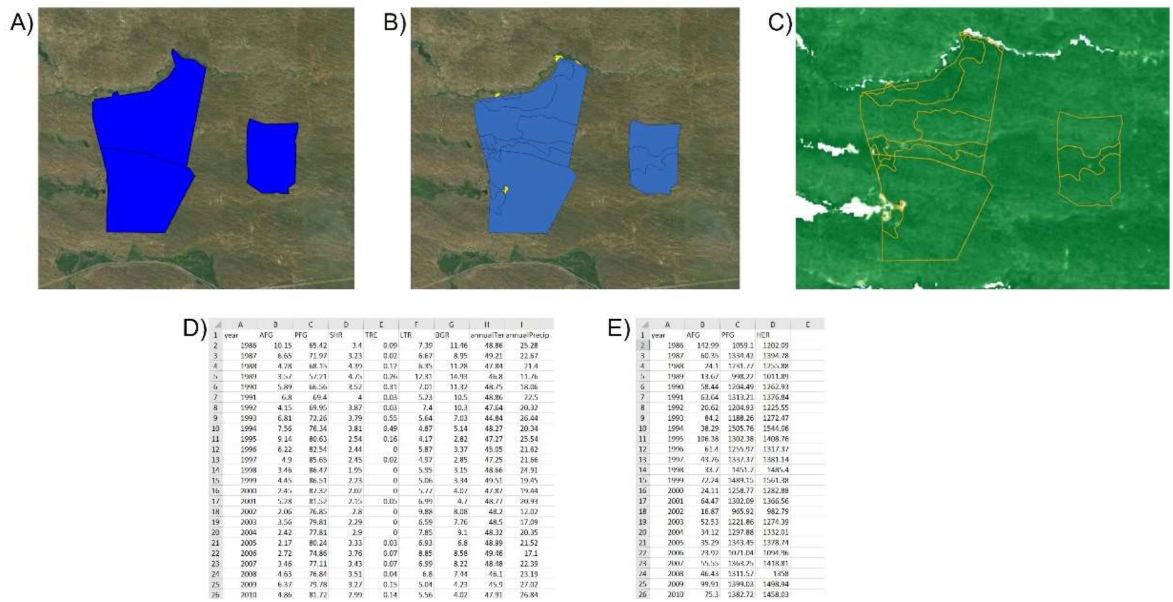


**Fig.3.2.** Shapefiles (A) developed for each pasture in ArcGIS Pro. NRCS ecological sites shapefile (B) trimmed to each study pasture (Sands and Sands-Choppy Sands Complex ecological sites in blue). Zipped ranch shapefile (C) uploaded to the RAP. Annual ground cover data (D) downloaded for Sands ecological sites within each pasture. Annual vegetative production data (E) downloaded for Sands and Sands-Choppy Sands Complex ecological sites within each pasture.

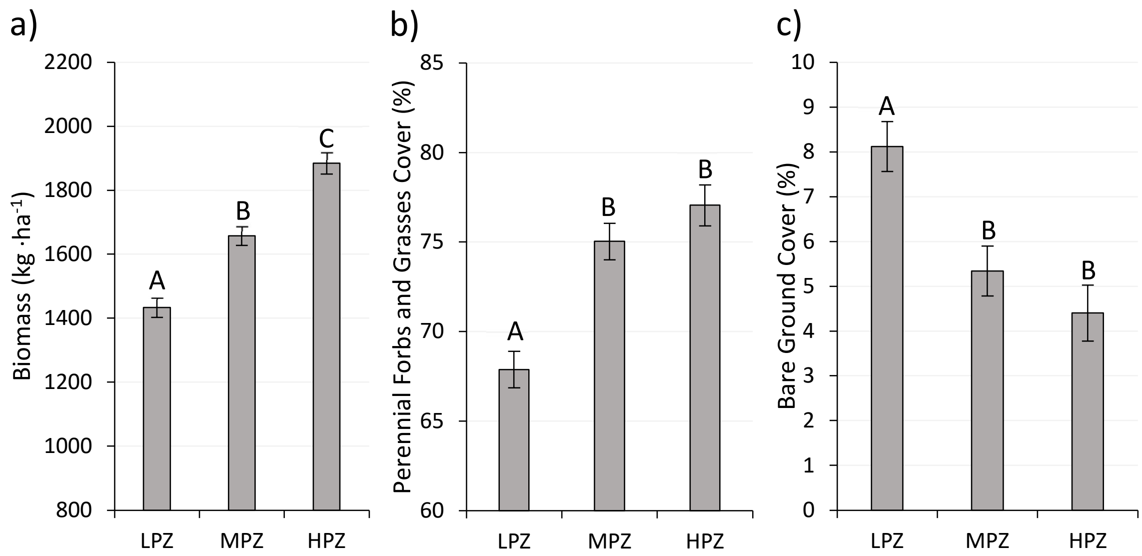


**Fig. 3.3.** Mean values among ranches in the low precipitation zone (LPZ), moderate precipitation zone (MPZ), and high precipitation zone (HPZ) for a) biomass production, b) percent perennial forbs and grasses cover, and c) percent bare ground cover. Different letters indicate significant differences.

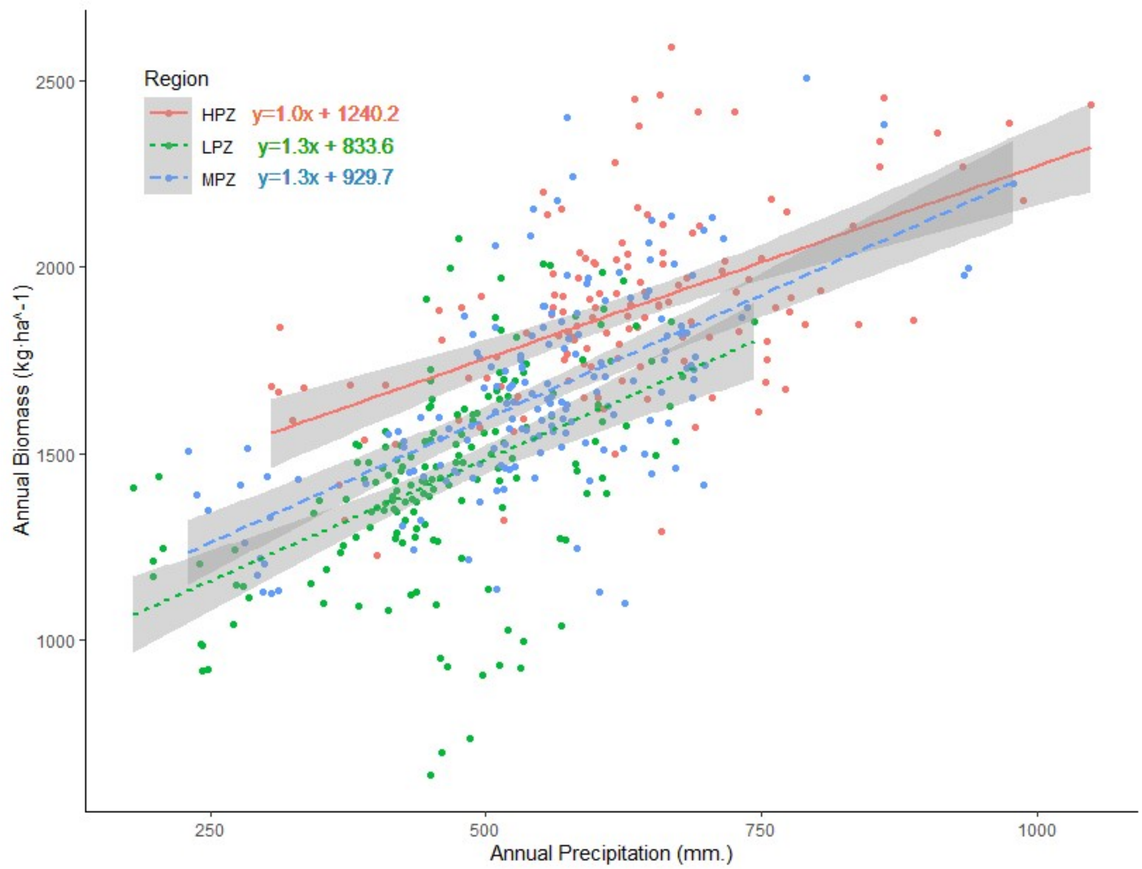


**Fig. 3.4.** Annual biomass response to annual precipitation among ranches in the low precipitation zone (LPZ), moderate precipitation zone (MPZ), and high precipitation zone (HPZ) from 1986-2019.

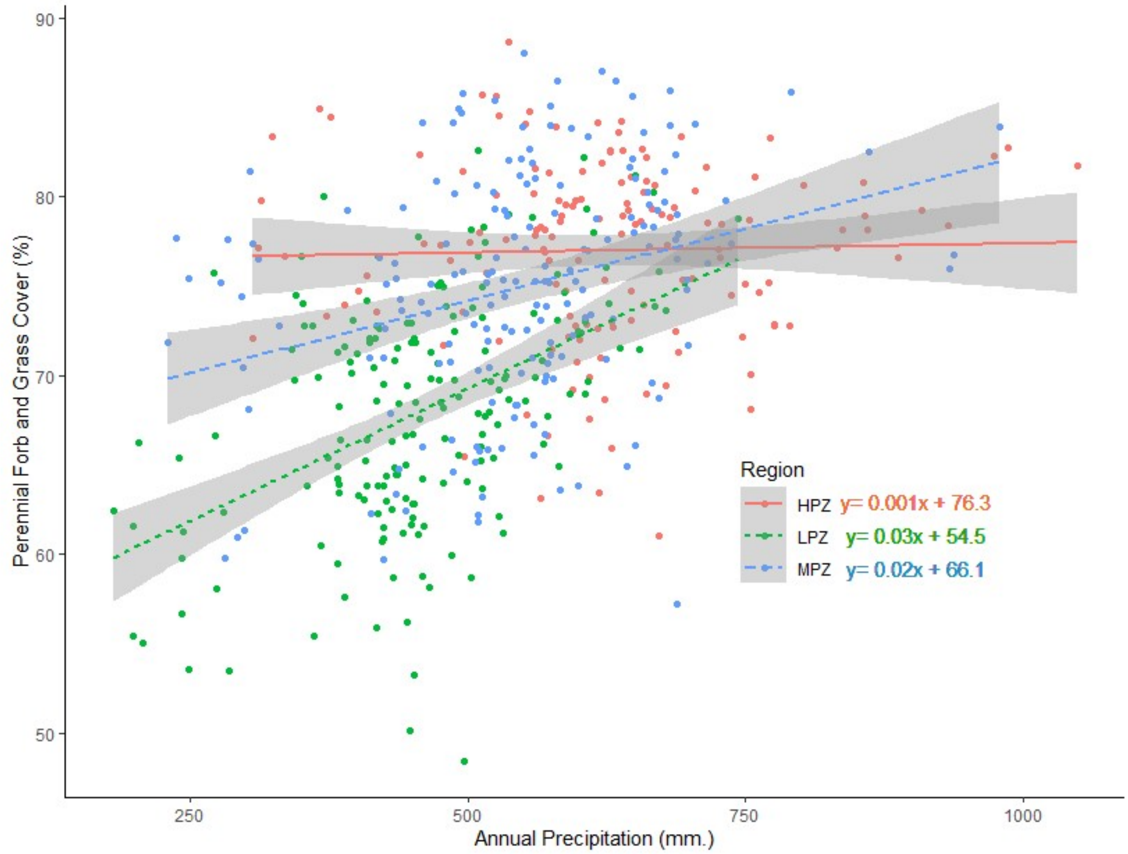


**Fig. 3.5.** Percent perennial forb and grass cover response to annual precipitation among ranches in the low precipitation zone (LPZ), moderate precipitation zone (MPZ), and high precipitation zone (HPZ) from 1984-2019.

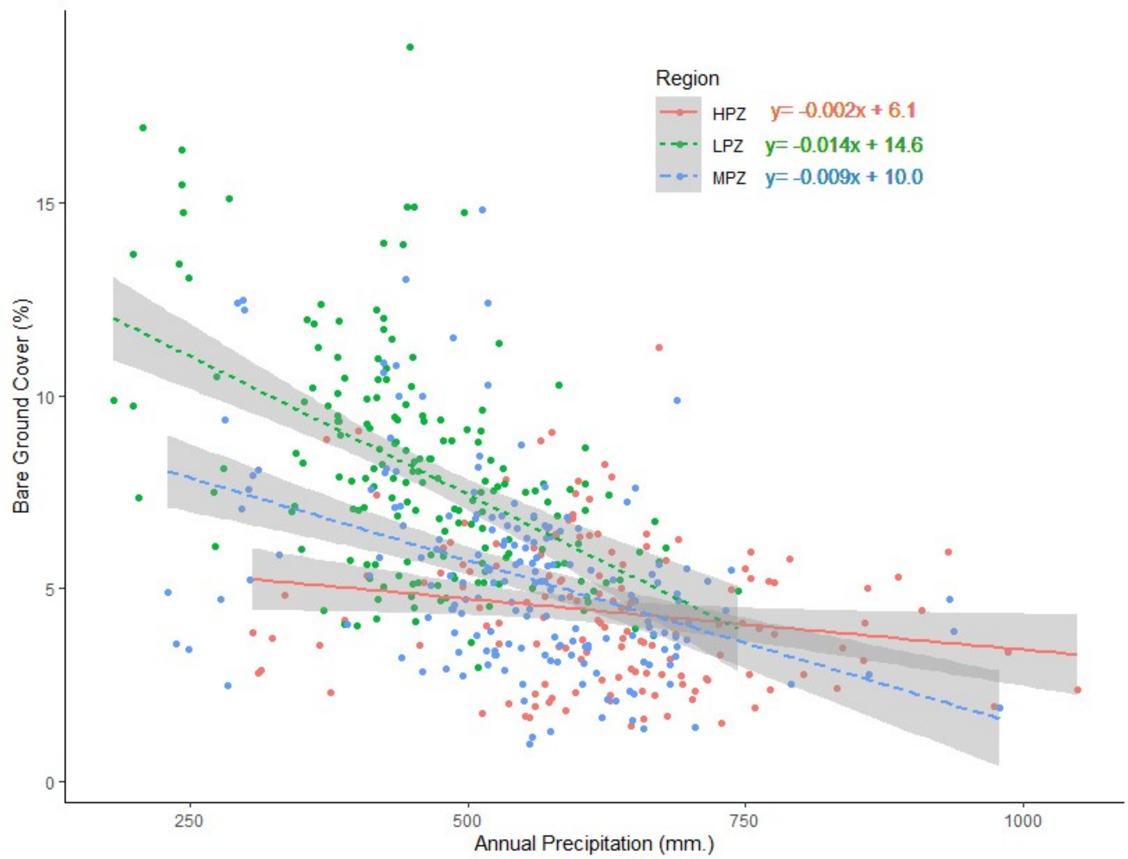


**Fig. 3.6.** Percent bare ground cover response to annual precipitation among ranches in the low precipitation zone (LPZ), moderate precipitation zone (MPZ), and high precipitation zone (HPZ) from 1984-2019.