The Intensively Managed Landscape Critical Zone Observatory: A Scientific Testbed for Understanding Critical Zone Processes in Agroecosystems

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Interactions between weather and management choices (e.g., tillage, fertilizer application, tile drain installation, and stream channel modification) alter near-surface properties, including soil characteristics, vegetative cover, and roughness, which affect surface and subsurface pathways of water, sediment, and nutrients (Papanicolaou et al., 2018).
The Intensively Managed Landscapes Critical Zone Observatory (IML-CZO) (Kumar et al., 2018) in the US Midwest is ideally suited for understanding the changes of these critical zone properties and the responses of associated processes in the context of the glacial and management legacies by observing water–sediment–nutrient transport at different points of the landscape during and between storm events.

The research and monitoring activities of IML-CZO are question-and-hypothesis driven (Kumar et al., 2018). Many of these questions transcend traditional disciplinary boundaries (e.g., hydrology, geology, geomorphology, soil science, and biogeochemistry), requiring a more holistic approach to understand the interconnections between climate, landscape processes, and management. An overarching question driving IML-CZO studies is the following: How have the interactions between weather/climate dynamics and management restructured landscape heterogeneity in agroecosystems and thus affected system response through changes in transport and residence times of water, sediment, and nutrients across scales? It is hypothesized that the management modifications to the landscape have caused the system to shift from a transformer of constituents to a transporter and that they have made the system more nonlinear in its responses (Kumar et al., 2018). Water, sediment, and nutrients are moving more often and more quickly due to human activities and spending less time at a single place, which allows transformations to occur.

To address the hypothesis, measurements are needed to capture a reference state of landscape conditions from which to assess the effects of the disturbance (Rose, 2004). A nested network of water–sediment–nutrient measurements is also needed during and between storm events (i.e., continuous measurements) to quantify the high spatial and temporal variability of the altered landscape properties, constituent transport, and residence times (e.g., Abban et al., 2016). Thus, IML-CZO is organized with a distribution of sensors to study biotic and abiotic landscape responses through event-based and continuous monitoring, experimental studies, and modeling of altered and control sites (Papanicolaou et al., 2008). IML-CZO examines human influences on landscape connectivity (both vertical and lateral) and the implications on stocks, transport, and fluxes of water, soil/sediment, and dissolved/particulate nutrients such as C, N, and P (Kumar et al., 2018; Papanicolaou et al., 2015a, 2015b).

We present herein the observational design and available datasets of IML-CZO to showcase an example of how an observatory can be structured to address fundamental research questions and hypotheses and to highlight the nature and type of data available for collaborative research efforts with existing Critical Zone Observatory (CZO) networks and other observatories across the globe. Following a decade’s worth of research in cooperation with local landowners, IML-CZO has amassed detailed hydrological, geomorphological, biogeochemical, and management databases to support integrated studies of critical zone properties and processes.

**Site Description**

**Overview of the Intensively Managed Landscapes Critical Zone Observatory**

IML-CZO is one of 10 critical zone observatories of the US National Science Foundation (http://criticalzone.org/). It consists of three watersheds in the US Midwest: the 270-km² Clear Creek Watershed, Iowa; the 3690-km² Upper Sangamon River Basin, Illinois; and the 44,000-km² Minnesota River Basin, Minnesota (Fig. 1). The research is primarily conducted in Clear Creek and the Upper Sangamon River, which are the focus herein. The Minnesota River is a partner site that supports related but independent studies on managed landscapes. Together, these sites represent a broad range of physiographic properties in the glaciated parts of the Midwest. The present-day characteristics at the sites reflect glacial and management legacies from the past and ongoing landscape processes and anthropogenic activities.

**Glacial Legacy**

The Upper Midwest has been shaped by successive glaciation episodes interrupted with periods of surficial weathering and soil development. This glacial legacy, as it relates to IML-CZO, has been described in Anders et al. (2018) and is summarized here.

Clear Creek sits on a dissected till plain that was glaciated during the pre-Illinois Episode (~0.5–2.4 Ma). The loess blanket is about 15 m deep and covers till and clayey paleosols (Bettis et al., 2003). Glaciation, periglacial, and distal glaciofluvial processes have produced a rolling landscape and a well-integrated drainage network with many small streams (Ruhe, 1969). The Upper Sangamon and Minnesota River basins were glaciated during the pre-Illinois, Illinois, and Wisconsin Episodes (~30–14 ka) (Anders et al., 2018). These areas are mantled with thin loess deposits that transition vertically to unweathered, fine-grained, glacial till within 3 m of the surface. The landscape is generally flat with poorly integrated, low-gradient drainage-ways (Keef et al., 2010; Patterson et al., 2003).

Following the Wisconsin Episode, subsequent warming–drying periods produced successive vegetation regimes ending with a savanna-like mosaic of tall-grass prairies, dispersed wetlands, and forested drainage-ways that were periodically cleared by fires (Mutel, 2008). Soils resulting from these climate–vegetation interactions include (i) prairie-derived Mollisols that are dark, organic-rich, granular soils with a thick top soil and (ii) forest-derived Alfisols that are dark gray, less granular, and more acidic with thin, clay-leached, top soils (Lin, 2011).

**Management Legacy**

In addition to the glacial legacy, the management legacy has shaped critical zone processes in the Upper Midwest. As early as 1870, this region began growing into an agricultural powerhouse. Cattle grazing followed European settlement. Cultivation then started in earnest in the early 1900s with the installation of subsurface tile drains and ditches (Mutel, 2008). The draining of
wetlands and prairie potholes provided access to new areas with rich organic soils and the potential for high crop yields.

Multiple-year crop rotations, such as a 5-yr corn–corn–oat–alfalfa–alfalfa rotation, were common until the 1970s (Fig. 2). The moldboard plow was used to till the soil, and manure was applied in spring and fall for fertilizer. The oats and alfalfa were planted simultaneously, with the oats as a companion crop to protect the alfalfa from excessive sunlight and weeds.

The effects of intensive tillage were felt immediately (Fig. 2). Punctuated spikes in erosion often exceeded the soil loss tolerance value (i.e., a benchmark erosion rate where soil productivity becomes limited). Additionally, there was a decline in soil organic C (SOC) from both management-enhanced erosion and respiration (Papanicolaou et al., 2015b).

Farming practices remained similar through the 1940s, as did crop yields. After World War II, the replacement of manure with inorganic N fertilizers initiated a steady increase in crop yields, which continues today (Fig. 2), supplemented by other new agrotechnologies. In the 1970s, agriculture in general spiked due to a combination of changing diets, severe weather in Russia, and US policy. Following consecutive years of low yields in Russia, US exports increased (Fig. 2). The US government called for planting more acres, “fence-post to fence-post,” which led to the development of mega-farms in the region and fueled more mechanized farming. A 3-yr corn–corn–soybean rotation became typical. Significant soil degradation and SOC loss continued despite discontinuing the moldboard plow (Fig. 2).

The Farm Bills in the 1980s reinstituted conservation practices into farming. A marked decline in erosion rates and a reversal of SOC losses were observed (Fig. 2). However, a recent surge in corn production following the 2007 Renewable Fuel Standard may reinitiate higher erosion (Eller, 2014). Currently, 2-yr corn–soybean or 3-yr corn–corn–soybean rotations are practiced with different intensities of tillage (Wilson et al., 2016). Many farmers use reduced and no-till practices in at least one of the rotation years, and anhydrous ammonium is applied only before corn planting (e.g., Arbuckle, 2016).

Watershed Characteristics
Clear Creek Watershed

Clear Creek is located in southeastern Iowa and the Southern Iowa Drift Plain. It is a direct tributary to the Iowa River and ultimately the Mississippi River. Unique combinations of land-use, soils, and geomorphology divide Clear Creek into three zones: the headwaters, mid-reaches, and lower reaches.

Landscape

Corn–soybean fields cover 60% of the watershed, grasslands cover about 23%, forests cover another 10%, and urban areas cover the remaining 7% (Rayburn and Schulte, 2009). The headwaters are almost entirely under row-crop agriculture (Fig. 1a). Upland erosion processes dominate in the headwaters due to steep slopes (Fig. 3a), with an average of 4% and a maximum of 18%. During runoff events, there is high connectivity with the channel, seen with sediment delivery ratios near 1 (Abaci and Papanicolaou,
Channel banks are usually small and vegetated with gradual slopes, which limit collapse. However, in some locations where the stream was channelized (Fig. 3b), mass failure can occur (Papanicolaou et al., 2017; Sutarto et al., 2014).

Most of the grasslands and forests are in the mid-reaches of the watershed (Fig. 1a), where slopes tend to be steeper and the soils have more sand. Streams have more consistent low flows and less flashiness in the grassed and forested areas (Fig. 3c). This middle zone is transitional where either upland or channel sediment sources can dominate depending on the prevailing interplay between management and weather variability (Abban et al., 2016).

The urban areas are mostly found in the lower reaches of Clear Creek, which contain the cities of Tiffin and Coralville. The upland slopes in this zone are less steep, and impervious patches accelerate the delivery of sediment-starved runoff to the channel. Thus, the lower reaches are more influenced by greater flashiness and persistent channel erosion processes (Fig. 3d) because the banks are higher and steeper with less stability (Papanicolaou et al., 2017).

Soils

Upland soils are formed in the Peoria Silt (Ruhe et al., 1967) and are relatively homogeneous. Dominant soil textures range from silty clay loam to silt loam (Prior, 1991). The most common upland soils include the well-drained Tama-Downs and Fayette-Downs associations, and the dominant lowland association is the poorly drained Colo-Nevin-Nodaway association (Dideriksen et al., 2007). Moreover, the soils transition from Mollisols in the headwaters to Alfisols near the mouth resulting from the pre-settlement savanna-like mosaic.

The loess-derived soils are very productive due to their ability to hold water and nutrients (Jones et al., 1967). However, the fields in Clear Creek have some of the highest erosion rates in Iowa (e.g., Cruse et al., 2006). Reported erosion rates average 20 Mt ha⁻¹ yr⁻¹, with individual fields reporting erosion rates up to 150 Mt ha⁻¹ yr⁻¹ (e.g., Abaci and Papanicolaou, 2009; Papanicolaou et al., 2009; Wilson et al., 2009, 2016).

Climate

The climate is humid-continental. The crop growth period is over 160 d, and summer temperatures are optimal so as not to stress plants (Dideriksen et al., 2007). Freeze-thaw periods are also common in late fall and early spring (Bertrand and Papanicolaou, 2009). Average annual precipitation is ~889 mm yr⁻¹. The majority of rainfall and associated stream flow occur in May and June after storm events. Due to the intensive agriculture and stream channelization, the intense spring storms can produce flash floods (e.g., Wilson et al., 2012).

Upper Sangamon River

The basin lies in the Bloomington Ridged Plain of the Till Plains Section of the Central Lowland Province (Leighton et
This region contains low, broad, morainic ridges with intervening wide stretches of relatively flat or gently undulating ground moraines. The Sangamon River is the largest tributary of the Illinois River, which ultimately flows to the Mississippi River. The upper part of the watershed above the Lake Decatur dam is the study domain for IML-CZO.

Landscape

The predominant land-use in the Upper Sangamon basin is row-crop agriculture (Fig. 1b), covering 82% of the watershed (Keefer et al., 2010). Corn and soybeans are the dominant crops. Urban areas cover 12% of the watershed, grasslands and forests cover 5%, and the remainder is covered with small grains, wetlands, open water, and other uses.

The mean slope of the upland is <1% (Fig. 4a). Many of the channels in the upper reaches are surface drainage ditches lined with berms (Fig. 4b), keeping them disconnected from the landscape (Rhoads et al., 2016). In the lower part of the watershed, the tributaries are downcut in the glacial deposits, forming well-defined valleys to maintain grade with the incised Sangamon River (Keefer et al., 2010). The floodplains along the Sangamon mainstem are almost continuously forested or placed into conservation (Fig. 4c), whereas the river channel itself has depositional pockets marked by large woody debris (Fig. 4d).

Soils

There are 14 major soil associations in the basin. The dominant associations are the poorly drained Drummer and Sable silty clay loams and the somewhat poorly drained Flanagan and Ipava silt loams (Fehrenbacher, 1990). These soils are very fertile, with a high water-holding capacity and relatively high organic matter content. The basin can be divided into three zones based on drainage characteristics of the soils and parent materials. In the west-central portion of the basin, the soils are poorly to moderately well drained and formed in loess (Fehrenbacher, 1990). Along the southeastern watershed boundary, the dominant soils are poorly drained to moderately well-drained and silty, formed in loess on nearly level to moderately sloping terrain. In the northeastern portion of the basin, there are poorly to moderately drained silty soils formed in loess, glacial till, and colluvium. In many areas, soil profiles are <3 m thick. The moderately well-drained to well-drained silty soils are formed in loess and in the underlying glacial outwash on nearly level to moderately sloping ridges, outwash plains, or terraces (Fehrenbacher, 1990).

Climate

The Upper Sangamon Basin is in the humid, continental, climate region, typical for central Illinois. It has slightly but not significantly higher average annual precipitation and temperature than Clear Creek. Average annual precipitation is about 1000 mm and follows a pattern similar to Clear Creek. Average annual temperature is 11°C, with an average high of 23°C in July and an average low of -4°C in January. The crop growth period is ~175 d long.

Monitoring Infrastructure and Available Datasets

IML-CZO has multiple observation sites to characterize landscape properties via periodic field campaigns and quantify
energy, water, solutes, and sediment fluxes on storm event and continuous scales at nested locations (Fig. 5). These reference sites are used to survey the level of heterogeneity across the watersheds. They are common across all CZOs (Chorover et al., 2015) and are used for comparison. The reference measurements are complemented with event-based measurements, unique to IML-CZO. Instrumented farms have been established for continuous and event-based measurements to support testing of the central hypothesis (i.e., system shifts from transformer to transporter due to the interplay between management and weather/climate). For data management, IML-CZO has developed a robust online data system and a Geodashboard interface to access these data for modeling efforts (Fig. 5).

Sites for Landscape Characterization

Representative sites in terms of soil, slope, and management have been identified in Clear Creek (Fig. 6a) and in the Upper Sangamon basin (Fig. 6b) to characterize heterogeneity across the landscapes and to establish reference conditions. Many of the sites are privately owned, and IML-CZO conducts observation-based research with support and participation from the land owners.

In Clear Creek, five sites have been used for landscape characterization (Fig. 6a). Two sites in the headwaters are under row crop agriculture. One field follows a 3-yr rotation with reduced ridge-till corn in the first 2 yr followed by no-till soybean. The other field has a 2-yr corn–soybean rotation with spring tillage in the corn year and fall tillage in the soybean year. Both sites have silt loam to silty clay loam soils and surface gradients of about 6%. The site in the middle zone of Clear Creek is a restored prairie at F.W. Kent Park (operated by the Johnson County Conservation Board) with silty clay loam soils and a 9% slope. It was retired from cultivation nearly 50 yr ago and re-seeded as a prairie in 2007. A 5-yr burn frequency is used for invasive species control, with the last burn before sampling occurring in 2012. This site best represents the premanagement conditions in the watershed. Finally, the two sites in the lower reaches of Clear Creek are agricultural fields that follow a 2-yr corn–soybean rotation with spring tillage in both years. These fields have silt loam to silty clay loam soils and gradients of only 1%.

The characterization fields in the Upper Sangamon consist of four sites under row-crop agriculture, one restored prairie, and one forested wetland (Fig. 6b). The agricultural sites are under 2-yr corn–soybean rotations. Two sites are under conventional tillage for both corn and soybean years. The third site is under conservation tillage during corn years and no-till during soybean years. The last site is under conservation tillage during corn years and no-till under soybean years. The soils are silt loams but have more organic matter than the Clear Creek counterparts. These fields have slopes <4%.
Common Measurements for Comparison with Other Critical Zone Observatory Networks

A subset of measurements collected in IML-CZO is common across all CZOs and can be used for cross-site comparisons (Chorover et al., 2015). These measurements include weather, CO₂ fluxes, water table fluctuations, and instream water quantity/quality parameters. Together, the data provide a detailed picture of ecosystem fluxes and the energy balance over a relatively large footprint. Table 1 summarizes the common measurements in terms of instruments and sampling resolution, with the locations of the measurement sites in Fig. 6.

Weather

Combined weather/soil microclimate stations in IML-CZO provide continuous measurements of precipitation, temperature, relative humidity, wind speed/direction, and solar radiation as well as soil moisture and temperature. In Clear Creek, the stations are located at the instrumented farms in the headwaters and the restored prairie at Kent Park (Fig. 6a). For the Upper Sangamon basin, four weather/soil microclimate stations are distributed in the watershed (Fig. 6b). One of these stations is operated by middle school and high school students as a junior observatory.

Supplement weather data are also available from National Weather Service COOP monitoring stations at Williamsburg, IA (8 km southwest of the Clear Creek headwaters) and Iowa City, IA (4 km south of the mouth), expanding the spatial and temporal extent of weather records for the watershed. These weather stations provide data from 1951 and 1893, respectively.

Eddy Fluxes

IML-CZO has installed eddy covariance flux towers to measure continuously CO₂ and water vapor fluxes as well as weather parameters, soil microclimate, photosynthetically active radiation, and ground heat flux. In Clear Creek (Fig. 6a), the towers were installed in 2014 at the instrumented farm in the headwaters and at Kent Park. The tower arms are adjusted following the height of the canopy. The eddy covariance flux tower in the Upper Sangamon basin was installed in 2016 near one of the row-crop characterization sites (Fig. 6b). The tower takes measurements at 10 and 25 m, with fluxes measured at 25 m
Fig. 6. Observational infrastructure in (a) Clear Creek and (b) the Upper Sangamon River basin. Red circles are eddy covariance flux towers. Yellow circles are water table wells. Blue circles are weather stations. Orange circles are in-stream monitoring locations. Gray circles are soil water monitoring sites. Green rectangles are sampled fields for site characterization.
capturing a fetch of several kilometers, depending on atmospheric conditions.

Supplemental data for eddy covariance flux parameters in Clear Creek are provided by the National Oceanic and Atmospheric Association, which has operated a Tall Tower in conjunction with the University of Iowa in West Branch, Iowa (15 km east of the Clear Creek mouth) since 2007. In the Upper Sangamon River, there is an AmeriFlux station at Bondville located at the edge of the watershed and run in conjunction with the University of Illinois, which has been operating since 1996.

Groundwater

Groundwater measurements in Clear Creek are collected in 7- and 20-m deep wells (Fig. 6a). Schilling et al. (2018) provides details regarding the wells, which are for measuring water table depths, temperature, and nitrates. A new concept of “groundwater response units” was used to characterize unique landscape–land cover associations for placing the wells and estimating groundwater recharge at a watershed scale (Schilling et al., 2018). The wells are distributed along transects spanning from the upland to the floodplain. These transects are located in row crop fields, Kent Park, and in residential and commercial areas in the lower part of the basin.

Instream Fluxes

Instream monitoring sites have been established for stage, discharge, suspended sediment, and water quality parameters (e.g., ammonium, chloride, chlorophyll a, dissolved oxygen, fluorescent dissolved organic matter, nitrate, pH, specific conductivity, temperature, and turbidity). In Clear Creek, three locations along the main channel have been placed to measure fluxes in the headwaters, the middle reaches, and the lower reaches to capture changes in fluxes due to changes in land characteristics (Fig. 6a). They measure 15, 60, and 100% of the drainage area, respectively. Measurements at the headwater site are available from 2006; data were collected at the site by the University of Iowa prior to IML-CZO.

Within the Clear Creek stream network, the mid-reach site is colocated with an active US Geological Survey (USGS) flow gaging station near Oxford, IA (#05454220) that has data from 1993. There is also another active stream gauge (#05454300) in Coralville in the lower reaches, <3 km from the watershed mouth, that has flow data from 1952.

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<td>5- to 15-min intervals</td>
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† NVDI, normalized difference vegetation index; PRI, photochemical reflectance index.
There are three instream sites located on the main stem of the Upper Sangamon measuring discharge (Fig. 6b). The sites measure 5, 40, and 60% of the drainage area, respectively. Data at the middle site are available from 1994; the Illinois State Water Survey collected measurements at the site prior to IML-CZO development (Keefer et al., 2010).

Within the stream network, the most downstream site at Monticello has a USGS station (#05572000) that has been collecting stream flow data since 1908. The Illinois State Water Survey has also collected weekly, single-point, depth-integrated suspended sediment samples at this site since 1981.

Two additional instream stations are being established on a tributary that flows into the Upper Sangamon just upstream of the Monticello site. Stage–discharge relationships are currently being developed. Suspended sediment sampling at the upstream station will determine the extent to which agricultural land-use influences sediment production from flat uplands. Sampling at the downstream site occurs where the channel has incised into the uplands and local relief increases substantially.

**Instrumented Farms for Continuous and Event-Based Measurements**

Sensor networks have been established in some of the characterization sites in collaboration with the landowners to capture water–sediment–nutrient fluxes continuously and on an event basis. In Clear Creek, three hillslopes are instrumented for monitoring and selected experimental studies (Fig. 6a).

The first hillslope (~15 ha) is for surficial studies due to a long, continuous slope (6%, 442 m long) and a direct connection to the channel through an ephemeral gulley. Experimental studies using rainfall simulators have been conducted along this hillslope to measure runoff propagation, critical soil strength, enrichment ratios, and soil erosion under different management practices (e.g., Papanicolaou et al., 2015b).

The second hillslope (~10 ha) is for subsurface studies. The hillslope has a 5% grade, but the 372-m long slope length is interrupted by sediment control basins with Alternative Tile Intakes, which are gravel and woodchip filters leading into a main tile line (Papanicolaou et al., 2015c). There are access ports along the tile line for sampling. A camera is at the tile outlet to monitor flow rate. This site also has water table wells and two large gravity lysimeters with soil moisture, temperature, and electrical conductivity sensors. Additional pore water sampling arrays consist of four silicon dioxide–tipped suction lysimeters that collect pore water continuously from depths of 20, 40, 80, and 150 cm.

The third hillslope (~8 ha) is for additional tile monitoring because the tile network is believed to reduce the travel times of subsurface material fluxes to the channel. Semiautomated, double-ring infiltrometers were used to determine saturated hydraulic conductivity above and in between the tile lines. Saturated hydraulic conductivity is highly variable in space and time (over three orders of magnitude) in IML-CZO due to the tiles; erosion, which alters texture; and compaction from farm machinery, which alters bulk density (Papanicolaou et al., 2015a). At the field’s edge, two tile outlets have instrumented V-notched weirs. At 5-min intervals, pressure transducers measure depth (and hence flow rate), and water quality sondes (Nitratex and Hydrolab) measure nitrate, pH, conductivity, and temperature. The tile outflow is also collected with automated water samplers.

In the Upper Sangamon basin, the instrumented field is on farmland endowed to the University of Illinois to support research and student internships (Fig. 6b). A previously used bioreactor experiment site was reactivated to measure tile discharge. A V-notch weir with pressure transducers and an automatic water sampler collect at either fixed time intervals or rates of the rising/falling limbs of the hydrograph. Isotopic compositions of N (δ15N) and O (δ18O) are measured to quantify the NO3− loss by denitrification because microbial denitrification causes fractionation in isotopic composition, whereas plant uptake does not.

**Intensively Managed Landscapes Critical Zone Observatory Data System**

The available datasets (http://data.imlczo.org/; Fig. 7) from the established monitoring instrumentation, campaign-style measurements, and targeted experiments in IML-CZO are stored on a customized, web-based data management system called “Clowder” (Kooper et al., 2016). Clowder (Fig. 8a) houses the raw, processed, and QC/QC data as well as metadata, tags, and other related files provided to enhance explanations and search criteria. The data and metadata follow the operational data model standard and can be queried by external servers. Currently, Clowder holds around 1.6TB across 36K files, organized in 429 datasets.

Clowder is capable of receiving manual uploads from singular measurement campaigns that include lidar, hyperspectral imagery, and soil characterization data. Other data are retrieved using Campbell Scientific LoggerNet software and wirelessly uploaded to Clowder from the measurement site. The Clowder data are organized using a three-level hierarchy.

An authorized account is required to upload or retrieve the data. For general public viewing, IML-CZO has an interactive, web-based application called the Geodashboard (http://data.imlczo.org/geodashboard/; Fig. 8b). A subset of the Clowder data is processed by parsers written in Python and ingested as structured JSON documents into the Geostreaming Application Programmer Interface, which is a spatiotemporal RESTful Application Programmer Interface to store data points in an optimized Postgres database, enable queries, and download the dataset (Fig. 8b). The Geodashboard visualizes a subset of parsed data and makes the data available for download using a specialized search interface. The Geodashboard holds 2.5M data points (each data point includes multiple measures) and 124 locations of interest.

The Geodashboard has an interactive map with each monitoring location in IML-CZO. When a site is selected, a popup is displayed on the map with the site name, data source, collection period, geospatial coordinates, and all available parameters. The popup also provides a means to view the data as graphs for each available parameter at a
site. Up to three parameter graphs can be displayed for each station. The data can also be downloaded as either a JSON file or a CSV file. A user may download all data or a filtered subset by any combination of date range, parameter, source, or location.

A mobile version of the Geodashboard for quick viewing while in the field is also offered by IML-CZO. The display pages have an altered interface for mobile functionality, where only a subset of data locations is presented. Similarly, the graphs are limited to a timeframe of the most recent 2 wk, and the download capability is disabled. The Geodashboard and the mobile app development is ongoing.

Observations and Significant Findings

Reference Condition Measurements

Discrete sampling campaigns were conducted at the characterization sites to define the level of heterogeneity in IML-CZO in terms of basic landscape properties. The campaigns included surface soil and deep core extractions, geophysical surveys, and remotely collected data (i.e., discrete and waveform lidar and hyperspectral imagery) in both Clear Creek and the Upper Sangamon. The data also provide a reference condition for the question-driven experiments conducted by IML-CZO researchers and can be used to calibrate the models used in IML-CZO.

Surface Soils

Over 1000 surface soil samples have been collected throughout IML-CZO. The samples were collected at depths of 0 to 5 cm and 5 to 10 cm along sampling grids in the characterization fields. Each grid consisted of four transects at different catena positions (i.e., crest, shoulder, backslope, toe) and three downslope transects following the main flow paths.

In Clear Creek, samples were collected in April 2014. Smaller campaigns were also conducted in May 2015 and previously in April 2007. In the Upper Sangamon basin, samples were collected in November 2015. These samples were used to identify the physical
ranges of bulk soil properties, including bulk density, texture, pH, and aggregate stability as well as organic geochemistry and isotopic signatures (i.e., total C and N, 13C/15N, lignin content, lipids, and fatty acids). A portion of the samples has been archived for future analyses. Standard practices were used to characterize the bulk density, pH, texture, and organic geochemistry (Soil Survey Staff, 1996). Aggregate stability was determined using rainfall simulators to account for the kinetic energy of the raindrops (Hou et al., 2018; Wacha et al., 2018). Total organic C measurements were conducted using visible near-infrared spectrometry with a multivariate regression model that was developed for the regional soils as part of the Natural Resources Conservation Service-Rapid Carbon Assessment project (Kastanek and Greenwood, 2013).

A significant finding for the physical soil properties is that the variability of a particular parameter, such as SOC, is less in Clear Creek than in the Upper Sangamon. It is believed that the steeper topography of Clear Creek results in a higher-energy, more connected system, which translates to more sediment movement and homogenization of the soil properties. The Upper Sangamon, being a low-energy, more disconnected system, has less lateral and downslope movement to homogenize soil properties along a hillslope.

Accompanying this physical characterization, additional soil and water samples were collected to identify the microbial communities of IML-CZO in coordination with the Microbial Community Systems group at the Argonne National Laboratory. The analytical methods for collecting, quantifying, and characterizing the microbial communities are standard procedures for the Earth Microbiome Project (http://www.earthmicrobiome.org/; Griffin et al., 2017).

The microbial communities in IML-CZO maintain distinct compositions in the soil and stream environments at the basin scale. The results indicate that strong landscape homogenization (similar land-use, cropping, and fertilization) and artificial drainage serve to reduce diversity of both terrestrial and aquatic microbiomes, disconnect the surficial soil microbiome from the aquatic microbiome, and increase connectivity and similarity of aquatic microbiomes.

Deep Cores

About 100 cores were collected in the Clear Creek and Upper Sangamon floodplains for characterization and to map the extent,
volume, and accumulation rate of post-settlement alluvium. The 2-m soil cores were described using standard procedures for physical and chemical parameters, including particle size distribution, total organic/carbonate C, bulk density, and bulk geochemistry (Bettis, 2006; Soil Survey Staff, 1996). Data from these cores, in combination with pore water chemistry and water table measurements, can evaluate how changes in recharge rate and the chemistry of infiltrating water affect weathering and the weathering profile in agroecosystems (Dere et al., 2016, 2017; Goff, 2016, 2017). Weathering rate increases over the last 50 yr associated with climate and land-use changes in intensively managed landscapes are altering the chemistry of local rivers (Ramankutty et al., 2002).

Multiple methods were used to establish a chronology through the post-settlement alluvium thickness, including fly-ash from coal combustion and activities of $^{137}$Cs and $^{210}$Pb (Grimley et al., 2017). A widespread buried C source in the pre-settlement soil beneath the post-settlement alluvium was documented, and current studies are evaluating its significance in the C budget.

In the Upper Sangamon basin, two additional cores were collected to assess subsurface geology. The extracted, continuous cores of the postglacial and glacial sediments showed the complexity and heterogeneity of the sedimentary succession and distribution of aquifer and aquitard units, which affect the thermal profile above the bedrock. The amount of SOC in the underlying glacial deposits changes throughout time (Grimley et al., 2017). The timing of enrichment and degradation are being determined through radiocarbon dating analysis.

Geophysical Surveys

Resistivity and passive seismic surveys in cooperation with the Iowa Geological Survey and the USGS have been conducted at five locations in Clear Creek to image the deeper subsurface and to refine seismic interpretations of fine-grained glacial materials. Two transects in the instrumented headwater farm showed relatively thin (3–5 m) sand and gravel bodies within the upper 30 m of the glacial till and the contact between the upper loess unit and the underlying glacial till as well as downslope thinning of the loess. Three transects across the Clear Creek valley in each of the three zones documented an extensive, shallow alluvial aquifer with confined and unconfined components separated by an organic-rich aquitard that likely affects nitrate dynamics in the aquifer.

An electrical resistivity survey was conducted in 2017 in the Sangamon River Forest Preserve. Nearly 1370 m of resistivity data were collected in the uplands, bluff, and river bottom west of the Sangamon River (Larson et al., 2017). Four resistivity layers were imaged at this site. The geologic setting is underlain by glacial and recent sediments over 100 m thick that overlie Devonian-aged bedrock. There are multiple layers of clay, till, sand, and gravel above the regionally significant Mahomet Aquifer. These layers are consistent with the lithology encountered in monitoring wells at the northwest side of the study site. This general sequence of sediment can be expected beneath the upland regions of the study area; however, the thicknesses and composition of the units may vary considerably.

Lidar

A series of lidar measurements was collected in Clear Creek in June 2008 in response to large floods in Eastern Iowa in May 2009 during a state-wide survey and in August 2014 in conjunction with the National Science Foundation (NSF) and the National Center for Airborne Laser Mapping. A corresponding flight by National Center for Airborne Laser Mapping also occurred in the Upper Sangamon in August 2014.

The 2008 and 2009 lidar surveys provided bare earth measurements because vegetation was sparse at these times. The bare earth vertical accuracy is $\pm$18.5 cm RMSE, with 1 m RMSE horizontal accuracy. The bare earth flights capture changes in the stream channel due to anthropogenically enhanced flash flooding and natural meandering. The survey data can help close the sediment budget by assessing floodplain deposition and bank erosion at the watershed scale, leading to scaling laws for sediment fluxes.

The 2014 flights used high-resolution airborne laser swath mapping with “green” lidar and a terrestrial near-infrared full waveform laser scanner to capture full canopy characteristics, including leaf area index and total biomass. The vertical accuracy is $\pm$37 cm RMSE for vegetation, with 1 m RMSE horizontal accuracy. These measurements provide estimates of throughfall for multilayer canopy models (Dutta et al., 2017) and are being used to assess the role of seasonal vegetation patterns on the distributions of sediment sources (Abban et al., 2016).

The lidar data show a dynamic landscape due to runoff and the resulting redistribution of soil and other constituents. Hillslope curvature defines the flow pathways of water, sediment, and associated nutrients. The directed delivery and transport of water and constituents shape the spatial and temporal scales of pollutant transport from source to sink.

Hyperspectral Data

To complement the 2014 lidar data, aerial hyperspectral data were obtained simultaneously using a compact airborne spectrographic imager. Additional hyperspectral data were collected in May 2015 in Clear Creek and in November 2015 in the Upper Sangamon basin. The spectral range of the imager was from 380 to 1050 nm. The spatial resolution of the images was 1 m. These coupled lidar-hyperspectral data were used to develop a better method for estimating leaf area density and leaf area index of individual trees in dense forest canopies and to identify tree species (Dutta et al., 2017). Verification samples were analyzed for clay content, bulk density, total C, and residue content. Each sampling location was geo-coded for accurate spatial mapping and geometric corrections.

Event-Based Measurements

A unique, event-based sampling framework has been developed in IML-CZO to capture the high spatial and temporal variability of water–sediment–nutrient transport processes that
have been accelerated by intensive land management. The event-based monitoring includes measurements on the landscape of water table fluctuations, enrichment ratios, and roughness as well as instream measurements of bank erosion, hysteresis, sediment sources, and sedimentation (e.g., Abban et al., 2016; Blair et al., 2018; Lee et al., 2017; Neal and Anders, 2015; Schilling et al., 2018; Wilson et al., 2012; Yu and Rhoads, 2018).

Wells

Water table fluctuations in IML-CZO are used to assess spatial and temporal variations of groundwater recharge and nutrient loading in relation to groundwater response units (Schilling et al., 2018). The response of two ridge-top wells, one in row-crop and one in restored prairie, over 1 yr are shown in Fig. 9. As seen with the circled areas in Fig. 9, the row-crop well shows a quick rise after rainfall, whereas the restored prairie has a muted response. The quicker response in the row crop field is attributed the lower SOC content (1.9%) relative to the restored prairie (3.5%), which holds less water. The lower SOC is a product of management-enhanced erosion and respiration (Papanicolaou et al., 2015b; Wilson et al., 2016). The presence of subsurface tiles, tillage practices, and the lack of perennial vegetation also accelerates the vertical flux of water (Papanicolaou et al., 2015a).

Recharge is estimated using these water table fluctuations where the water table rise in an aquifer is assumed proportional to the amount of recharge the aquifer received (there is no groundwater pumping in the watershed). A greater proportion of basin-wide recharge occurs on the floodplains than on upland divides and side slopes, hence the predominant flux to the aquifer was vertical (Schilling, 2009; Schilling et al., 2018). Mean nutrient concentrations in the wells are then multiplied by mean annual recharge to estimate the annual nutrient loading. Row-crop areas are found to contribute ~95% of the annual baseflow nitrate load exported from the watershed. In contrast, orthophosphorus and chloride loading rates to groundwater are higher in urban and suburban areas (Schilling et al., 2018).

Subsurface Thermal Profile

A fiberoptic distributed temperature sensing system was installed in a 100-m-deep borehole in an agricultural field of the Upper Sangamon basin to monitor the subsurface thermal profile (Fig. 10). It has been shown that changes in subsurface temperatures alter the physical, geochemical, and biological systems (Frank et al., 2015; Kurylyk et al., 2014).

Three years of measurements show that the heterogeneous subsurface geology, including glacial till over the thick, regional glacial sand and gravel Mahomet aquifer imparts controls that vary heat transport forming a nonlinear thermal profile (Luo et al., 2016). Flowing water in the Mahomet aquifer increases the conduction of heat with depth (Cui et al., 2014; Molina-Giraldo, 2011). Overall, the influence from changes in atmospheric conditions propagated at least 16 m into the ground, further affecting the thermal profile. Further study will provide better understanding of the relationships between the geothermal regime in shallow subsurface, climate change, artificial conduits (wells), and agricultural practices on a larger temporal scale.

Groundwater–Surface Water Interactions

The pattern of groundwater–surface water interactions in regulating ecohydrogeological and biogeochemical cycles in the critical zone can also be shown with the distributed temperature sensing to characterize hydrologic systems at different spatiotemporal scales (Selker et al., 2006). To investigate this phenomenon in IML-CZO, a 1-km-long fiberoptic cable was placed along the bed of the Sangamon River near the Mahomet in-stream site to measure water temperature on the river bed during the summer and winter when the groundwater–surface water temperature differential is the greatest. The initial data from the late summer in 2017 have identified potential groundwater discharge zones for further investigations.

Enrichment Ratio Experiments

To quantify the spatially and temporally variable redistribution of SOC, enrichment ratio measurements were conducted in May 2014 in Clear Creek and in April 2016 in the Upper Sangamon basin. The enrichment ratio, which is expressed as the proportion of SOC in transported sediment to the proportion of SOC in uneroded soil, is a unique measure of change in available SOC through enrichment or depletion of organic soils. Enrichment ratio values vary in agroecosystems depending on hillslope location, size fraction availability, aggregate stability, and storm magnitude (Fig. 11) (Papanicolaou et al., 2015b).

A mobile unit of Norton ladder rainfall simulators that have been calibrated to provide natural

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**Fig. 9.** The response of two wells in Clear Creek, one in row-crop and one in restored prairie over, a year. The circled areas show the row-crop well with a quick rise after rainfall, whereas the restored prairie has a more muted response.
distributions of raindrops observed in Iowa (Elhakeem and Papanicolaou, 2009) was placed along the main flow pathways in the characterization sites. Over 200 samples of runoff and transported sediment (including aggregated and unaggregated material) were collected through a V-notch weir at the outlet of the plots.

In upslope sections, enrichment ratios range up to 3.25 due to preferential mobilization of finer material by rainsplash erosion (Fig. 11). Although under high-runoff events (i.e., runoff coefficients close to 1), the composition of the mobilized soil is similar to the composition of the in situ soil, resulting in little to no SOC enrichment of the transported soil (enrichment ratios close to 1). In the downslope area, the average enrichment ratios under net erosion conditions are generally lower in magnitude compared with the corresponding values in the upslope. Material mobilization by predominant concentrated flows in this area is not selective, resulting in similar soil compositions in mobilized and in situ soils (enrichment ratios close to 1).

![Temperature profiles from the land surface into the deep critical zone. Temperature profiles are affected by variations in air temperature and changes in geological and hydrogeological properties of the geologic materials. The geology log from the borehole is shown to the right of the fiber optic distributed temperature sensing temperature measurements. The temperature was recorded monthly from June 2015 to April 2016.](image)

![Temperature profiles from the land surface into the deep critical zone. Temperature profiles are affected by variations in air temperature and changes in geological and hydrogeological properties of the geologic materials. The geology log from the borehole is shown to the right of the fiber optic distributed temperature sensing temperature measurements. The temperature was recorded monthly from June 2015 to April 2016.](image)

![Time series of event-based enrichment ratios in the (a) upslope and (b) downslope zones of a representative hillslope in Clear Creek. Enrichment ratio values are separated by corresponding runoff coefficients: 0.00 to 0.25 (green diamond), 0.25 to 0.50 (orange triangle), 0.50 to 0.75 (blue square), and 0.75 to 1.00 (red circle) (reprinted with permission from Papanicolaou et al., 2015b).](image)
Roughness Measurements

Runoff in intensively managed agroecosystems during a storm event is influenced by different forms of roughness (e.g., aggregates, vegetation, oriented roughness from tillage). The flow resistance from these roughness types varies in space and time because they are affected by management–weather interactions (Papanicolaou et al., 2018).

Changes in soil surface roughness have been measured on experimental plots at the Clear Creek instrumented farm using an instantaneous digital surface-profile laser scanner with a 1-mm resolution (Abban et al., 2017). The studies demonstrated that the response of soil surface roughness is nonlinear with respect to the initial roughness condition set by the management–weather interactions. Moreover, the change in random roughness at the site (1.3–4.5 mm) increased saturated hydraulic conductivity by as much as 42%.

To build on these measurements, the Center for Transformative Environmental Monitoring Programs, a community user facility for environmental sensing supported by NSF, flew a small, instrumented unmanned aerial system over the Clear Creek instrumented farm. Structure from Motion photogrammetry (Lucieer et al., 2014; Pai et al., 2017) and terrestrial lidar were performed to identify high-resolution topographic features of the flow paths with resolutions of <1 cm after heavy rain events (Fig. 12a).

The photogrammetry data were acquired in May 2017 (prior to planting) and in November 2017 (after harvest). A 12.4-megapixel RGB camera collected images with substantial overlap (>75% front and side overlap) in parallel, with raster missions defined by Universal Ground Control Station software (UgCS). Crossline camera imagery was captured at similar resolution and overlap settings to ensure optimal coverage (i.e., at least 80% front and side overlap). To reference and validate the photogrammetry data, at least 39 ground control points with visibly delineated survey points were spaced evenly across the fields.

The high-resolution Center for Transformative Environmental Monitoring Programs maps (Fig. 12a) are being used to identify flow paths for modeling and future field studies using rare earth element tracers. The images show rill development, which can be extrapolated to the system response of the uplands and used as a surrogate for channel development through bank erosion during events (Fig. 12b and 12c).

Bank Erosion

Bank erosion has been exacerbated by intensive agriculture because farmers have straightened channels and cleared floodplain vegetation to facilitate flow conveyance (e.g., Landwehr and Rhoads, 2003). Our studies indicate an active interface between the floodplain and the stream channel especially during events (Wilson et al., 2012). Figures 12b and 12c show how channel reaches in Clear Creek and Upper Sangamon that were channelized are regaining their meandering structure (e.g., Langel, 1996; Rhoads et al., 2016; Sutarto et al., 2014). These studies highlight the need for event-based studies to capture the drivers behind channel responses through fluvial and mass erosion as well as mass failure (Papanicolaou et al., 2017).

Specifically for streams experiencing frequent flash floods, there is high heterogeneity in soil properties along the bank face (Sutarto et al., 2014), which influences the type of bank erosion. Newly deposited sand at the crest and midbank sections is believed to contribute to the “effective” soil strength of the stream bank. Selective entrainment of the unbound/exposed silt-sized particles leaves sand-sized sediment that armor the bank surface. The armor here is enhanced by cementation, and fluvial erosion strength can increase several-fold when appropriate amounts of sand and clay are mixed and cement together (Papanicolaou et al., 2017).

Photo-electric erosion pins are used to capture the effects of this cementation in terms of changes in mass erosion (Papanicolaou et al., 2017). Photo-electric erosion pins contain a series of photodiodes that are charged when they become exposed to sunlight as the bank retreats are able to identify the transition from surface to mass fluvial erosion when the applied shear stress surpasses a second threshold.

Hysteresis

Streamflow measurements in IML-CZO are used to capture hysteresis that occurs in the stage–discharge relationship due to flow unsteadiness. Conventional methods for monitoring stream flows assume that flow is uniform and steady. Flow uniformity is rarely obtained in natural streams during storm events due to irregular stream geometry in cross-sections and in the streamwise direction.

Continuous stage measurements were obtained with two sensors set 160 m apart and colocated with the USGS station in the mid-reaches of Clear Creek. The free-surface slope determined with the stage sensors used in conjunction with the surveyed cross-section provided continuous estimates of streamflow as unsteady flow events developed. This method is akin to the conventional slope-area method used in streamflow monitoring, with high marks left on the landscape by large floods (Dalrymple and Benson, 1967).

The measurements illustrated that hysteresis is present in the stage–discharge rating for practically each storm occurring in the basin (Lee et al., 2017). The hysteresis loops display up to 11% difference between discharges measured on the rising limb of the hydrograph compared with those on falling limb for the same flow stage. Conventional ratings do not capture this difference between stage and discharge. This difference is larger than the 5%; good quality, threshold typically accepted for a conventional rating curves.

Sediment concentrations in Clear Creek also typically display a clockwise hysteresis (Fig. 13) response to rising and falling discharge during storm events (Wilson et al., 2012). The slope of the concentration–discharge response decreases through a series of events signifying source depletion. Monitoring over a series of events shows differences not only in total loads but also in sources of the transported sediment and the nonlinear relationship between the sediment concentration and the flow discharge (i.e., hysterisis).
Hysteresis is also seen in the response of the $^{13}$C/$^{12}$C ratios of particulate organic C to discharge. The headwaters and mid-reach sites in Clear Creek exhibit clockwise patterns, whereas the lower reach site displays a counterclockwise pattern. This is hypothesized to result from the input of corn-derived C (a C₄ plant) as part of the surface erosion in the uplands where row crops are more dominant. As the pulse of $^{13}$C-enriched material travels downstream and arrives after peak discharge, the hysteresis reverses.

These studies show the importance of capturing the nonlinearity in water–sediment–nutrient fluxes across a series of events. The interactions of weather and management produce variable response in space and time (Abban et al., 2011).
Sediment Source Studies

Knowledge of sediment source dynamics can help in understanding watershed connectivity and the nonlinearity of sediment delivery. Sediment source studies using naturally occurring radionuclides (\(^{7}\)Be, \(^{210}\)Pb, and \(^{137}\)Cs) and stable isotopes (\(^{13}\)C, \(^{15}\)N) were performed in Clear Creek in 2007, 2009, and 2014 (Abban et al., 2016; Wilson et al., 2012). High activities of \(^{7}\)Be in the suspended sediment are indicative of freshly eroded sediment from the landscape as it is delivered to the surface soils during a rain event. The peak in \(^{7}\)Be activity can be tracked with the sediment moving downstream.

In the Upper Sangamon, source tracing of fine sediment (<63 µm) indicates that uplands and stream channels are poorly connected and that sediment from uplands is not the major source of sediment in headwater portions of the watershed (Neal and Anders, 2015; Yu and Rhoads, 2018). Instead, instream sediment is derived mainly from near-channel sources, including banks and floodplains, especially in areas dominated by grazing. The lack of connectivity between uplands and stream channels reflects the low relief of the landscape and the existence of artificial levees along drainage ditches that prevent sediment-laden hillside runoff from directly entering streams flowing within the ditches. Intensive grazing of floodplains along relatively natural sections of the river enhances sediment production by eliminating the stabilizing effect of riparian forest on bank erosion and by disturbance related to cattle trampling of streambanks and floodplain surfaces.

The use of a Bayesian-based unmixing model can provide the relative partitioning of sediment sources to the stream suspended load (Abban et al., 2016). The enhanced unmixing model incorporates stochastic representation of watershed processes for sediment sourcing. Besides being able to account for variability in source contributions and sediment delivery to the watershed outlet, the model depicts the connectivity across the watershed under different rainfall and land cover conditions. These studies provide new insight into the partitioning between terrestrial and instream sediment sources over a growing season. Considerable terrestrial fluxes are noted in the Clear Creek watershed during late spring and early summer, coincident with relatively bare land cover and high storm magnitudes (Abban et al., 2016). This understanding will assist management efforts by correctly identifying the spatial and temporal distribution of source contributions and allowing resources to correctly target more effective erosion control and thus water quality management/improvement.

Lake Decatur

Lake Decatur was created in 1922 by the damming of the Sangamon River and has acted as a sediment and nutrient trap for the watershed. It can potentially serve as a record of watershed processes and, because of its high sediment trapping efficiency (~75%) (Blair et al., 2018), is an important sink for materials eroded from the landscape. Globally, reservoirs are significant locations for C sequestration (Maavara et al., 2017) and bio-methane production (Deemer et al., 2016). Lake Decatur can provide insight concerning the behavior of the reservoir C cycle within the context of the broader watershed.

Sediment accumulation rate was hypothesized to be the master variable controlling C sequestration and methane production in Lake Decatur, and this drove the sampling strategy. The lakebed sediments were sampled by gravity and vibra-coring along and across the channel. Longer cores captured the pre-dam surface, providing a chronological benchmark.

Cores were extruded and sectioned for geochemical characterization. Activities of \(^{137}\)Cs and \(^{210}\)Pb provided constraints on sediment accumulation rates. Concentrations and stable isotopic compositions of particulate organic C, particulate N, pore water methane, and dissolved inorganic C were used to reconstruct the history of organic C deposition and its fate. The evolution of organic C inputs from submerged local vegetation, eroded soil C, and nutrient-driven algal sources over the lifetime of the reservoir was identified (Blair et al., 2018). Additional cores were kept intact and analyzed at the NSF and University of Minnesota LacCore facility (http://lrc.geo.umn.edu/laccore/) to obtain high-resolution optical and magnetic susceptibility records that will be used to study historical event–scale processes in the watershed.

Modeling

To explore a mechanistic understanding of surface and near-surface critical zone processes in intensively managed landscapes, a 3D coupled ecohydrological and biogeochemical model, Dhara,
was developed (Le and Kumar, 2017; Woo and Kumar, 2017). It includes vertically resolved water–energy dynamics, two-dimensional surface water and nutrient runoff, and 3D subsurface water and nutrient transport and transformations. The subsurface water and nutrient dynamics are implemented using a dual-permeability approach to capture a preferential flow process. This model is structured for large-scale simulations with ~1-m horizontal resolution. The model has the ability to resolve the following: (i) the impacts of micro-topographic variabilities, such as topographic depressions, on surface and subsurface water and nutrient dynamics (Le and Kumar, 2017; Woo and Kumar, 2017); (ii) the impacts of tile drains on the spatial distribution of water and nutrients (Woo and Kumar, 2016); (iii) photosynthetic acclimation in response to atmospheric CO₂ (Drewry et al., 2010a, 2010b); and (iv) the age of water and nonreactive/reactive tracers in the soil (Woo and Kumar, 2016).

Future Directions

Future efforts will focus on organized, event-based measurements examining landscape connectivity and how the degree (or lack) of connectivity affects source, flux rates, soil aggregate formation/disintegration, and transformations. This includes identification of the hydraulic forcing and geomorphic/geologic controls in knickpoints in intensively managed landscapes of the US Midwest. Oversteepened bed slopes in the headwaters of these systems are generally unstable and usually morph into knickpoints. Knickpoints affect bed incision, stream energy, bank stability, and groundwater level through downcutting. Observations of the mechanisms controlling knickpoint formation can lead to first-order models for knickpoint migration and flux prediction (Bressan et al., 2014).

Other observations will include improved mapping and prediction of surface–subsurface structural patterns of landscape features (e.g., roughness, pore spacing) in intensively managed landscapes. These structural patterns reflect the nonlinear interactions between humans and the landscape. Human-influenced organization of the landscape has implications to the magnitude and variability of the water–sediment–nutrient fluxes exiting the landscape as well as transformation and reaction times (Kumar et al., 2018; Papanicolaou et al., 2018). The processes occur across a spectrum of spatiotemporal scales and define the trajectory of the state of the natural system by contributing to, as well as being affected, by the system’s memory.

Observations are needed that focus on subsurface processes that are fundamentally difficult to observe. The observations usually occur through surrogate measurements. For example, geophysical methods use electromagnetic and sound waves to characterize the subsurface, including water flow and storage properties. Measurements will be designed to quantify the partitioning of water along different flow paths linking the stores and the residence time of water and sediment. The residence times of water and sediment link with the reaction rates of biological, chemical, and biogeochemical processes to advance the quantitative understanding of these processes (Papanicolaou et al., 2018). The spatial support scales of these measurements vary widely, but many are at a small scale. Models must be developed to relate measurements to the fundamental properties at the desired scale. The precision of these estimates must be provided to determine whether alternate hypotheses can be distinguished.

The coupled use of emerging biochemical nutrient sensors, soil moisture measurement networks, and an expanded, real-time, stream water quality sensor network can provide estimates of the changes in nutrient stores and fluxes associated with storm and inter-storm periods. Future use of all of the above-mentioned data in advanced atmospheric, hydrodynamic, and ecosystem models could enable the forecasting of nutrient flushing, water quality, and long-term impacts on the ecosystem, and would likely provide critical insights into coupled system behavior.

Creating an archive of basic social science data is as essential to socio-economic research as baseline hydrologic information is for environmental engineers and scientists. Both types of data are needed to study coupled natural–human systems. Just as CZOs propose to invest in facilities to measure and assimilate baseline natural system information, a parallel investment in social science data assembly and assimilation is essential. The NSF, in partnership with NASA, NOAA, USEPA, USGS, and possibly national health agencies, and with collaboration from the private sector, should develop one or more programs that address the need for an interagency sensor laboratory for social and natural science should be considered.

Summary and Conclusion

The short- and long-term interactions between evolving management practices and weather/climate in the critical zone of agroecosystems significantly impact critical zone properties and processes. These interactions tend to amplify or deamplify rates of transport and transformation, creating preferential pathways, including surface and subsurface transformation rates and water–sediment–nutrient transport pathways. Henceforth, a complementary designed, event-based and continuous monitoring is needed to capture the high temporal and spatial variation, the response of the critical zone under complex short- and long-term processes by comparing temporal fluxes to reference conditions. In particular, IML-CZO has accumulated a wealth of data and an advanced web-based data storage repository to support a range of process-based modeling and prediction for assessing changes in the glaciated Midwest agroecosystems in the Anthropocene in response to climate and landscape modification.

Herein, we presented the observations and available datasets of the highly characterized and well instrumented watersheds of IML-CZO to provide a glimpse for other researchers and to spur intellectual advancement and collaboration for critical zone research.

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