

Special Section: Frontiers in  
Hydropedology: Interdisciplinary  
Research from Soil Architecture  
to the Critical Zone



#### Core Ideas

- Konza Prairie is a reference ecosystem for evaluation of current and former grasslands.
- Hydrologic change includes climatic and geologic factors such as karstification.
- Future research is needed to expand vadose zone knowledge.

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# Developing a Conceptual Framework of Landscape and Hydrology on Tallgrass Prairie: A Critical Zone Approach

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Agricultural intensification and urbanization have greatly reduced the extent of tallgrass prairie across North America. To evaluate the impact of these changes, a reference ecosystem of unperturbed prairie is required. The Konza Prairie Biological Station in northeastern Kansas is a long-term research site at which a critical zone approach has been implemented. Integration of climatic, ecologic, and hydropedologic research to facilitate a comprehensive understanding of the complex environment provides the basis for predicting future aquifer and landscape evolution. We present a conceptual framework of the hydrology underpinning the area that integrates the extensive current and past research and provides a synthesis of the literature to date. The key factors in the hydrologic behavior of Konza Prairie are climate, ecology, vadose zone characteristics and management, and groundwater and bedrock. Significant interactions among these factors include bedrock dissolution driven by cool-season precipitation and hence a climatic control on the rate of karstification. Soil moisture dynamics are influenced at various timescales due to the short- and long-term effects of prescribed burning on vegetation and on soil physical characteristics. The frequency of burning regimes strongly influences the expansion of woody species in competition with native tallgrasses, with consequent effects on C and N dynamics within the vadose zone. Knowledge gaps exist pertaining to the future of Konza Prairie (a model for US tallgrass prairie)—whether continued karstification will lead to increasingly flashy and dynamic hydrology and whether compositional changes in the vegetation will affect long-term changes in water balances.

Abbreviations: KPBS, Konza Prairie Biological Station; LTER, Long-Term Ecological Research.

The Konza Prairie (Fig. 1) in northeastern Kansas is one of the few remaining native tallgrass prairies in the United States that have not been irrevocably altered by agricultural intensification and land management. It may be considered as a reference ecosystem against which former prairie landscapes may be benchmarked. However, the Konza Prairie itself is a landscape that is gradually evolving as a result of natural environmental processes, primarily the weathering of its complex merokarst geology (Macpherson, 1996; Macpherson et al., 2008), encroachment and vegetative species change (Briggs et al., 2002, 2005; Knapp et al., 2008; Ratajczak et al., 2012), and climatic influences. A comprehensive understanding of this evolution allows elucidation of historical conditions, projections regarding the future of this ecosystem, and commentary on the status of other prairie and former prairie areas relative to this region. Failure to adequately characterize the environmental processes affecting a region—be they hydropedologic, hydrogeologic, ecologic, or climatic—makes interpretation of anthropogenic change difficult to discern. Adopting a critical zone approach that incorporates the broad range of contributing factors, including climatic, hydropedologic, and geologic drivers, will help tackle the challenge of understanding these complex environments. Our objective in this review is to provide a synthesis of more than three decades of landscape and hydrologic research on the Konza Prairie and to develop a

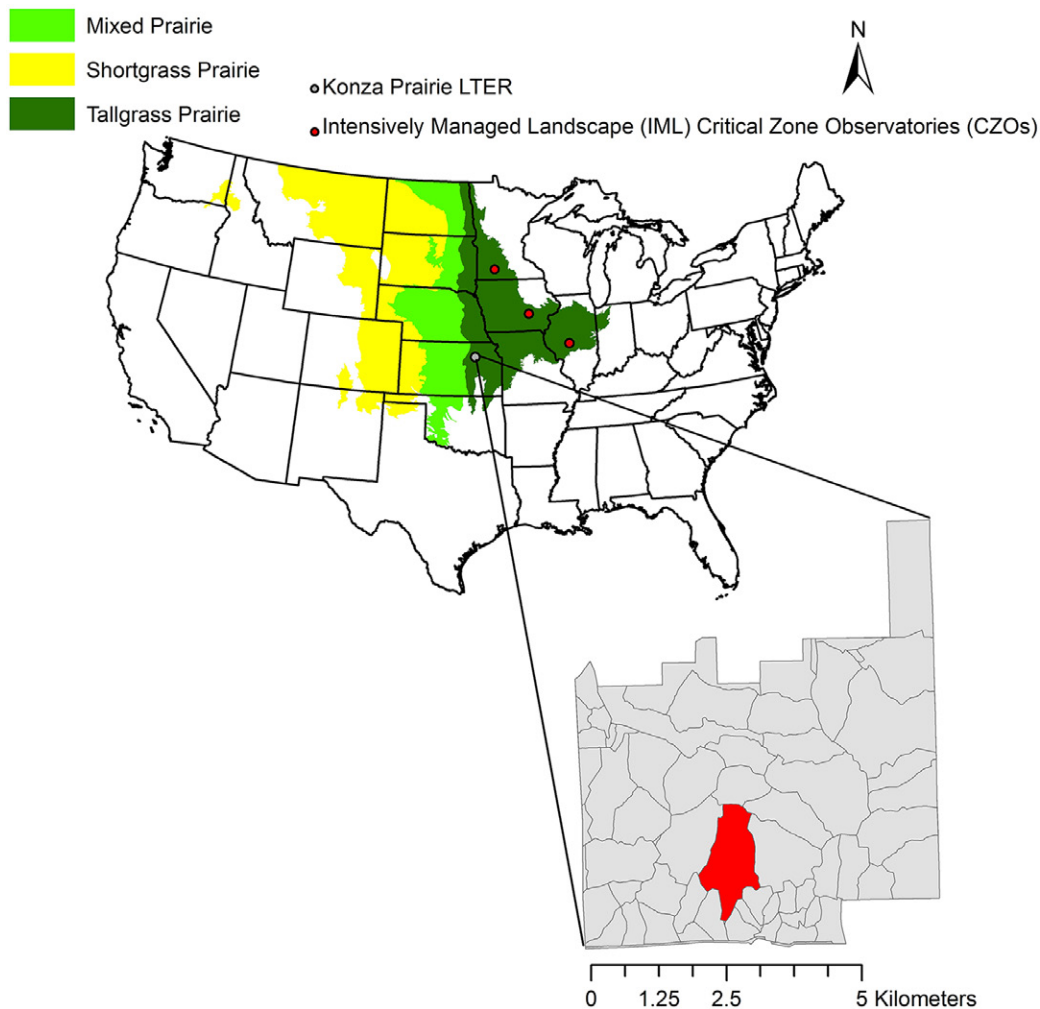


Fig. 1. Map of prairie regions of the United States prior to conversion to agriculture (estimated from US Forest Service ecological provinces map; Cleland et al., 2007) and watershed map of Konza Prairie. Highlighted region denotes Watershed N4D.

conceptual framework for forecasting changes in tallgrass prairie. It should be noted that other research (particularly on the subjects of ecology and biodiversity) has been conducted at Konza; however, the studies cited here are those that most pertain to the hydrologic behavior of this critical zone.

### Prairie Definition and Loss

Mesic prairie grasslands once covered much of the continental United States and are estimated to extend roughly from southern Canada to Oklahoma (Fig. 1) (Axelrod, 1985). These regions were distinguished by perennial  $C_4$  grasses such as big bluestem (*Andropogon gerardii* Hack.), Indiangrass [*Sorghastrum nutans* (L.) Nash], and switchgrass (*Panicum virgatum* L.) and by the characteristic processes of vegetative burning (Hulbert, 1984) and grazing by large ungulates such as bison (*Bison bison*) (Knapp et al., 1999). Prairies typically range from tallgrass to mixed-grass to shortgrass types in a westerly progression across the continent. This gradient exhibits a broad similarity to declining precipitation east to west, although no distinct delineation between these prairie regions exists (Anderson, 2006). It is estimated that  $>570,000 \text{ km}^2$  was

characterized by tallgrass prairie as recently as the 1700s (Howe, 1994) prior to the establishment of European settlers and the ensuing land-use change: first by the establishment of agriculture and later by urbanization (Maizel et al., 1998) and the intensification of production (Tilman, 1999). Agricultural expansion, particularly the production of row crops (Samson and Knopf, 1994), led to the widespread and sustained conversion of fertile, well-drained prairie soil by tillage. Woody expansion has also caused significant changes, as the reduced implementation of scheduled burning and the suppression of wildfires has allowed tree and shrub species to become established on former grasslands (Briggs et al., 2005). Other factors, such as intensive overgrazing, also contribute to woody expansion on prairie grasslands (Smith, 1940; Coetzee et al., 2008), as ungulates may preferentially graze the nutritious and palatable grass species as opposed to less digestible shrubs.

It has been estimated that 98% of US prairie has been lost (Noss et al., 1995) and, in some states, virtually eradicated. A summary of tallgrass prairie decline by area indicated losses ranging from 82.6 and 85% for the states of Kansas and South Dakota, respectively, to

in excess of 99% for Illinois, Indiana, Iowa, Minnesota, Missouri, North Dakota, and Wisconsin (Samson and Knopf, 1994). This loss has made it difficult to evaluate the former hydrology of these landscapes or to comment on how current scenarios relate to former conditions. It should be noted that the deforestation of the Amazon rainforest receives major attention both within the scientific community and in the wider public. Conversely, the mass loss of native American prairie has been relatively overlooked, the implications of which are not wholly understood (Hoekstra et al., 2005).

## Konza Description

The Konza Prairie Biological Station (KPBS) (39°6.1' N, 96°35.7' W) covers 3487 ha within the Flint Hills, a 2.6 million ha ecoregion defined by rolling hills underlain by cherty limestone. Its topography (which has relatively steep slopes compared with much of the Great Plains) and relatively shallow, stony soils limited conversion to cropping systems in this region, and it represents the western border of the former tallgrass prairies (Anderson, 2006; Fig. 1).

Since 1980, the Konza Prairie has been part of the National Science Foundation Long-Term Ecological Research (LTER) program. The prairie is divided into 60 watersheds (Fig. 1) that are subject to replicated watershed-scale treatments, including bison and cattle grazing, and five burn frequencies (annual and 2-, 4-, 20-, and >20-yr intervals). The level of research and instrumentation varies among these watersheds, with some being highly studied for many years (e.g., N4D in Fig. 1) and others relatively unstudied. Measurements and instrumentation that are common across treatments include permanent vegetation sampling transects, soil moisture sensing equipment, groundwater monitoring wells, and rainfall collectors. The prescribed burn frequencies, in addition to grazing by native ungulates, represent natural processes of tallgrass prairie, which are distinct from the agricultural management of former prairie landscapes. A variety of national monitoring programs have been established at the site including the National Ecological Observatory Network and the USGS Hydrology Benchmark Network. The objectives of these programs target elucidation of natural ecological drivers, among which hydrogeology is a key controlling factor. The watershed-scale design of the station can facilitate the establishment of comparative research between sites within the Konza Prairie and those at other tallgrass prairie sites having similar pedological and geological characteristics. Criteria, including regionalization and typographical selection, perhaps in conjunction with suitable physical models, should be considered on a site-specific basis when considering the use of Konza Prairie (or any other site) as a benchmark for critical zone research (Hawkins et al., 2010).

Konza Prairie exhibits a temperate mid-continental climate, typified by warm, humid summers and cold, dry winters. Average air temperature and annual precipitation are 13°C and 835 mm,

respectively, with ~75% of rainfall occurring during the growing season (April–September) (Hayden, 1998). Much of this rainfall occurs in relatively short, high-intensity thunderstorms (Clement et al., 1991), although weather patterns exhibit high variability both spatially and temporally. The topography is complex, incorporating limestone benches and relatively steep slopes as is consistent with the Flint Hills region. Elevation ranges between 320 and 444 m asl with relatively steep slopes (e.g., 10–25% gradient in Watershed N4D), reflecting physical and chemical weathering of strata with different susceptibilities to weathering. Average soil depths range between 1 and 2 m, although exposed bedrock is common. Soil profiles are deepest at the base of slopes and thin to absent upslope. Soils are predominantly silty clay loam and silty clays of the Florence (clayey-skeletal, smectitic, mesic Udic Argiustolls) and Tully (fine, mixed, superactive, mesic Pachic Argiustolls) soil series at the summit, Benfield (fine, mixed, superactive, mesic Udertic Argiustolls) and Clime (fine, mixed, active, mesic Udorthentic Haplustolls) on the side slopes, and Ivan (fine-silty, mixed, superactive, mesic Cumulic Hapludolls) on the floodplains and lowlands (Ransom et al., 1998; US soil taxonomic system). Rock fragments are common throughout the soil profiles, which are typically well drained. Macpherson et al. (2008) observed rapid interaction between the soil surface and groundwater, with a quick water-table response (2.5–5 h; Brookfield et al., 2017) to precipitation events. This reflects both the shallow depth of the water table (a 6-yr mean of 5.5 m below ground level) and the karstic nature of the geologic units as well as potentially well-developed stream–aquifer connections. Surface drainage is primarily via Kings Creek, a tributary of the Kansas River, although intermittent streams also contribute. Kings Creek has two distinct tributaries: an upper reach (fifth order), which drains 1059 ha of deciduous forest, and a lower reach (third order), which drains 134 ha of tallgrass prairie (Gray, 1997). Discharge from the creek is highly variable annually and seasonally, with both no-flow and flooding periods.

The underlying bedrock is characterized by repeating, alternating, almost-horizontal units of relatively high hydraulic conductivity limestone and low hydrologic conductivity mudstone layers, which are 1 to 2 and 2 to 4 m thick, respectively (Macpherson, 1996). The hydraulic conductivities range from  $\sim 10^{-8}$  to  $10^{-3}$  m s<sup>-1</sup> (Pomes, 1995). The geology can be described as merokarst (Brookfield et al., 2017), an early stage of karst landscape development intersected with fluvial drainage. These include highly developed fractures and preferential flow but, unlike traditionally defined karsts, are frequently overlain by soil and vegetative layers (Dreybrodt, 1988). Bedrock joints having apertures of up to 4 cm are present, which suggests a high propensity for rapid movement of water to and within the aquifer. This well-developed fracture network and interbedded rock layers means that the water-table level and direction of flow are difficult to characterize. For example, the limestone layers may act as perched aquifers, each with distinct aquifer chemistry. The interactions between each water body are



dynamic in space and time and require further quantification (Macpherson, 1996; Macpherson and Sophocleous, 2004).

## ◆ Elements of Hydrological Change

Developing a theoretically sound conceptual hydrological framework for any geographic region is challenging because it is constrained by our understanding of past and future patterns based on observation of current processes. Robust conceptual frameworks are, however, an essential step toward the development of numerical and predictive models that are reliable within the bounds of uncertainty (Oreskes et al., 1994; Christakos, 2002). While it is difficult at present to quantify the relative importance of each contributing factor, several components are likely controls over the hydrology at Konza Prairie and should be focal points for future research.

A conceptual framework to help understand the complex hydrology at Konza Prairie is proposed in Fig. 2. The upper portion of Fig. 2 indicates key drivers of Konza Prairie hydrologic behavior identified from the literature. They fall into five broad and interacting categories: climatic, hydrogeologic or vadose zone, groundwater, ecological, and management factors. The lower portion of the figure is used to describe the hypothesized or confirmed outcomes of these interacting drivers and to outline potential linkages and feedback mechanisms. Where either hydrologic drivers or outcomes have been evidenced in the literature, references have been provided. It is critical to recognize that such a conceptual model cannot include every possible factor that may contribute to the hydrology and changes thereof (either observed or hypothesized). Rather, the purpose of this figure is to highlight those that have been prominently identified from the literature to date. Various aspects of this hydrologic model are discussed below. It should be noted that because the hydrologic system is implicitly an integrated one, the delineation of climate, vadose, and groundwater sections should not be considered as discrete compartments but simply provide a framework to aid comprehension of a complex reality. Furthermore, the patterns and processes indicated in this framework operate at different timescales, some of which (such as species composition) may be directly observable and others of which are only estimable with the aid of indirect assessment and modeling exercises (e.g., climate and hydrologic projections).

### Climate and Ecology

While it is beyond the scope of the current review to thoroughly extrapolate the long-term effects of climate on vegetation and, hence, ecohydrology, it seems likely that such relationships will have consequences at Konza and other tallgrass prairies. Indeed, the climate–soil–vegetation dynamic has been highlighted as “the core of hydrology itself” (Rodriguez-Iturbe, 2000). Multiyear research on grassland plots in prairie remnants in Minnesota revealed significant loss of species diversity during drought, which

was not mitigated despite recovery of pre-drought biomass in the subsequent 2 yr (Tilman and El Haddi, 1992). Logan and Brunzell (2015) investigated landscape water-use efficiency and C and water exchange from annually burned and encroached watersheds under drought and non-drought conditions. The results of that study and others (Briggs et al., 2002; Nippert et al., 2013; DeSantis et al., 2011), including stable isotope analysis (Ratajczak et al., 2011), indicated an increased reliance by woody plants on water resources deeper within the soil profile and on the groundwater itself under drought conditions. This behavior was greatest on those watersheds subject to woody or shrub encroachment. While this may facilitate a feedback mechanism, exacerbating the lowering of the water table and depletion of stored water during drought years, Hoover et al. (2014) demonstrated that dominant grass species (e.g., *A. gerardii*) within the KPBS prairie system fully recovered annual net primary productivity just 1 yr subsequent to extreme drought. While woody species have been described as decoupled from certain ecosystem drivers, such as soil moisture, because of their capacity to extract more deeply stored resources (Nippert et al., 2013; Muench et al., 2016), the resilience of tallgrass grass species may buffer potential prairie loss under most drought scenarios. It should be considered that the stability of prairie ecosystems subject to drought does not hinge solely on drought intensity but also on the frequency, duration, and interaction with management factors. Precluding potential future drought conditions, the shift toward increased winter precipitation that has been observed at KPBS (Brookfield et al., 2017) may favor deep-rooted shrub species (Nippert et al., 2013).

The preponderance of interacting drivers, only some of which are detailed here, makes it challenging to predict the future of undisturbed prairie. It is yet inconclusive as to whether a climate-driven shift toward woody species or maintenance of native prairie will occur; however, there is an apparent consensus within the literature that appropriate burning regimes will help to mitigate potential trends toward the former. Interestingly, Wedin and Tilman (1990) commented that the appropriate frequency of burning might not resemble that which has been used historically and should be evaluated with respect to current conditions (ecological, climatic, and hydrologic). The ability to conduct long-term field studies at KPBS, coupled with modeling approaches (e.g., Hoover and Rogers, 2016), will allow a more thorough understanding of these dynamics. It has been proposed that although 43% of the Flint Hills region is subject to burn intervals that are currently adequate to constrain woody expansion (<3 yr), some 33% of grasslands have an interval of >11 yr. This is wholly unlikely to prevent prairie loss, particularly in areas bordering existing shrubland (Ratajczak et al., 2016). A failure to enact effective burning regimes will probably result in a major landscape transition within the next 20 to 60 yr (Ratajczak et al., 2016).

Under current climatic conditions, ~75% of the annual precipitation (835 mm mean annual) occurs between April and August

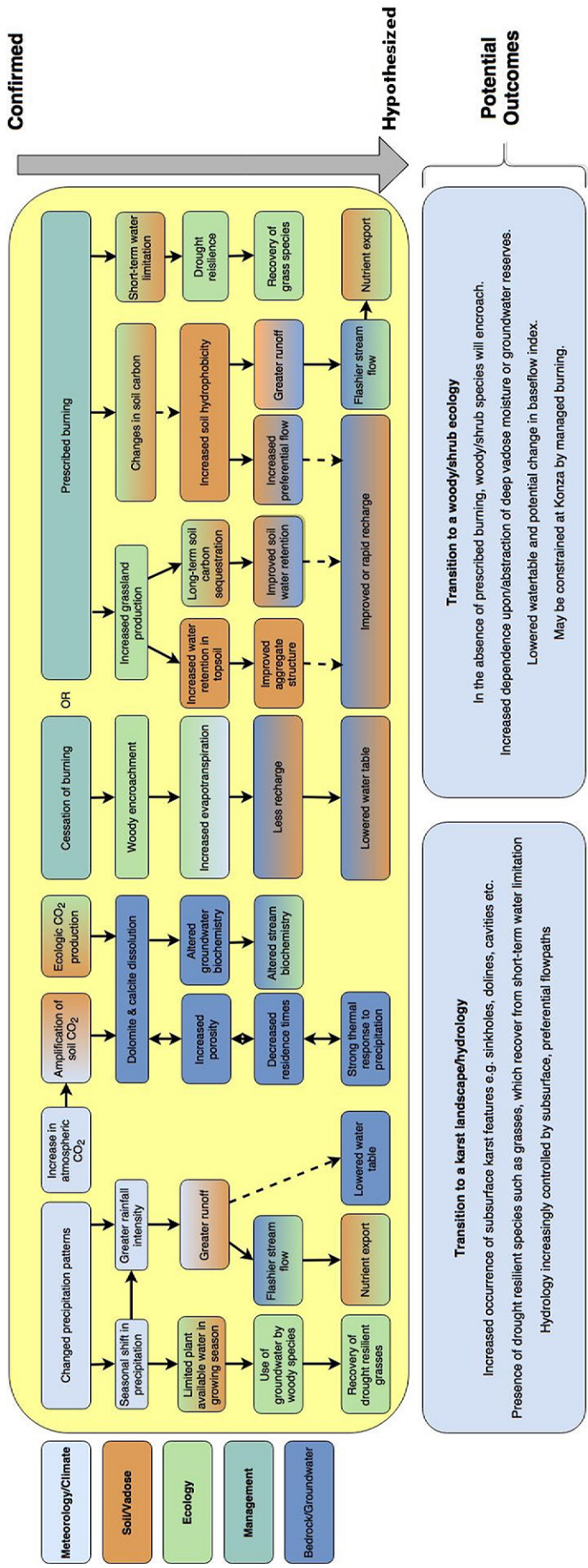


Fig. 2. Conceptual framework of tallgrass prairie hydrology across the critical zone based on research at Konza Prairie, Kansas. Solid lines indicate confirmed relationships and dashed lines indicate hypothesized relationships. The processes in this framework happen across various time scales.

when vegetation is active and evapotranspiration rates are high, while the other ~25% occurs during the non-growing season (Hayden, 1998). In addition, precipitation during the growing season is often dominated by convective storms, while frontal precipitation patterns tend to govern the non-growing season period (Tsybin and Macpherson, 2012). The net hydrologic effect is flashy, intense pulses of water movement during the non-growing season that probably do not support substantial groundwater recharge, while less-flashy pulses reduce competition by vegetation, and less intense storms promote groundwater recharge. Climate scenarios predict that during the next ~100 yr the mean annual precipitation should remain fairly stable but its timing may change, with greater proportions of winter precipitation. Modeled estimates of future precipitation in eastern Kansas suggest general declines in summer and increases in winter precipitation volumes (Brunsell et al., 2010). The timing of groundwater recharge may shift toward winter as a result of this, although the partitioning of rainfall into recharge and runoff may also be impacted subject to factors including rainfall intensity and evapotranspiration.

Aside from precipitation and temperature, other weather and climate factors may influence prairie ecology (and hence hydrology). McPhee et al. (2015) found that increased atmospheric N deposition in accordance with moderate and high projections for 2050 promoted the establishment of C<sub>4</sub> tallgrass species above that of C<sub>3</sub> grasses. Conversely, Wedin and Tilman (1990) proposed that chronic N loading could result in preferential establishment of both woody species and invasive exotics, such as brome (*Bromus inermis* Leys.), vs. native prairie blue-stem varieties. Not only does prescribed burning help mitigate this through physical destruction of undesirable species but also through volatilization of N from plant litter, thus decreasing the total N availability, which may otherwise become elevated with time (Wedin and Tilman, 1990).

Analysis of the hydrologic effects of precipitation timing on groundwater levels and temperature by Brookfield et al. (2017) supported these distinct periods of precipitation-driven groundwater recharge and demonstrated how the lag time between precipitation and groundwater level varied within and between years. They revealed that in all seasons, groundwater elevation responded rapidly to precipitation events, with initial response typically occurring within 2 h of the event and peak response between 2.5 and 5 h. The strongest groundwater level responses were predicted in wet years on account of elevated groundwater levels and water

content in the vadose zone and an increased rate of recharge. Recharge driven by winter precipitation has a more variable temporal response, controlled by the timing of rainfall and timing and speed of snowmelt. In short, winter-season precipitation plays a key role in delivering cool water to the groundwater table at Konza Prairie, which has implications for the potential evolution of the underlying karst.

In merokarst environments, groundwater temperature plays two important roles in controlling bedrock dissolution. First, because calcium carbonate mineral solubility is inversely related to temperature, calcite, the dominant mineral in the limestone at Konza Prairie, can more readily dissolve at lower temperatures. Dissolution can also be indirectly affected because mineralization of organic matter generally increases with temperature (Craine et al., 2010) and results in the release of  $\text{CO}_2$ . If that  $\text{CO}_2$  is dissolved in water to form  $\text{H}_2\text{CO}_3$ , it can then facilitate calcite dissolution. Given climate-induced warming, it is generally thought that groundwater temperature will also increase. Conversely, in areas where winter-season precipitation plays a key role in groundwater recharge and is projected to increase in the future, potential increases in groundwater temperatures may be offset (Brookfield et al., 2017).

In relation to bedrock dissolution at Konza Prairie, two distinct hypothesized outcomes are proposed. The first hypothesis is that lowered groundwater temperatures may promote calcite dissolution in the bedrock (Macpherson et al., 2008), leading to an increase in the pace of karstification at depth. Alternatively, lower aquifer temperatures relative to the average annual air temperature, coupled with warmer air temperatures, may perturb the distribution of  $\text{CO}_2$  production and thus weathering rates. Degradation of aquifer and aquitard organic matter probably generates some  $\text{CO}_2$  in the subsurface at Konza Prairie, particularly in the fine-grained layers (McMahon and Chapelle, 1991; Krumholz et al., 1997). However, the main source of  $\text{CO}_2$  is probably soil respiration (Tsy-pin and Macpherson, 2012). Degradation rates generally increase with temperature (Craine et al., 2010). Thus,  $\text{CO}_2$  production may increase more in soils in response to climate change than deeper within the subsurface where groundwater temperature increases are mitigated by recharge from cool-season precipitation. As a result, a steeper gradient in weathering rates with depth may emerge. Of course, it would be overly simplistic to propose that either of these two scenarios should occur exclusively of one another. More probable is that both physicochemical and biogeochemical factors will influence the process of karstification to a greater or lesser degree.

## Hydropedologic and Vadose Behavior

Moving from climatic drivers, the role of topography, soil, and geology must be considered when conceptualizing the hydrology of a region. Here we discuss the nature and role of this component including both its intrinsic characteristics and factors such as burning and grazing that directly affect it. Although the soil of

the Konza Prairie is thin, the vadose zone (including both soil and unsaturated bedrock) will exert a control on aspects of hydrology including groundwater recharge, plant-available water, evapotranspiration, and solute transport. As such, many of the management factors, such as prescribed burning (see Fig. 2) or grazing by native species, occur at the soil surface. Hence, these factors can be considered as a components or drivers of vadose behavior. Rainfall partitioning across the KPBS indicated a profile of 8.9% recharge, 14.3% runoff, and 74.6% evapotranspiration, although these proportions differed based on soil series and slope position (Steward et al., 2011, based on a large-scale model rather than site-specific observations). Such high evapotranspiration is not surprising for prairie grasslands (Nippert et al., 2011; Brunzell et al., 2014), which are typified by transient drought periods. The highest water-table levels do not necessarily correspond to the greatest annual precipitation, as a result of runoff (Macpherson, 1996), and the timing of high-intensity precipitation events (and the rate of evapotranspiration) and antecedent soil moisture conditions strongly influence the partitioning of recharge and runoff (Brookfield et al., 2017). Regarding infiltration, Govindaraju et al. (1996) measured the saturated hydraulic conductivity ( $K_{\text{sat}}$ ) on plots near Kings Creek using Guelph permeameters and reported values of  $0.09 \text{ m d}^{-1}$  ( $n = 37$ ,  $\text{SD} = 0.09 \text{ m d}^{-1}$ ) with a spatial variability of  $\sim 2$  to 3 m across the soil surface.

As is to be expected, vegetative burning regimes conducted at Konza Prairie have both short- and long-term implications for hydropedologic behavior, and the watershed-scale replication provides a unique natural laboratory to examine these effects at an appropriate scale. The short-term effects of burning on the water balance largely relate to changes in moisture content occurring during the burn and changes in runoff partitioning and albedo directly afterward, prior to the establishment of a new vegetative cover. However, longer term moisture dynamics will reflect not only these factors but also structural changes to the soil itself and ecological factors. Craine and Nippert (2014) analyzed biweekly to monthly soil moisture data (taken at 25-cm increments to depths of 150 cm) in an annually and infrequently (>20-yr interval) burned watershed during 28 yr (1983–2010). They indicated that the infrequently burned watershed exhibited greater moisture content at all depths during the short term as a result of increased litter cover and decreased evapotranspiration, but in the long-term, that burning regime led to drier soil as woody plants became established. Intermediate to deep soil moisture reserves (in the 75–150-cm depths) were most affected, while surface moisture showed no distinct differences between the two burn regimes. While decreases in soil moisture at these depths in response to periods of low precipitation were of a similar duration to those in the annually burned watershed, the reduction in soil moisture was considerably greater. The value of even longer monitoring to reflect the entire life cycle of more long-lived woody plants vs. those of grass species was noted in that study. An indicator of very long-term changes may be identified from a change in moisture behavior first observed in 2010,



the final year of the study; at the 150-cm depth, the infrequently burned watershed began to exhibit periodic troughs in soil moisture. This corresponded to a woody species cover of 70% of the watershed area and mining of deep soil water reserves. Depletion of moisture resources in infrequently burned watersheds may constrain woody expansion and increases the likelihood of localized xeric conditions. Although analysis of watersheds subject to other burn frequencies implemented at Konza Prairie was not conducted, a wildfire in 1991 in the infrequently burned watershed generated a larger reduction in soil moisture than occurred from burning at the annual site. This may reflect greater fuel available from woody species, leading to more prolonged or higher intensity burning. In a closely related study, Bremer and Ham (1999) observed cumulative evapotranspiration (during 150 d) of 503 and 408 mm for burned and unburned sites, respectively. However, this does not comment on the differences in soil moisture as a result of variable burn frequencies over multiple years, and it seems probable that the resulting effects of species establishment and the age of individual plants would play a significant role in longer term evapotranspiration. Investigation of the intermediate burn frequencies therefore is a pertinent area for future research. Knapp et al. (2001) investigated the effects of water limitation on plant species, finding a high response in prairie composition to altered precipitation regimes. Specifically,  $C_4$  grass species outperformed  $C_3$  forbs when plant-available water was constrained, and the opposite was true under increased moisture conditions. This has implications for the dominance of tallgrass (such as Konza) vs. mixed or shortgrass prairie in an annually burned environment. The implications at less frequently burned locations are not yet clear, although the bulk of the literature discussed above indicates that woody species are likely to constrain both  $C_4$  and  $C_3$  plants under such conditions.

While grazing does not directly control recharge, its effects on vegetative species may have consequences for soil moisture regimes and, hence, recharge. A 15-yr study of grazing and burning interactions revealed that the presence of bison in both infrequently and annually burned watersheds increased the abundance of woody species (Briggs et al., 2002). While a number of factors may contribute to this (e.g., increased seed dispersal and reduction in competition from grass species being preferentially grazed), the researchers proposed a reduction in the accumulation of fuel loads that support burning. This may seem counterintuitive, especially considering the historical extent of treeless prairies and large bison herds. However, the fragmentation of the remnant prairie biome has resulted in increased proximity of grassland to seed sources of woody species. The resultant effect on their expansion, particularly in the presence of native grazers, may require burning regimes of greater frequency than those that were sufficient to maintain the original prairie landscape.

Ajwa et al. (1998) compared C and N contents and fractions throughout the soil profiles of tallgrass prairie (<7.5 m) and agricultural (<9 m) plots at Konza Prairie. While the agricultural plots

had greater total and organic C throughout the profile than the tallgrass prairie plots, the potentially mineralizable C ( $C_0$ ) was typically greater in the tallgrass prairie plots. The site-specific hydrological implications of this distinction have not yet been wholly studied. High total organic C has been associated with well-developed soil structure aggregation (Mikha and Rice, 2004), conductivity (Saxton and Rawls, 2006), water retention (Rawls et al., 2003; Saxton and Rawls, 2006), and porosity (Six et al., 2000). The effects are most significant on the mesopore size class (Hudson, 1994; Emerson, 1995), which strongly influences preferential water flow and water and nutrient balances (Luxmoore and Ferrand, 1993).

In addition, there may be more subtle effects on soil structure and hydrology depending on the C species present. Rice and Garcia (1994) examined C and N dynamics on Konza Prairie soils subjected to prescribed burning. While burning slightly decreased total organic C ( $0.1 \text{ g kg}^{-1}$ ), it increased the active (or labile) C pools (microbial biomass and mineralizable C) relative to the stable pool. Labile C has been associated with increased soil macroaggregation (Mikha and Rice, 2004), which in turn increases soil porosity and saturated hydraulic conductivity (Benjamin et al., 2008), key indicators of soil physical quality (Dexter, 2004a, 2004b, 2004c).

It seems probable that the C and rooting dynamics occurring in the vadose zone have imparted a propensity for preferential flow through macropores. Brookfield et al. (2017) observed that even assuming saturated conditions in the vadose zone and the highest observed water tables (4.4 m below ground level in that study), response times in groundwater level at Konza Prairie are too rapid for primarily matrix infiltration. This indicates that a significant proportion of water percolating through the vadose zone does so via macropores or other preferential flow paths. The importance of this cannot be understated from a hydrological perspective because of its implications for system flashiness, nutrient transport, and the partitioning of the vadose zone into discrete hydrologically active and inactive regions. As yet unresolved is the degree to which stream–aquifer seesaw exchange also contributes to the rapid hydrologic response to precipitation. Increased water repellence as a result of burning may also contribute to preferential behavior. DeBano (2000) described the vaporization, migration, and condensation of hydrophobic organic particles during burning (either wild or prescribed fires). This can increase runoff in instances where repellent layers form on or near the soil surface or may create films along macropores such as root channels, which will effectively route infiltrating water rapidly through the soil profile without saturating the interaggregate matrix. This has yet to be evaluated at Konza Prairie.

Regarding erosion of surface soils, Kaste et al. (2006) coupled radionuclide tracing and a digital elevation model to assess sediment transport across the landscape of Konza Prairie. Results

demonstrated that erosion during the past several decades has been focused on convergent areas of the landscape and is driven by overland flow. There was little evidence of sediment deposition or storage, with export downstream from the system likely. These findings are valuable for contextualizing observations in cultivated landscapes in which sediment transport is both greater than in natural ecosystems and has been found to be determined more strongly by land use and management than by topography. Larson et al. (2013) did not find either burning or grazing by native bison to significantly drive sediment or nutrient export, suggesting that these natural processes are intrinsic to the ecotype. That study provided a comparison in which the anthropogenic effects on stream total P and total N led to concentrations two and four times greater than those observed at Konza Prairie (Dodds et al., 2009). High-intensity rainfall subsequent to burning could lead to increased erosion and nutrient loss in the absence of vegetative cover, although that has not been observed at Konza Prairie to date. Overall, the potential consequences of erosion for Konza Prairie hydrology remain inconclusive, although the findings of Kaste et al. (2006) may suggest an overall minimal impact on surface morphology.

## Groundwater and Bedrock

Changes in the chemistry of aquifer water under Konza Prairie have been observed (Macpherson et al., 2008; Tsy-pin and Macpherson, 2012), which implies long-term alterations to structural characteristics of the bedrock. Because groundwater  $\text{CO}_2$  partial pressure is one to two orders of magnitude higher than atmospheric  $\text{CO}_2$ , and because atmospheric  $\text{CO}_2$  increased by 7% (observed during the 15-yr study period; Macpherson et al., 2008), atmospheric deposition as the direct cause of groundwater  $\text{CO}_2$  concentrations is not supported, and shallow groundwater appears to be a sink for  $\text{CO}_2$  in the global C cycle. Although others have argued for carbonate weathering as a global C sink through transformation to aquatic phototrophs (e.g., Liu and Dreybrodt, 2015), the abundance of aquatic phototrophs at Konza Prairie is too low to be a significant C sink (Liu, 2014); another mechanism is required to account for the increasing groundwater  $\text{CO}_2$ . This may be, as discussed below, climate-induced increased soil respiration or, as discussed above, the land-cover change to increased woody vegetation. To date, there have been no studies specifically addressing these hypotheses.

As groundwater  $\text{CO}_2$  has increased, increases in Ca (5%), Mg (29%), and  $\text{CO}_3$  alkalinity (13%) have also occurred, suggesting that the added  $\text{CO}_2$  is driving weathering of calcite and dolomite in the bedrock (i.e., karstification). Tsy-pin and Macpherson (2012) monitored both soil and groundwater  $\text{CO}_2$  concentrations and concluded that mineral weathering is occurring in both the aquifer and the overlying soil. This is typical of merokarst, in which water leached through the soil accumulates high  $\text{CO}_2$  concentrations and, hence, has a high capacity for weathering of carbonate bedrock (Dreybrodt, 1988). Based on this understanding, both the vadose and groundwater hydrology of Konza Prairie may, therefore, be

in transition along a continuum of hydrological evolution, which reflects natural change, as opposed to the anthropogenic land-use change that has been observed throughout the Great Plains. The literature has proposed two likely causal factors: (i) amplification of atmospheric  $\text{CO}_2$  via the vadose zone, possibly as a result of climate warming (Bond-Lamberty and Thomson, 2010), or (ii) generation of  $\text{CO}_2$  in the soil or bedrock. Both hypotheses suggest as yet unquantified microbial or biogeochemical processes that require further investigation, particularly focusing on the vadose zone. Regarding the potential results of this dissolution, laboratory studies on the effect of increasing  $\text{CO}_2$  on soil structure indicate increased effective porosity and permeability and corresponding decreases in pore tortuosity and surface roughness (Noiri-el et al., 2004). On a watershed scale, these changes may lead to shorter groundwater travel times, as water moves more rapidly through an enlarged fracture network, potentially lowering the water table (depending on regional boundary conditions); increasingly flashy stream behavior; and variations in nutrient retention and export.

In a study of hydrologic behavior at Konza Prairie incorporating both onsite measurements and modeling of evaporation, recharge, and base flow, Steward et al. (2011) indicated a depth to groundwater exceeding 8 m for much of Konza Prairie, although near-stream areas and various positions within the undulating topography may be significantly shallower. In that study, the erosion productivity indicator model and MODFlow lumped parameter hydrologic models were supplied with 21 yr of meteorological input data. Results partitioned precipitation into recharge, runoff, and evapotranspiration for each soil series and slope combination represented across the LTER program and simulated the contribution of base flow to Kings Creek. Calibration of the model results against hydrologic observations within the KPBS indicated that incorporation of input variables reflecting zones of higher or lower conductivity are required to realistically simulate the preferential and spatially variable recharge dynamics. This was achieved using the PEST hydrological parameter estimation software (Doherty, 2015). Results indicated that  $\sim 75\%$  of precipitation is partitioned into evapotranspiration, with further losses via runoff limiting recharge to  $<10\%$ , in agreement with Hansen (1991) and Gutowski et al. (2002). Approximately 2% of recharge was predicted to contribute to surface-water flow in Kings Creek (Steward et al., 2011). However, if aquifer porosity is significantly changed by dissolution, the hydraulic conductivity and, hence, base flow dynamics, will be correspondingly affected. Further, field observations support large sections of headwater streams acting as losing streams and the fact that the four gauged headwater watersheds having flowing water when the downstream Kings Creek USGS gauging station does not both suggest that stream-water loss to shallow groundwater is common and dynamic.

Extension of the Steward et al. (2011) study to include not only different meteorological hypotheses but also discretization of layers into multiple aquifers and increased aquifer hydraulic conductivity



may aid in future scenario testing. It should also be considered that should the water table become deeper, the control of the overall watershed hydrology will become more contingent on variably saturated dynamics. Hence, the incorporation of unsaturated zone models and vadose monitoring into future research is essential to accurately characterize the system. This could be achieved by the incorporation of site-specific data (which has already been documented as summarized here) and regional-scale, coupled numerical models (e.g., Twarakavi et al., 2008). While the model framework described by Steward et al. (2011) successfully produced regional water balances, quantification of localized hydrology at a smaller scale or greater resolution would require more detailed mapping of karst features contributing to preferential flow patterns.

## ◆ Knowledge Gaps and the Future of Konza Prairie

As shown in Fig. 2, extensive research at Konza Prairie has already determined key drivers and patterns of behavior influencing its current and future hydrology. Moving from top to bottom, the upper segment of this figure indicates those features that have been documented in peer-reviewed publications, while those lower within the segment indicate potential outcomes that may occur. Solid arrows indicate well-established relationships between drivers and results (e.g., dolomite and calcite dissolution leading to increased aquifer porosity and hence water-table decline). Dashed lines indicate hypothesized linkages, such as where improved soil aggregate structure may lead to increased infiltration and recharge and a shift in plant species composition dependent on that water resource.

While we acknowledge that hydrological changes may occur outside of those presented here, we propose two broad possible outcomes based on the existing observations. The first hypothesis is that Konza Prairie, or parts thereof, will display increasing karst features and its hydrology will become flashier and dominated by preferential flow patterns. High levels of prairie karstification have been observed in Illinois (Ahmed and Carpenter, 2000), so we consider this pattern to be the most likely to occur, although, as discussed above, the controlling factors require further elucidation. A corresponding ecological shift is also likely in response to changed and perhaps limited water resources. It is difficult to project whether the rate of dissolution is likely to be maintained or to exhibit significant changes given the inherent dynamism of a hydrologic system. Certainly, the rate of hydrogeologic change occurring at Konza Prairie has only been observed over a relatively limited timescale. To extrapolate and test various scenarios beyond those observations, research will probably involve the integration of established data sets, new climate and vadose monitoring, and geochemical and hydrologic models.

Alternatively, in the absence of prescribed burning, woody species are liable to encroach. Because of the management of fire frequency

at Konza Prairie, this option seems improbable, but at comparable prairie regions it is certainly possible. Furthermore, it has been well established that such encroachment has led to the loss of regions that would formerly have been characterized as prairie. It is difficult to wholly quantify what the net hydrologic effect of such a shift could be; however, the watershed-scale treatment design operated by the KPBS provides ample opportunity to further investigate these dynamics.

Regarding such hypothesized outcomes, further research is needed in these areas to determine the interactions of acknowledged and predicted factors. Two aspects are particularly challenging. First, feedback mechanisms are difficult to quantify in terms of their likelihood and effect. Such mechanisms include altered recharge patterns influencing ground- and surface-water chemistry and plant-available water content, leading to changes in species composition and further shifts in the water balance. At present, the postulated outcomes remain just that and require investigation via structured research, some of which is already underway, that is facilitated by the commitment to long-term and comprehensive exploration.

The second challenge pertains to interactions across the fields of research. Considering the conceptual diagram (Fig. 2), integration of certain fields of research has been established. For example, the meteorologic, geologic, and hydrologic fields have multiple cross-disciplinary studies (e.g., Macpherson and Sophocleous, 2004; Brookfield et al., 2017). Similarly, the ecologic and hydrogeologic studies have been incorporated with one another (e.g., Ransom et al., 1998). To develop a truly critical zone approach in which the disparate environmental drivers are wholly integrated to give a holistic understanding of the system, further cross-disciplinary research is required. The vadose zone, being the interface between the groundwater and bedrock and the surface and atmospheric components of the system, has been identified as a key area for infrastructural development, with the objective of providing the requisite data for such research. Pilot vadose monitoring arrays providing continuous measurements of soil moisture, temperature, potential, and gas at 10-min intervals, in addition to pore water and gas sampling, were installed in a fall- and spring-burned watershed in 2016. Development of a network of these arrays across the various watershed-scale treatments is intended and will fill in the gaps between the surface measurements undertaken by the National Ecological Observatory Network and groundwater and surface water monitoring operated by the KPBS and collaborators at various universities and to address key questions already raised by previous research.

Research into the groundwater and bedrock conditions suggests that a fundamental shift in hydrology is underway and, consequently, should be taken into account when predicting the future of Konza Prairie and the wider Flint Hills region. A foundational concept of this mechanism will further the integrated critical zone

approach and aid in any comparative studies using Konza Prairie as a reference prairie ecosystem. This review has presented a tentative conceptual framework of hydrologic change on Konza Prairie across the various ecological spheres, which will be examined, validated, and amended through current and future research.

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