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SCIENTIFIC BRIEFING

Influence of the 2021 Brood X cicada emergence on near surface hydrology in forested and urban landscapes

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Abstract

The 2021 emergence of the 17-year Brood X cicadas (*Magicicada septendecim*, *M. cassinii*, and *M. septendecula*) saw billions of cicadas emerge from the soil throughout the midwestern and eastern United States. The emergence left connected burrows visible at the surface, which are hypothesized to affect near surface hydrologic processes. To investigate these processes, we used single-ring, dual head infiltrometers to measure field saturated hydraulic conductivity (K_{fs}, $n = 70$) across patterns of emergence and land use in south-central Indiana, USA. Our experimental design included locations with and without cicada burrows in forested (undisturbed) and urbanized (disturbed) areas. Across undisturbed sites, we found a significant 80.8% increase in K_{fs} between soils with (median = 14.1 cm/h; $n = 20$) and without (median = 7.8 cm/h; $n = 20$) cicada burrows. At disturbed sites, we found no significant difference in K_{fs} between sites with (median = 4.2 cm/h; $n = 18$) and without (median = 4.4 cm/h; $n = 12$) cicada burrows. We found a significant correlation between the number of burrows present at the surface and K_{fs} rates for undisturbed sites ($\rho = 0.42$; $p = 0.008$), while no correlation was found for the disturbed sites ($\rho = -0.09$; $p = 0.62$). Our measurements suggest that the effect of burrows on K_{fs} is minimized in urbanized areas, potentially due to compaction and other impacts from human disturbance that mitigate the presence of macropores left by cicadas. In contrast, surface-connected macroporosity from Brood X cicada burrows in undisturbed areas act as a conduit for precipitation into the soil profile and bypass flow into deeper horizons and the shallow groundwater table, with implications for runoff dynamics, soil and groundwater recharge and quality, and nutrient cycling.

KEYWORDS
macropore, saturated hydraulic conductivity, single ring infiltrometer, soil water infiltration

1 | INTRODUCTION

Macroinvertebrates can modify and restructure the soil ecosystem via burrowing habits. These unique habits have been shown to modulate near surface hydrology, the processing of organic matter, and nutrient cycling (Colloff et al., 2010; Davidson et al., 2012; Davidson & Lightfoot, 2006; Meysman et al., 2006; Sanders et al., 2021; Van Schaik et al., 2014). Previous research shows that burrowing and

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emergence of macroinvertebrates generates surface-connected macropores and/or tunnelling, enhancing aeration and the rapid movement of water into the soil profile (De Bruyn & Conacher, 1994; Elkins et al., 1986; Lee & Foster, 1991). These biopores allow preferential or bypass flow that can reach deeper soil horizons (Van Schaik et al., 2014). Observing the impact of burrows on soil water infiltration rates can help determine whether precipitation partitions as infiltration or runoff (Mohammed et al., 2018; Pinault et al., 2005) with the potential for the enhancement of infiltration (Derby & Knighton, 2001; Klaus & Zehe, 2011). The effects of burrowing on hydrology have been studied for earthworms (Shipitalo & Butt, 1999; Van Schaik et al., 2014), mole crickets (Bailey et al., 2015), and termites (Mando et al., 1996), to name a few. Investigations have found that the presence of these organisms increases the amount of water entering the soil column, resulting in a reduction of surface runoff. As an example, Bouché and Al-Addan (1997) found that the amount of soil water infiltration was directly proportional to earthworm biomass, burrow length, surface amount, and volume.

In May and June of 2021, billions of Brood X cicadas (an invertebrate that ranges in length between 2 and 5 cm) emerged from burrows (as the soil temperature reached 18°C for 3 days or longer) in large portions of the midwestern and eastern United States (Graber-Stiehl, 2021). The Brood X emergence, unique to deciduous trees and/or forests in midwestern and eastern North America and distinct from other cicada broods (Williams & Simon, 1995), occurs every 17 years for mating purposes, with the next emergence predicted to occur in the year 2038. Once mating is completed and eggs are hatched in tree canopies, the nymphs from the eggs drop from the tree to the ground, where they then burrow into the soil and feed on the xylem sap flowing in tree roots (Clay et al., 2009a). Burrow depths can range from 7 to 60 cm and commonly terminate at the deepest point into a bulbous feeding cell that is slightly larger than the width of the burrow (Maier, 1980; Smith & Hasiotis, 2008). The cicadas remain in the feeding cell until reemerging at the soil surface, leaving surface-connected burrows that are approximately 1–2 cm in diameter (Maier, 1980; Smith & Hasiotis, 2008). These burrows are terminal and disconnected from other cicada burrows (Luken & Kalisz, 1989; Smith & Hasiotis, 2008). The emergence of cicadas is not spatially uniform, with some areas observing as many as 1.4 million cicadas per acre (Williams & Simon, 1995) and other areas with limited to no cicadas. This spatial variability is largely a result of the changes in land use/land cover (e.g., urbanization) during the last emergence cycle, which can disrupt the cicada larvae within the soil profile or affect their capability to burrow or emerge.

The 2021 Brood X emergence provided a unique opportunity to examine how associated burrowing and widespread emergence can affect soil hydrology in a structured manner. While previous work has found that cicada emergence led to localized increases in soil moisture (Andersen, 1994), the effects of the cicada burrows on local hydrology have yet to be studied. In contrast with the slow, constant activity of burrowing species such as ants and earthworms, cicadas episodically and rapidly disturb the soil with large burrows (Luken & Kalisz, 1989), likely resulting in equally swift and proportionate changes in local hydrology. We hypothesize that areas of high cicada emergence will have greater infiltration rates than proximal areas with little or no emergence, and that this effect will persist in both undisturbed forested and disturbed urban sites. To address this, after peak emergence occurred in mid-May to mid-June, we measured field saturated hydraulic conductivity (K_{fs}) at disturbed, urban sites within Bloomington, Indiana, USA (where all sites were still under tree canopies) and undisturbed, forested sites.

2 | STUDY AREA AND METHODS

2.1 | Study area and site selection

Our study sites were located in and around Bloomington, Indiana, USA (39.1653° N, 86.5264° W; site radius ~25 km) in areas where cicadas were documented to have had a high rate of Brood X emergence in 2004 (Clay et al., 2009a; Clay et al., 2009b; Kritsky et al., 2005; Speer et al., 2010). These areas of prior emergence intensity from 2004 corresponded with high emergence intensity in 2021 (Cicada Safari, 2021).

To assess the impact of cicada emergence on local hydrology, we measured soil infiltration rate as field saturated hydraulic conductivity (K_{fs}; e.g., Nimmo et al., 2009; Hardie et al., 2013; Morbidelli et al., 2017). K_{fs} is defined as the rate of water flow through soil under fully saturated conditions. Infiltration measurements were made in forested and urban areas, with each area selected based on current soil disturbance and soil disturbance since the last Brood X emergence in 2004 (Figure 1). We define disturbance based on whether the soils are currently influenced by human activities and whether these activities remained similar since the last emergence in 2004 (e.g., residential lawn in 2004 as well 2021), as these activities reduce infiltration rates via compaction and disruption of soil structure (e.g., Gregory et al., 2006; Meek et al., 1992; Woltemade, 2010) and can impact cicada nymph nesting and burrowing. Since one or multiple trees must be present to provide food and mating space, all sampling sites were close to or under tree canopies.

Measurements were made beginning in mid-June and ending mid-September 2021 before foot traffic and storm events accumulated debris that filled the cicada burrows, an effect that was visually observed in September 2021. Undisturbed measurements were taken in the Indiana University Research and Teaching Preserve (Griffy Woods), a site undisturbed since the last cicada emergence in 2004. These measurements were contrasted with measurements from urban areas (residential lawns and parks) across Bloomington, Indiana, hereafter known as ‘disturbed’ sites. All disturbed sites experience weekly or bi-weekly lawn maintenance during the growing season and are areas known to be frequented by humans and therefore subject to human activity such as foot traffic. Importantly, we do not define

FIGURE 1 Saturated hydraulic conductivity measurement sites for (a) disturbed/urban (labelled A) and (b) undisturbed/forest sites (labelled B) near Bloomington, Indiana, USA

TABLE 1 Summary of K_{fs} measurement sites in disturbed and undisturbed areas. IURTP: Indiana University Research and Teaching Preserve. Physical soil property information was extracted from the SSURGO database (Soil Survey Staff, 2021)

Site type	Disturbed Urban	Undisturbed IURTP forest
Number of K_{fs} measurements	30	40
Number of K_{fs} measurements with burrows	18	20
Number of K_{fs} measurements without cicada burrows	12	20
Soil type/textural class	Crider-Urban land complex silt loam	Hagerstown silt loam
Sand/silt/clay fraction %	10/75/15	10/70/20
Bulk density (g/cm^3)	1.43	1.30
Ground cover	Weekly mowed grass	Leaf litter
Tree cover type	Patchy or individual deciduous broadleaf trees	Deciduous broadleaf forest

'disturbance' as large-scale changes such as land use change or logging, but rather as day-to-day disturbances that influence soil hydrology. The surficial soil textural class for all sites was a silt loam (Soil Survey Staff, 2021). More details on the disturbed and undisturbed sites are summarized in Table 1. In total, we made 30 infiltration measurements in disturbed soils (18 with cicada burrows and 12 without) and 40 infiltration measurements in undisturbed soils (20 with cicada burrows and 20 without). The period of data collection was moderately wetter than normal (National Oceanic and Atmospheric Administration, 2021).

Once disturbed and undisturbed sites were selected, we first identified and counted the number of cicada burrows within the infiltration ring (area of 181.5 cm^2) used for K_{fs} measurements; this count serves as a proxy for the density of emergence (Figure 2; see Section 2.2 for more details). We then collected co-located K_{fs} measurements (approximately 2–3 m apart) on soils with confirmed and visible cicada burrows and on nearby soils without cicada burrows at the soil surface (Figure 2). The use of co-located measurements allowed for the direct comparison of soils in the same landscape and soils setting (Brakensiek & Rawls, 1994). While we are unable to verify with absolute certainty that the soils were similar, we endeavoured to make sure the areas were as similar as possible. To ensure that

FIGURE 2 Example measurement locations, tools, and observations, including (a) an area with a large number of cicada burrows, (b) an emerging cicada (circled for clarity), (c) burrows ($n = 4$; circled for clarity) within the infiltration ring, and (d) the experimental setup using the SATURO dual-head infiltrometer with proximal measurements of infiltration with and without cicada burrows

differences in K_{fs} were solely attributable to soil properties and the presence/absence of cicada burrows, sites were not used if roots or burrows from other animals/insects that would otherwise affect infiltration measurements were clearly visible at the surface. K_{fs} data were not used if the infiltration rate data did not follow the typical temporal K_{fs} measurement pattern of increases and decreases from pressure cycle changes (see Section 2.2), which would indicate a water leak or that larger subsurface structures (e.g., roots or other animal/insect burrows) might be influencing infiltration rates.

In addition, we also sought to eliminate any sites where subsurface cicada burrows were observed in the profile of the core but not observed at the surface, as we were not able to quantify the density of cicada emergence at these sites. We therefore carefully inspected all soil 'cores', after extracting the infiltration ring with the soil 'core' inside, to ensure that sites with no observable burrows at the land surface did not display subsurface burrows (indicating the burrows had been filled). In instances where no surface emergence burrows were noted at the beginning of the infiltration measurement, but burrows were found at the bottom the soil 'core' after extracting the infiltration ring with the soil 'core' inside, the measurements were excluded from the analyses.

2.2 | Measurement of field saturated hydraulic conductivity

K_{fs} is a key hydrologic variable for characterizing the movement of water in soils and the partitioning of water at the land surface (Chapuis, 2012; Shuster et al., 2021). In situ observations of K_{fs} are typically made via infiltrometers, all differing in measurement time, effort, and uncertainty (Angulo-Jaramillo et al., 2000; Nimmo et al., 2009). We estimated K_{fs} at the soil surface using the SATURO single-ring, dual head automated infiltrometer (METER Group, 2017, Pullman, WA, USA) for all sites (Figure 2). This infiltrometer is portable and does not require a significant amount of water (normally <20 L), allowing for multiple measurements in a day for remote field sites (individual measurements take 2–4 h). The SATURO unit uses two pressure heads to estimate K_{fs} (Reynolds & Elrick, 1990):

$$K_{fs} = \frac{\Delta(i_1 - i_2)}{D_1 - D_2} \tag{1}$$

where i_1 and i_2 are the infiltration rates for a high and low pressure head (cm/s), respectively, D_1 and D_2 are the high and low pressures

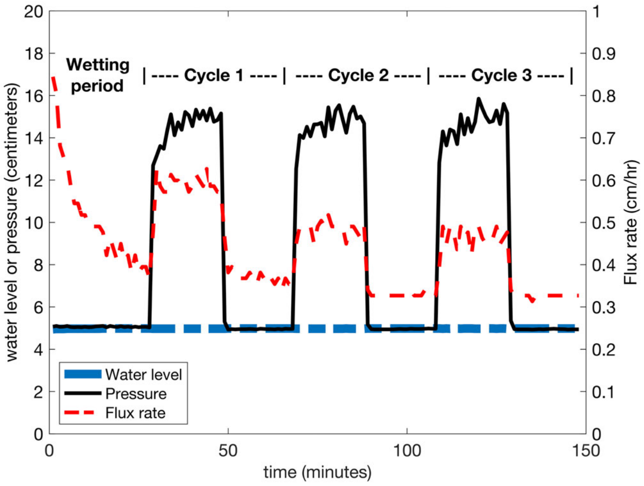

FIGURE 3 Example of water levels (left axis), pressure heads (left axis), and flux rates (right axis) during a SATURO saturated hydraulic conductivity measurement, with three cycles and 5 and 15 cm low- and high-pressure head, respectively. A high-pressure head of 10 cm was used for sites with cicada burrows present

(cm), respectively (see Figure 3). Δ is based on the geometry of the infiltrometer ring (cm), where:

$$\Delta = C_1 d + C_2 b \tag{2}$$

d is the insertion depth of the infiltrometer ring (10 cm for this study), *b* is the radius of the infiltrometer ring (7.6 cm for this study), and C_1 and C_2 are 0.993 and 0.578, respectively, and are constants (Nimmo et al., 2009). D_2 was always set to 5 cm. D_1 was set to 15 cm if no cicada burrows were present and 10 cm if cicada burrows were present. This difference was used to ensure that the pressure head was not high enough to artificially force preferential flow through the macropores. Additionally, these different pressures are accounted for in the final estimation of K_{fs} (see Equation 1).

After the initial wetting period intended to achieve fully saturated soil (25–30 min depending on the initial soil moisture content), the SATURO unit cycles through high- and low-pressure heads (see Figure 3) and then multiplies the final conductivity by the difference in i_1 and i_2 divided by difference in D_1 and D_2 (Equation 1). An example of the SATURO pressure cycling can be found in Figure 3. Across our measurements, the number of cycles differed based on the initial soil moisture content taken at a 20 cm depth (taken using Campbell Scientific HydroSense II). If the initial soil moisture content was higher (≥25%), the SATURO unit was set to two pressure cycles; if the initial soil moisture content was lower (<25%), three pressure cycles were used. This threshold, however, was arbitrary and based on preliminary analyses using the SATURO unit. The measurements were repeated at a different site if the temporal pattern of K_{fs} did not follow the pattern shown in Figure 3. At each site, we used the SATURO to generate an estimate of K_{fs} and associated estimate of error. The error of the measurement is the standard error of the K_{fs} mean during the final cycle and represents the amount of noise in the measurement.

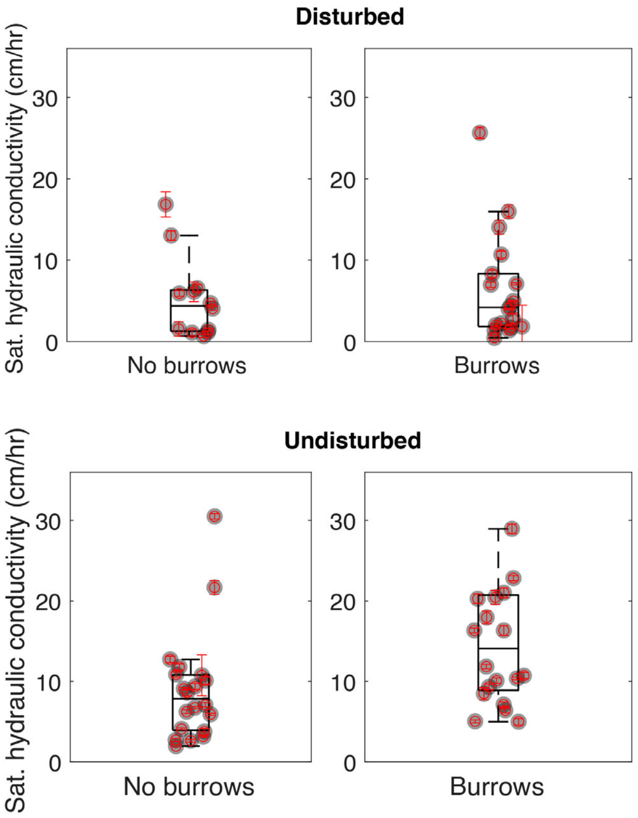

FIGURE 4 Boxplots of field saturated hydraulic conductivity rates for disturbed (top) and undisturbed (bottom) sites with (right) and without (left) cicada burrows. Error bars for each point represents the standard error of the measurement

2.3 | Statistical analyses

We assessed whether K_{fs} differed between sites with and without cicada burrows for disturbed sites and undisturbed sites using the nonparametric Wilcoxon rank sum test ($\alpha = 0.05$). We also investigated whether the number of cicada burrows was related to K_{fs}, quantifying this relationship with a Spearman rank correlation (ρ) with an α level of 0.05 indicating significance.

3 | RESULTS

3.1 | Influence of cicada burrows on infiltration rates

To assess whether cicada burrows impacted infiltration rates, we compared K_{fs} between sites with and without cicada burrows (Figure 4). For undisturbed sites, we found a significant ($p = 0.009$) difference in K_{fs} between sites with and without cicada burrows. The median K_{fs} at sites without cicada burrows was 7.8 cm/h (interquartile range (IQR) of 6.9 cm/h; $n = 20$). In contrast, the median K_{fs} was 14.1 cm/h (IQR $= 11.8$ cm/h; $n = 20$) at sites with cicada burrows. This amounted to a median difference of approximately 6.3 cm/h and an

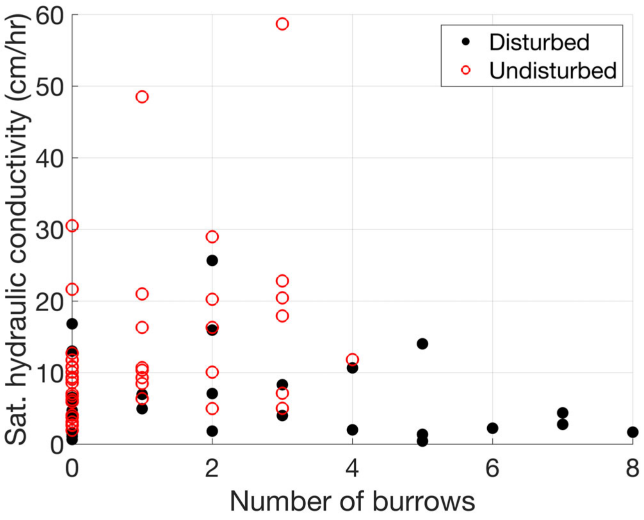

FIGURE 5 Comparison of saturated hydraulic conductivity rates and the number of cicada burrows within the infiltration ring for disturbed (top) and undisturbed (bottom) sites

80.9% increase in K_{fs} (Figure 4). At disturbed sites, we found no significant difference ($p = 0.53$) between K_{fs} measurements from areas with versus without cicada burrows. For urban sites with and without burrows, the K_{fs} median values were similar (sites with burrows: 4.2 cm/h, IQR = 6.5 cm/h, $n = 18$; sites without burrows: 4.4 cm/h, IQR = 5.0 cm/h; $n = 12$).

We also examined whether the number of surface cicada burrows within the SATURO infiltration ring (a proxy for cicada disturbance intensity) was related to K_{fs} (Figure 5). This analysis included sites with and without burrows. We found a significant correlation between the number of burrows present at the surface and K_{fs} rates for undisturbed sites ($\rho = 0.42$; $p = 0.008$), while no correlation was found for measurements from disturbed sites ($\rho = -0.09$; $p = 0.62$).

4 | DISCUSSION

4.1 | K_{fs} across disturbed and undisturbed soils

In total, we collected 70 measurements of K_{fs}, with 54% of these measurements being in soils containing cicada burrows. From the 46% of measurements made in soils without cicada burrows, our estimates of K_{fs} are within the expected ranges for a silt loam (0.3–11 cm/h; Saxton & Rawls, 2005; Rienzner & Gandolfi, 2014; Pachepsky & Park, 2015). While this range of observed K_{fs} may seem wide, K_{fs} is often shaped by local conditions such as compaction and soil structure (Shuster et al., 2021).

Overall, we found higher K_{fs} in undisturbed soils (forests) without cicada burrows as compared to disturbed soils (urban parks and lawns) regardless of the presence/absence of cicadas. Previous work has noted a reduction in K_{fs} rates due to agricultural or urban compaction (e.g., Gregory et al., 2006; Hamilton & Waddington, 1999; Kelling & Peterson, 1975; Pitt et al., 1999) compared to undisturbed soils. As an example, Gregory et al. (2006) found that K_{fs} rates in non-compacted forest soils ranged from 37.7 to 63.4 cm/h compared to 0.76 to 17.5 cm/hr after urban development, resulting in a reduction ranging from 70% to 99%. This estimated reduction is similar to the K_{fs} reduction found in this work (K_{fs} was 77.2% higher in undisturbed soils).

4.2 | Cicada burrows impact K_{fs} in undisturbed soils but not disturbed soils

K_{fs} was greater in undisturbed soils that contained cicada burrows compared to undisturbed soils without burrows (Figure 4). This indicates the potential for cicada burrows to increase K_{fs}, likely via preferential flow, a result found in previous work with different soil macroinvertebrates (e.g., Capowiez et al., 2014, 2021; Mando et al., 1996). In our study, K_{fs} was 80.9% greater in undisturbed soils with cicada burrows. This estimate is similar to those made for burrows associated with other species, with ant macropores estimated to increase infiltration by 10%–15% (Colloff et al., 2010), and cranefly (*Tipulidae*) burrows leading to an increase in infiltration rate by an order of magnitude compared to soils without burrows (Holden & Gell, 2009). Similarly, termites were shown to increase cumulative infiltration compared to nearby soils without termites (Mando et al. (1996) found a 125% increase; Elkins et al. (1986) found a 72% increase). Our results suggest that, in certain landscapes, cicada burrows increase infiltration (K_{fs}; Figure 4).

In disturbed soils, we found no statistical difference in K_{fs} between soils with and without cicada burrows. We speculate that while emergence burrows were present at the soil surface, the underlying cicada burrow may have collapsed from continued compaction (from foot traffic, lawn mowing, and other disturbance) after emergence. This would limit preferential flow and therefore reduce K_{fs} (Schrader et al., 2007; Whalley et al., 1995). Generally, an artefact of urban land development is compaction that reduces soil permeability and infiltration (e.g., Chen et al., 2014; Kelleher et al., 2020). Previous work has demonstrated that the continuity of earthworm burrows decreased in compacted soils, with implications for horizontal and vertical preferential flow (Langmaack et al., 1999).

4.3 | K_{fs} did not increase with the number of cicada burrows at disturbed sites

The number of cicada burrows observed within the infiltration ring was not related to K_{fs} rates for the disturbed sites. While a significant, positive correlation between the number of burrows and K_{fs} was found for undisturbed sites, the lack of a significant correlation for the disturbed sites was counterintuitive. Previous work for other burrowing invertebrates has found linear relationships between the number of burrows and infiltration rate (Léonard & Rajot, 2001; Van Schaik et al., 2014). However, cicada burrows have distinct differences from other types of burrows. Cicada burrows are terminal and disconnected from other cicada burrows (Luken & Kalisz, 1989; Smith & Hasiotis, 2008). The terminal nature of cicada burrows further inhibits macropore flow compared to soils with macropore networks where water can be rapidly transported vertically and horizontally in the soil column (Van Schaik et al., 2008). However, in disturbed areas where compaction is prevalent, the burrows may have collapsed from continued compaction, as previously mentioned, thus negating any influence that the burrows may have had on increased K_{fs}.

Further, previous work has found that increased bulk density from compaction can lead to a shallower burrow depth (Stovold et al., 2004), suggesting that cicada burrows in disturbed soils could be shallower in depth compared to undisturbed soils. Speculatively, if shallower burrows fill more rapidly, additional inflow could then move into the surrounding soil matrix, which is a function of the soil type and structure (Van Schaik et al., 2014), or produce surface runoff. Thus, while cicada burrows may rapidly infiltrate water up to saturation, it is possible that the unique structure of cicada burrows may limit their impact of burrows on K_{fs} at saturation. This may be true in disturbed settings where the surrounding soil matrix has soil properties conducive to lower infiltration rates. Future work would benefit from more measurements in areas of intense emergence (>4 cicada emergence burrows).

4.4 | Implications

Given the spatially widespread, intense emergence of cicadas, our documented influence of cicada burrows on K_{fs} for disturbed and undisturbed soils has implications for hydrological processes and ecosystem services including surface runoff reduction, soil moisture retention, and nutrient cycling. Increasing soil infiltration rates are a major component of surface runoff management (Bouwer, 1966; Reynolds et al., 1985; Talsma, 1987), so Brood X cicada emergence likely has a temporary role in reducing surface runoff in forested areas and perhaps an insignificant role in improving infiltration in disturbed soils. Increased infiltration can also enhance soil moisture, which is necessary for biodiversity, ecosystem productivity, and nutrient cycling (Dobriyal et al., 2012). Thus, Brood X cicada emergence could cause a temporary increase in connection between the hydrological cycle and forest nutrient cycles in undisturbed soils, as the increased infiltration carries soluble nutrients and other organic litter from the forest floor underground. Although several studies have investigated the influence of mass cicada emergence and death on the 'pulse' addition of nutrients to ecosystems (Menninger et al., 2008; Speer et al., 2010; Whiles et al., 2001; Yang, 2004), our results suggest that in addition to those findings, changes to infiltration rates from Brood X cicada emergence may accelerate forest nutrient cycles in locations where emergence occurred. This could have implications for ecological processes in forests involving decomposers, flora, and fauna, and should be explored further using tools such as remote sensing to estimate changes in vegetation.

5 | CONCLUSIONS

In May and June of 2021, billions of Brood X cicadas emerged from the soil in the midwestern and eastern United States, leaving behind holes at the soil surface and burrows into the soil that potentially affect soil water infiltration rates. Our results indicated that in areas with minimal human disturbance (e.g., forests), cicada burrows had a significant effect on saturated hydraulic conductivity, while no effect was found in areas affected by human disturbance (e.g., urban areas). Additionally, we found a significant relationship between the number of cicada burrows (observed within the infiltration ring) and saturated hydraulic conductivity for undisturbed settings, while no relationship was found for disturbed settings. Given the spatially widespread emergence of Brood X, our findings have implications for other science domains such as vegetation water uptake, surface water runoff, groundwater recharge rates, nutrient cycling, and decline in soil water/groundwater quality, as we hypothesize that the cicada burrowing will act as a conduit in undisturbed areas, leading to a more connected route between precipitation and the subsurface.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in CUAHSI HydroShare at http://www.hydroshare.org/resource/d6c3adec8f714a23bc106d9fc3ac5091.

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