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# Emergent role of critical interfaces in the dynamics of intensively managed landscapes

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Complex interactions among water, dissolved and suspended material, and gases occur within the critical zone. These interactions depend upon and influence geologic and geomorphic processes, the chemical composition of constituents, and biological activities of microbes, higher organisms and associated ecological communities. All

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these components of the critical zone are co-evolving through inter-dependencies that extend over various space and time scales. In intensively managed agricultural landscapes, critical zone interactions are extensively disrupted to facilitate agro-ecosystem services. However, such disruptions are not evenly distributed across the landscape. Our research, conducted over eight years at the Intensively Managed Landscapes Critical Zone Observatory, demonstrates that the dynamics of intensively managed critical zones do not operate uniformly across time and space. Instead, *critical interfaces,* or zones of transition between different aspects of the landscape system, play a disproportionately important role in regulating material fluxes through mechanisms of storage, transport, and transformation, often through threshold responses and intermittent connectivity across these interfaces. We provide insight into how critical interfaces affect the intricate dynamics of water, energy, carbon, nutrients, and sediment in intensively managed landscapes. Since anthropogenic activities are continually and extensively modifying critical interfaces, sound understanding of the impact of these modifications is essential for intensive management to also be sustainable management.

## 1. Introduction

The emergence of human activity as a dominant force influencing Earth's environmental systems is now widely recognized throughout the scientific community. This recognition has given rise to the notion of the Anthropocene as an informal and possibly formal designator of this new age of human influence (Crutzen, 2002; Gibbard et al., 2022; Zalasiewicz et al., 2021). Specific concern has arisen about how human activities in the Anthropocene are changing in what has become known as the critical zone (CZ) – the shallow subsurface, surface, and lower atmosphere of terrestrial environments (Richter and Mobley, 2009). This concern is particularly acute in intensively managed landscapes (IMLs), such as those affected by industrial agriculture, where ongoing human activities have fundamentally and radically altered environmental processes within the critical zone and where these activities must now be considered part of the process domain (Kumar et al., 2018; Wilson et al., 2018)). As a result, the critical zone in IMLs is a highly dynamic system responding to multiple interacting stressors arising from sustained human action and climate change.

Industrial agriculture involves large anthropogenic energy input annually (Richardson and Kumar, 2017) and this energy input, both directly and indirectly, strongly influences processes at multiple spatial and temporal scales. For example, in the formerly glaciated portion of the Midwest USA, widespread modification of the landscape for agriculture has changed land cover and drainage systems over vast areas and has altered chemical, physical, and biological processes inherited from the glacial legacy (Anders et al., 2018). In this IML, sustained agricultural production has led to fundamental changes in the fluxes of water, sediment, carbon, and nutrients. These changes affect both the evolutionary trajectory of the critical zone and the sustainability of agro-ecosystem services. The overarching impact of these changes has been characterized as a critical transition from a primarily transformation-dominated system to a transport-dominated system (Kumar et al., 2018). Before European settlement in the 1800s, the landscape supported long residence times, low transport rates, and sustained the slow transformation of materials in the low gradient and low energy environments (Schilling and Drobney, 2014). But over the last two hundred years, increasingly intensive agriculture has necessitated the redesign and management of these landscapes that create faster transport of water and associated particulate and dissolved constituents (Vitousek et al., 1997). Because the pre-settlement landscape was poorly drained, human efforts to facilitate drainage have involved channelization of streams, headward extension of drainage networks, and implementation of tile drainage systems (Macrae et al., 2019; Rhoads et al., 2016). These efforts facilitate mechanized agriculture and increase crop productivity by reducing waterlogged conditions during the planting and growing seasons. However, they also, along with massive application of fertilizers, lead to "leaky" transport-dominated systems that promote rapid downstream transport of nutrients and sediment, producing water-quality problems throughout the upper Midwest and the Gulf of Mexico (Robertson and Saad, 2021).

Within many landscapes including IMLs, the dynamics of the critical zone do not operate uniformly over time and space. Previous work has recognized the existence of hotspots and hot moments in the dynamics of some landscapes with respect to biochemical activity (McClain et al., 2003; Vidon et al., 2010). These concepts refer to small areas (hotspots) or brief time intervals (hot moments) that have disproportionate reaction rates relative to the background biogeochemical activity in the landscape. In some IMLs, particularly those in the agricultural upper U. S. Midwest, the existence of hotspots and hot moments is difficult to identify because most the landscape has been extensively "homogenized" by human transformation (Stover and Henry, 2018). Processes still may not operate uniformly in such landscapes, but instead of being focused locally or for brief intervals, process intensities that play a disproportionate role in regulating material storage, transport, and transformations tend to vary spatially and temporally across broad interfaces within the landscape. Examples of such interfaces, referred to collectively as **critical interfaces** (CI), include transitions between the atmosphere and land surface, between hillslopes and river channels, and between the biotic-abiotic interfaces in the root zone (Fig. 1). The roles of critical interfaces in landscape dynamics include *(i)* serving as transition areas (or boundary layers) for the transmission of material and gaseous fluxes; *(ii)* regulating the connectivity between material fluxes through the critical zone and/or the contact duration between chemical constituents; *(iii)* functioning as loci of biogeochemical transformations; *(iv)* amplifying or attenuating the strength of flux signals or altering the time scales of flux variations; *(v)* acting as controls of the time variability of material fluxes or biogeochemical activity, particularly by governing threshold behavior, and *(vi)* synchronizing the co-evolutionary dynamics of different parts of the landscape. These interfaces can be natural (e.g., near land-surface depressions, floodplains) or human made (e.g., tile network, riparian buffers).

IMLs are complex systems that exhibit a dynamic interplay between structure and function. The structure of the critical zone is continually evolving under the influence of anthropogenic activities. The functional response of IMLs is a direct expression of the dominant role played by the critical interface, which is highly variable in space and dynamic in time. The variability of the critical interface is manifest at short time scales through responses to weather events and intensive management practices, resulting in an organized heterogeneity consisting of a mosaic of row crops that changes seasonally and annually (Hernandez Rodriguez et al., 2023). Over a longer period of several years to decades, these landscapes and critical interfaces continue to be redesigned through anthropogenic activities that modify micro-topographic and micro-roughness variability, preferential flow pathways (Papanicolaou et al., 2015a, 2015b), hydraulic conductivity, and pore structure in the soil (B. K. B. Abban et al., 2017; Papanicolaou et al., 2015b).

These changes in turn cumulatively impact the surface and subsurface fluxes of water, energy, carbon, and solutes across the landscape, leading to emergent and threshold behavior. The restructuring of heterogeneity also alters soil micro-aggregate structure and its strength (Filley et al., 2019; K. M. Wacha et al., 2018; Yu and Rhoads, 2018), affecting surface processes such as erosion rate (Wilson et al., 2012) and mobilization of soil organic carbon (Yan and Kumar, 2021; Yan et al., 2019). The spatial variability and dynamics of the subsurface nitrogen cycle are also structured by topographic depressions, tile drain networks, and macropores in the soil, creating a differentiated expression across the landscape (Woo and Kumar, 2019).

Channelization has increased the density of flow paths and their spatial extent, resulting in increased connectivity across the landscape and creating fast response times and strong coupling between various fluxes. This has given rise to increased upland erosion of sediment (Blair et al., 2018; Grimley et al., 2017; Neal and Anders, 2015; Papanicolaou et al., 2018; Wilson et al., 2012; Yu and Rhoads, 2018) and soil organic carbon (SOC) and their deposition in floodplains (Yan and Kumar, 2021). The concept of connectivity extends to the transport of aquatic microbial communities (Griffin et al., 2017) that then adapt to soil and sedimentary environments, as well as dynamical systems where new approaches based on information theory reveal threshold behavior in the connectivity of fast response variables in the land-atmosphere exchange fluxes (Goodwell et al., 2018) and solute dynamics (Jiang and Kumar, 2019). Understanding the interplay between structure and function in IMLs through the lens of critical interfaces is necessary to develop effective management strategies that enhance ecosystem services and sustainability in the face of changing environmental conditions.

The purpose of this paper is to provide insight into the dynamics of critical-zone processes within intensively managed landscapes in the Midwest region of the USA by synthesizing findings from over eight-year-long study at the Intensively Managed Landscapes Critical Zone Observatory (IML-CZO) (Wilson et al., 2018) within the framework of the critical interface concept. The paper does not attempt to provide a comprehensive review of all literature relevant to critical-zone processes in IMLs, but instead highlights how the dynamics of intensively managed critical zones do not operate uniformly over time and space, and that instead, critical interfaces have a relatively large regulatory role in the storage, transport, and transformations of material and energy, often through threshold responses and intermittent connectivity between these interfaces. Moreover, because anthropogenic impacts are continually and extensively altering critical interfaces in intensively managed landscapes, understanding how this human intervention affects critical zone processes is crucial for sustainable management decisions. Four central issues are examined in relation to the role of critical interfaces: landscape connectivity between uplands and river corridors, especially in relation to sediment dynamics; near-surface controls on fluxes of eroded soil and land-atmosphere exchange; the role of the root-zone/shallow subsurface critical interface in nutrient dynamics; and the influence of the upland-river corridor critical interface on carbon dynamics.

## 2. Geologic legacy, land-use change, and landscape connectivity

In the formerly glaciated Midwest region of the United States, critical zone processes occur within landscapes shaped by natural geomorphic processes and by human-driven changes. Of particular importance in this region is the influence of past geomorphic processes, particularly those associated with continental glaciation that occurred during the Quaternary Period (2.58 million years ago - present). The influence of these past events and processes on the contemporary critical zone and its future evolution is referred to as the "geologic legacy". This legacy has influenced the chemical, physical, and biological processes of the contemporary critical zone (Anders et al., 2018). The basic structure of critical interfaces, including characteristics of the near-surface environment, root zone, and river corridors, largely reflects this glacial legacy. On the other hand, the entire critical zone has been modified extensively by human activities, particularly agriculture. Together, geologic legacy and human activity determine the structure, dynamics, and connectivity of different critical interfaces within the modern critical zone. Understanding the context of contemporary landscape conditions is essential for assessing the role of critical interfaces in critical

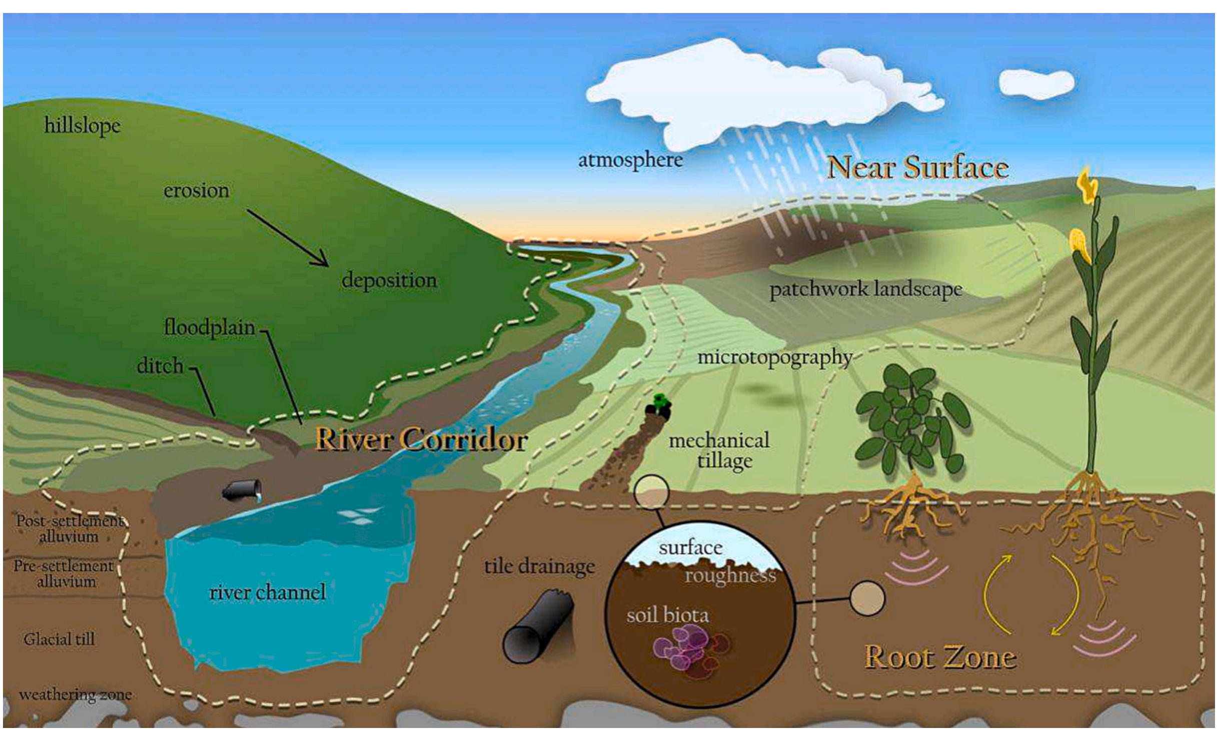


**Fig. 1.** The near-surface, root zone and river corridor are important critical interfaces in intensively managed landscapes in the Midwest region of the United States where the landscapes has been sculpted through glacial episodes overlain with intensive human modification to support industrial agriculture. The mosaic of crop fields and their annual rotation create a dynamic patchwork landscape with underlying microtopographic features, which are modified through tillage, installation of tiles and construction of ditches. The seasonal growth patterns of crops and their harvest creates an active root zone. The material moved from the landscapes are periodically deposited and re-mobilized in the river corridor.

zone dynamics.

### 2.1. Geologic legacy & land-use change

Widespread glaciation throughout the Midwest has largely produced depositional landscapes characterized by low relief (Fig. 2). Despite this relatively subdued topography, the region is not topographically uniform. Some limited areas were not glaciated, including the Driftless Area (Southwest Wisconsin and Northeast Illinois) and areas south of the furthest glacial extent. Mature, deep dissection of these unglaciated landscapes by rivers has created well-drained landscapes with high relief, narrow valleys, and steep hillslopes (Knox, 2001; Stanley W. Trimble, 2013). By contrast, majority of the region was overridden by the Wisconsin Episode (Marine Isotope Stages (MIS) 2–4: ~75,000- ~ 14,000 years ago) Laurentide Ice Sheet and is characterized by poorly drained landscapes with relatively low relief and abundant closed depressions (Anders et al., 2018). Older glaciated landscapes that were overridden by ice during the Illinois Episode (MIS 6: ~191,000- ~ 130,000 years ago) and during the pre-Illinois Episode glaciations that occurred >425,000 years ago have topographic relief and drainage dissection of intermediate or comparable maturity relative to the unglaciated areas and landscapes impacted during the Wisconsin Episode glaciations.

The composition and thickness of sediments within which soils have formed also vary spatially in conjunction with the timing of glaciation (Anders et al., 2018). In unglaciated regions, modern soils have formed in loess and preglacial sediments that overlie thin weathered bedrock. In glaciated regions, soils generally have formed in thick glacial deposits overlain by loess. The composition of these soils and their parent materials reflect the lithology and mineralogy of multiple bedrock and sediment sources that have diverse origins and transport trajectories, including materials formed by alteration in past critical zones (Anders et al., 2018). Soil parent material eroded from bedrock has significantly different mineralogy and grain-size distribution than sediment re-

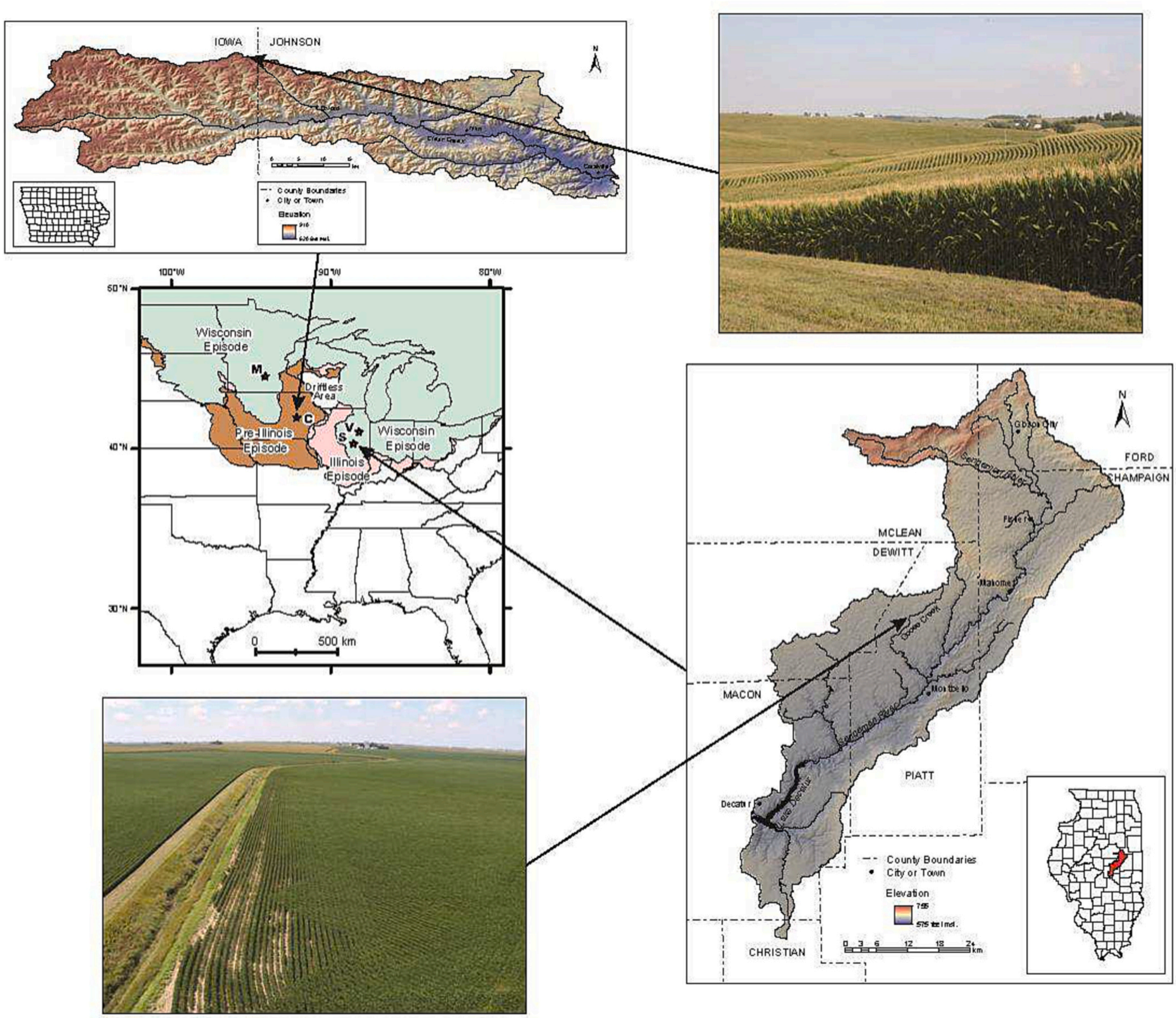


**Fig. 2.** Extent of past glaciations in the eastern region of the U.S. based on Fullerton et al., 2003. Wisconsin Episode includes Marine Isotope Stages (MIS) 2–4. Illinois Episode correlates with MIS 6, Pre-Illinois Episode includes all earlier glacial and interglacial events of the Quaternary Period. The white-colored polygon delineates the Driftless Area where there is no evidence of glacial activity. Stars mark sites mentioned: M is the junction of the LeSueur River and the Minnesota River, C is Clear Creek Watershed (CCW), V is the Middle Fork of the Vermilion River watershed, and S is the Upper Sangamon River Basin (USRB).

entrained from older glacial and nonglacial deposits. Heterogeneity of the primary mineral weathering processes is fundamental in the development of secondary clays that leads to less crystalline material and contributes to high moisture retention and cation exchange (Binkley and Richter, 1987). The various histories of the soils' constituents have led to variability in the age of soil organic carbon (OC), which can range over several thousands of years within the same depth interval (Wang et al., 2018).

Heavily superimposed on this geologic legacy is the imprint of human activity. Beginning in the early 19th century, landscapes and critical zones throughout the upper U.S. Midwest were pervasively altered by intensive agricultural land-use practices (Kumar et al., 2018). In much of the region, native vegetation, particularly prairie grasses and scattered forest, has been replaced by land use dominated by a corn and soybean crop rotation. Nutrient availability is greatly enhanced by applications of artificial fertilizer. The land is now frequently tilled, producing continuous disruption of the root zone and near-surface critical interfaces. Tillage produces organized small-scale roughness that influences soil and carbon transport on the uplands (see section 5.1). It also reduces aggregate strength and the capacity of the soil to withstand erosion, particularly during the winter and early spring when fields may be fallow. The result has been increased soil erosion rates that also change the chemistry of organic matter exported from the land surface (Section 5.1). Connections between near-surface and root-zone critical interfaces and river corridors has been enhanced by the construction and maintenance of drainage ditches that extend natural channels into uplands, by the straightening of streams, and by the installation of underground tile drainage systems, all of which facilitate the efficient movement of water and sediment across upland landscapes to externally draining river systems (Imlay and Carter, 2012). Abundant

**Fig. 3.** (top) runoff from a low-gradient farmed hillslope impounded behind an artificial levee along a drainage ditch with ponded water draining into the ditch through a surface drain, (bottom left) subsurface tile draining into a drainage ditch with steep eroding banks, (bottom right) roadside ditch connected to a drainage ditch via a pipe through ditch levee at a bridge crossing.

topographic depressions, which formerly acted as non-contributing areas, are now connected to river corridors through the tile drainage system. Other rural infrastructure including roads, road-side ditches, and small dams have also changed the landscape's capacity to hold or move water.

### 2.2. Landscape connectivity and critical interfaces

The three study areas of the IML-CZO, namely Clear Creek watershed in Iowa, Upper Sangamon River Basin in Illinois, and Minnesota River Basin in Minnesota, provide contrasting examples of how intensive agricultural land use superimposed on landscapes with different degrees of stream incision and valley development can lead to differences in critical zone dynamics and connectivity between different critical interfaces. Our work has identified differences in landscape connectivity among these different watershed systems and provides a context for exploring geographic variability in critical interface connectivity in relation to agriculture and geologic legacy. Clear Creek Watershed (CCW) in Iowa, formed on a pre-Illinois Episode glacial landscape, contains upland areas with a well-integrated drainage network (Fig. 2). As a result, the hillslopes are well connected to the adjacent channels. Therein, most streams are unchannelized or have evolved in response to past human modifications. In the headwaters of Clear Creek, incised valleys are sufficient to effectively drain the farmed uplands, and hillslopes are typically farmed to the edge of stream channels in the valley bottoms. Additionally, in the lower reaches of the CCW, the distal portions of floodplains along Clear Creek and its major tributaries are also farmed. Floodplains under tillage have been tiled to facilitate the more rapid movement of surface water to the river.

In contrast to the CCW, the drainage network of the Upper Sangamon River Basin (USRB) in Illinois, which developed on a relatively young glaciated landscape impacted most recently during the Late Wisconsin Episode (~20,000 years ago), is much less integrated. The main channel of the Sangamon River has incised into this depositional glacial landscape to form a broad valley bottom bounded by moderately high bluffs standing about 20 to 25 m tall (Fig. 3). The adjacent uplands have a low relief, with many areas containing wet soils that must be artificially drained (Fig. 3). The wet soils are often associated with large expanses of closed depressions that are poorly integrated into the regional drainage network. Prior to the implementation of modern agriculture practices and the establishment of drainage districts occurring in the late 19th century, many tributaries did not extend into the uplands. Instead,

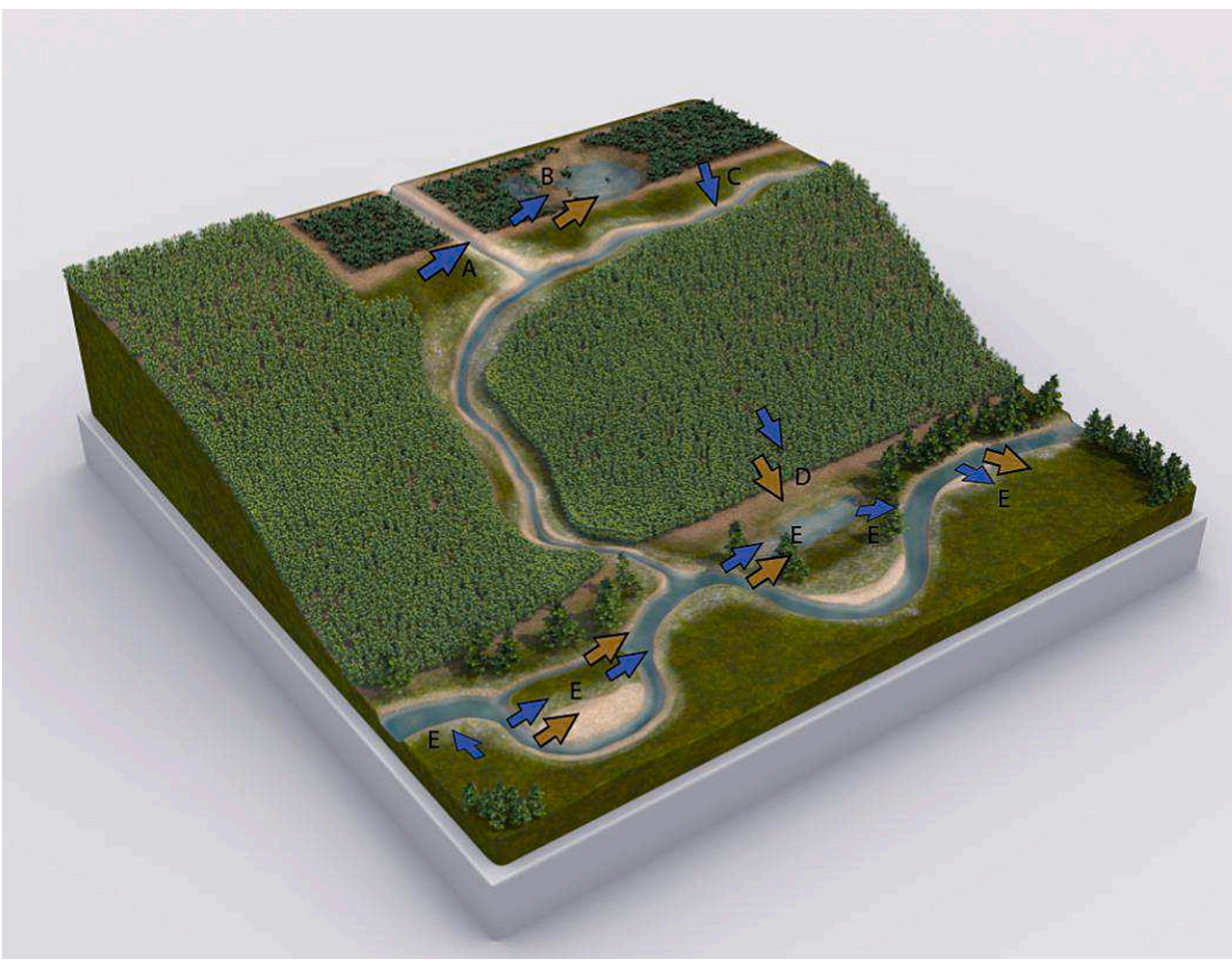


**Fig. 4.** Connectivity of landscape elements in the Upper Sangamon River Basin. Block diagram is vertically exaggerated to emphasize landscape position. Uplands are low-relief and occupied by intensive agriculture (upper portion of block diagram). The floodplain is situated within a broad valley created by glacial meltwater. Connectivity of water (blue arrows) and sediment (brown arrows) varies within the landscape. In the uplands, drainage ditches (arrow A) and small tributaries (arrow C) receive water from uplands via tile drains, grassed waterways, groundwater and limited overland flow. Closed depressions (arrows at B) are common on the landscape and trap water and sediment. Bank erosion occurs in tributaries, producing sediment, but much of the sediment eroded on the uplands is transported short distances and redeposited with limited connectivity to ditches or tributary streams. Transport on hillslopes along valley bluffs (arrows at D) move water and sediment to the edge of the floodplain on the valley bottom. Within the floodplain (arrows at E) there is exchange of water and sediment between the floodplain and channel mediated by the morphology of the channel banks and the adjacent floodplain. Image Credit: Alex Jerez, ITG, Beckman Institute. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

tributaries dissected portions of the landscape close to the bluffs along the main stem of the Sangamon River (Rhoads et al., 2016). Also, the connection of the relatively steep bluffs to the river channel is limited by the broad floodplain. As a result of this landscape structure, sediment, water, and nutrient fluxes from hillslopes were poorly connected to the river corridor. Critical interfaces at the surface and in the root zone acted as transformers that stored and chemically altered materials within these interfaces. A broad buffer "interface" existed between these interfaces and the river corridor. The advent of intensive agricultural activity involved extending tributary channels headward across the uplands by way of excavating drainage ditches and installing underground tiles to expedite the drainage of these closed depressions (Rhoads et al., 2016). The movement of water and sediment from the near-surface and root zone of the relatively flat uplands is still influenced by the watershed's low topographic relief, but the construction of roadside ditches, surface drains, and subsurface tiles have enhanced connectivity between critical interfaces, whereas artificial levees along drainage ditches produced by frequent excavation and local dumping of excavated spoil impede connectivity between hillslopes and headwater channels (Fig. 4).

The Minnesota River Basin has an evolutionary landscape history similar to the USRB, but in contrast has a much greater amount of postglacial incision. Here, catastrophic postglacial drainage of Glacial Lake Agassiz incised through the glacial deposits (Matsch, 1983) forming the broad and well-developed Minnesota River valley that is situated >70 m below the relatively flat Wisconsin Episode glacial landscape (Gran et al., 2011). This incision has developed tributaries extending into the bluffs along the main stem of the river onto the adjacent uplands. Drainage along the tributaries has incised narrow valleys with high, steep walls that are directly connected to the downstream channels. Areas in the uplands further away from the bluffs remain poorly drained, and therefore not well connected to the river corridor, despite limited floodplain development.

Previous work in the Driftless Area (Knox, 2001; Trimble, 2013) provides information from a high-relief, dissected and unglaciated landscape that complements our findings for glaciated landscapes. Other landscapes in the upper U.S. Midwest remain targets for future work. For example, the Middle Fork of the Vermilion River in Illinois (Fig. 2) has a deeply incised valley, narrow floodplains and high river bluffs developed on a landscape impacted by Wisconsin Episode glaciations. This river system may have responded differently to agricultural activity than the neighboring USRB with its relatively broad and less deeply incised valley.

### 2.3. Post-settlement erosion and deposition

Through our research we have documented the impact of differences in connectivity on the erosion and deposition at different spatial and temporal scales. At the watershed scale we assessed the changes in long-term sediment accumulation rates in the floodplains of river corridors in the CCW and the USRB associated with land use change that affects the root zone and near-surface environments (Grimley et al., 2017). This work provided information on long-term linkage among these interfaces and how those linkages have changed with human impact on the landscape. We also conducted short-term sediment tracing studies during a series of hydrological events or over single events to identify variability in sediment sources to channels during storm events and relate this variability to changes in connectivity to source areas of sediment (B. Abban et al., 2016; Neal and Anders, 2015; Yu and Rhoads, 2018). We documented how landscape connectivity influencing sediment and water transport also influences the transport and transformation of particulate organic carbon, as described below in section 5

#### 2.3.1. Post-settlement alluvium and landscape connectivity

Post-settlement alluvium (PSA), also known as legacy sediment (James, 2013, 2018), refers to alluvial deposits that have accumulated following significant land-use changes, particularly following European colonization of North America and Australia, where deposition rates rapidly increased following these changes. The distribution and thickness of PSA along river corridors can provide an integrated record of landscape response to intensive agricultural activity and the widespread removal of native vegetation (Jackson et al., 2005; Portenga et al., 2016; Walter and Merritts, 2008). Following a well-established body of work on PSA in the Driftless Area (Lecce, 1997; Knox, 1987; Magilligan, 1985; Trimble, 1983) we mapped PSA in CCW and USRB (Grimley et al., 2017). Within soils developed in thick loess that are highly erodible and mantles a moderate relief topography in CCW, the PSA record obtained is similar to those observed in the Driftless Area. The connectivity between uplands and river corridor has resulted in the significant accumulation of PSA along the base of hillslopes, especially on the headwater floodplains (Grimley et al., 2017). A buried pre-settlement soil is easily observed in lower parts of the Clear Creek valley, where PSA in terrace-like features has been incised. PSA is visually distinct from the underlying alluvial and glacial sediment, indicating that the incision of the uplands extends below the A-horizon. We find roughly an order of magnitude increase in sedimentation rates since European settlement – a result consistent with post-settlement increases in the Driftless Area (Grimley et al., 2017). More recent decreases in sedimentation rates are attributed to changes in land-use practices, erosion of the entire easily erodible part of the soil profile from the uplands, and incision of the PSA by streams, limiting further deposition on the terrace surface. Overall, this integrated response to intensive agricultural activity was facilitated by the high degree of connectivity between near-surface critical interfaces of the uplands and the river corridor which facilitated sediment transport from agricultural fields into channels.

Absolute PSA sedimentation rates in the USRB are about half those in Clear Creek or the Driftless Area, considering similar valley widths (Grimley et al., 2017). Three factors that may explain the lower PSA sedimentation rates in the USRB are (1) thinner and finer-grained (less erodible) loess deposits, (2) lower relief, and (3) a greater degree of disconnection of upland sediment sources from channels. In the USRB, PSA is generally not visually distinct from pre-settlement soils, reflecting a large component of resedimented A-horizon material from thick upland prairie soils. There is no clear signal of incision of the PSA in the main stem of the Sangamon River where PSA continues to accumulate on the modern floodplain. While the USRB is similar to other areas in the Central Lowlands, in that we observe an order of magnitude increase in sedimentation rates following settlement, it does not show an obvious impact on sedimentation rates with changes in post-1930s land use/management including increases in tile drainage, increasing presence of soybeans as a crop, and soil conservation efforts. As in other Central Lowland rivers, PSA thickness in the USRB scales with valley width suggesting that accommodation space is important in determining volumes of storage. The low rates of PSA sedimentation suggest that the connectivity between the uplands and channels following human alterations remains low in the USRB relative to other watersheds in more high-relief portions of the Midwest. However, the order of magnitude increases in accumulation rate following agricultural development is consistent with magnitudes of increase in high-relief environments. The lack of incision of the PSA could indicate that the timescale for adjustment to agriculture is longer in the USRB than in the more highly dissected landscapes of Clear Creek and the Driftless Area, or that the amount of disturbance is not sufficient to induce adjustment. Lack of sensitivity to changes in more recent land use practice reflects the lack of connectivity between uplands and the channel – even if soil conservation practices changed sediment movement on the uplands, that signal may not have propagated to the river system.

In considering the deposition of PSA, it is important to consider the connectivity between sediment transported within the river channel and diffusion or advection of this sediment onto the floodplain during storm events. This connectivity hinges on the extent to which sediment-laden water from the channel is conveyed onto the floodplain. Mapping of flow pathways at different water stages using high-resolution lidar elevation data to build detailed numerical models to simulate channel-floodplain connectivity along many lowland meandering rivers, such as the Sangamon River, reveals that these connections are more complicated than previously suspected (Lindroth et al., 2020). The delivery of water and sediment to floodplains is often confined along discrete flow pathways. Deposition on the floodplain is spatially variable with the greatest deposition observed in areas proximal to incised channels that convey sediment-laden water across the floodplain (Arnott, 2015). These findings indicate that the accumulation of PSA has the potential to be spatially variable due to patterns of connectivity between uplands and channels and between channels and their floodplains.

#### 2.3.2. Landscape connectivity and sediment sources to channels

We conducted sediment tracing studies to identify sediment sources to rivers at the event timescale and evaluate the importance of landscape connectivity in influencing sediment delivery to streams. In Clear Creek, upland sediment sources are contributing to in-channel suspended sediment loads for both large and moderately sized events. The V-shaped morphology of the stream valley in the headwaters leads to greater connectivity between hillslopes and the channel. Within the South Amana subbasin in the Clear Creek watershed, the sediment delivery ratio (SDR) decreases from >0.9 for the hillslope scale (<1 $km^2$) to ~0.2 for sub-drainage areas of 10–20 $km^2$ based on a soil erosion model (Abaci and Papanicolaou, 2009). Soil erodibility is amplified by agricultural activity (Abaci and Papanicolaou, 2009; Blair et al., 2021; T Hou et al., 2018; Hou et al., 2020b; Kim et al., 2020; M. Li et al., 2020; Rose et al., 2018; Xu et al., 2019). As the watershed widens to a U- shape downstream, eroded surface soils are more likely to be intercepted by the lower gradient portion of the landscape (Abaci and Papanicolaou, 2009; Ferro and Minacapilli, 1995). Sediment delivery ratios are ~0.1 based on the model extrapolations, approximately half of what is estimated for CCW (Abaci and Papanicolaou, 2009). As a result, the local surface soil inputs to the channel are attenuated. Row crop cultivation also decreases from the upper reach to the lower reaches. Collectively these factors contribute to the decrease in importance of local surface soil inputs relative to other sediment sources such as bank erosion (Blair et al., 2021; Kim et al., 2020; Papanicolaou et al., 2017; Sutarto et al., 2014). Hillslope responses are variable below a threshold and above the threshold transport is uniform across particle sizes.

In the USRB, sediment tracing studies indicate that the near-surface critical interface of the uplands is not well connected to the river-corridor critical interface of the main Sangamon River valley with few transport pathways for sediment present. Two studies of sub-catchments find little contribution from uplands and large contributions from near-channel sources in naturally meandering reaches (Neal and Anders, 2015; Yu and Rhoads, 2018). They do not find upland contributions from ditched reaches, suggesting that upland sediment is effectively disconnected from ditched streams. Disturbance by cattle grazing contributes significantly to in-channel sediment, although cattle grazing is a minor land use within the basin. These studies did not capture a large-magnitude event, and this remains a target for future work. Carbon isotope ratios ($^{13}C/^{12}C$) of particulate organic carbon in river suspended sediment collected during a storm event signal the input of eroded row crop soils (Blair et al., 2018) (see also Section 5.3). Corn, a C4 plant, results in a $^{13}C$-enrichment in the soil and is a large-scale tracer for surface soil inputs. A similar $^{13}C$-enrichment was observed in Lake Decatur sediments, which lie at the terminus of the USRB (Blair et al., 2018). These observations indicate some degree of connectivity between agricultural fields and the river. The connection may exist as a series of erosional-depositional steps that are either more frequent or longer (or both) during especially wet periods (Blair et al., 2022) (see also Section 5.4).

The differences in connectivity between Clear Creek and USRB have created differences in the response to intensive management and suggest the need for different best management practices. In Clear Creek, the tight coupling of uplands to streams indicates that reducing sediment transfer from uplands to streams requires the management of hillslopes. Specifically, grassed waterways and contour plowing techniques reduce sediment transfer. In the USRB, by contrast, careful management of near-channel land use is indicated as a way to reduce in-channel sediment loads derived from channel banks. Specifically, reducing grazing near stream channels and maintaining forested riparian corridors, where possible, is indicated. However, the response of the USRB to low frequency, high magnitude events remain a critical knowledge gap. The dynamics of USRB when thresholds for connectivity (i.e., connection of water from closed depressions, connection of roadside ditches and hillslopes) are exceeded, and fluxes of material from hillslopes to river corridors dramatically increase, may account for a significant fraction of the transfer of sediment and carbon. Evaluation of threshold-related changes in connectivity remains a major objective of future work in the USRB.

Connectivity (or the lack thereof) across critical interfaces between uplands and streams is not only important for determining sediment fluxes at watershed scales, but also has critical implications for understanding carbon fluxes. A considerable amount of particulate carbon transport occurs in conjunction with sediment flux. The section 5 of the paper explores this issue in detail.

## 3. Near-surface critical interface controls on lateral and vertical fluxes

The near-surface interface is the site of biogeochemical transformations in addition to material and energy fluxes in IMLs. These processes occur from the scales of soil aggregates, the fundamental units of soil structure, to the landscape-scale spatial heterogeneity induced by crop types and agricultural practices. Between these scales, microtopographic depressions underlay features of soil aggregates and vegetation types, and further exert controls on soil moisture dynamics, streamflow, and vertical land-atmosphere fluxes of heat, carbon, and water. Through our IML-CZO research, we have explored the role of anthropogenic activities overlaid on geologic landscape legacies on near-surface processes, and characterized thresholds that dictate these processes at the near-surface critical interface which spans multiple scales.

### 3.1. Soil aggregates and surface roughness

The interactions of rainfall and management with the soil structure and the microbiome of the critical zone are dominant controls on energy and water partitioning at the scale of soil aggregates, i.e. soil particles made up of mineral-organic matter associations (Fig. 5). Aggregates are particularly vulnerable to agricultural management and mechanical breakdown due to raindrop impact. The breakdown and subsequent re-aggregation of soil aggregates can be a critical factor in controlling spatial heterogeneity in soil biogeochemical reactivity and the ability of soil to provide critical services for agriculture (Papanicolaou et al., 2015a). The vulnerability of soil aggregates to rainfall and management is reflected in the soil aggregate stability index. Larger aggregates have a wide range of stability values but are generally less stable, while smaller aggregates are more stable and tend to have higher concentrations of SOM due to higher specific surface area (K. M. Wacha et al., 2020). Soil surface roughness evolves in response to rainfall, indicating feedback where hydrologic response and surface evolution are interrelated. It has previously been shown that rain drops decrease the microroughness of a bare soil surface in an agricultural landscape (Potter, 1990; Vermang et al., 2013). However, in areas where the influence of rain splash exceeds that of runoff, our studies have found that the soil surface roughness exhibits a consistent increase under different rainfall intensities, due to different initial roughness conditions (B. K. B. Abban et al., 2017). Initially smooth soil surfaces, with microroughness length scales <5 mm, which are typical of fields under no-till management, behave differently from surfaces with initial roughness magnitudes in

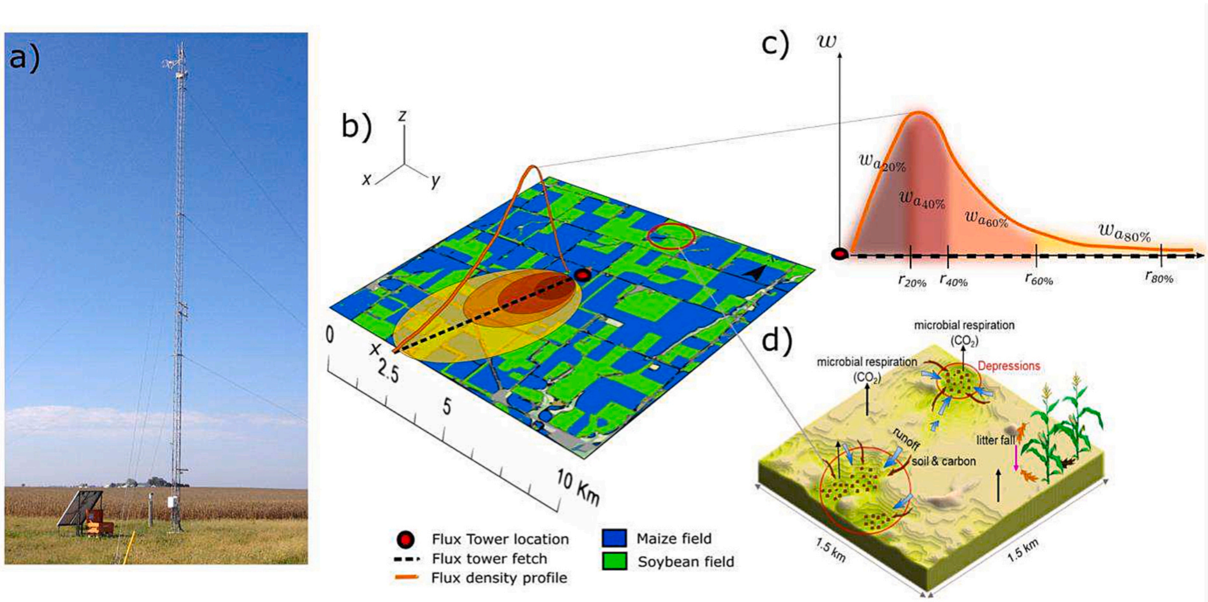


**Fig. 5.** An eddy-covariance flux tower (a) measures heat, water, and carbon fluxes at the near surface interface. (b) Each observation is dependent on a dynamically changing flux footprint, or upwind contributing area. (c) This contributing area is comprised of a potentially heterogeneous landscape in terms of crop type, topographic depressions or other landscape attributes. (d) Illustration of processes affecting near surface fluxes within a landscape patch.

the range of 5–50 mm that are more typical of tilled surfaces. This suggests that there is a threshold roughness below which surface roughness increases due to raindrops, while above it, surface roughness decreases. Additionally, our studies have found that aggregate stability is inversely proportional to the degree of agricultural disturbance (K. M. Wacha et al., 2018). Models that do not account for these aggregate breakdown mechanisms could lead to significant errors in spatial redistribution estimates of SOC at the hillslope scale, which can propagate to larger scale estimates of fluxes at the near-surface critical interface.

Other types of roughness present along a hillslope include soil clods, isolated elements (e.g., residue, corn stalks), and vegetation, which have a profound effect on flow partitioning between runoff and infiltration, runoff timing and magnitude, soil mobilization, and deposition (Papanicolaou et al., 2018). It has been found that the removal of vegetation from the landscape that leaves a bare surface or a surface with only isolated roughness has a more pronounced effect on the shape and magnitude of the runoff hydrograph than the effects of profile curvature. However, there is a threshold, dictated by hillslope gradient and storm magnitude, beyond which these different roughness types no longer influence the runoff hydrograph. Oriented roughness, which is introduced by tillage, is compounded on the soil surface roughness, and has also been shown to affect runoff, sediment, and carbon enrichment (K. M. Wacha et al., 2018). Elements of oriented roughness along topographic contours and perpendicular to the flow tend to act as small check dams leading to a decrease in connectivity. Meanwhile oriented roughness elements that are parallel to the flow help confine and concentrate the runoff, resulting in increased connectivity (K. M. Wacha et al., 2020).

Both the break-down and build-up of soil aggregates can occur interchangeably following rain events and associated soil wetting-drying cycles. A study of soil aggregate turnover using rare earth element tracers in a field in the USRB showed that the proportion of larger aggregates decreases relative to smaller aggregates following an initial series of rain events with relatively high rain power, suggesting the occurrence of net breakdown in larger aggregate fractions due to raindrop impact and air slaking (Zhou et al., 2022). After a subsequent drying-wetting cycle of the soil, there was a formation of large macroaggregates due to increased particle binding caused by clay shrinkage upon soil drying and microbial/crop root growths upon rewetting of dried soil. In addition, small macroaggregates tend to turnover faster than extra-large macroaggregates and free particles potentially due to their higher SOC content (Zhou et al., 2022). Thus, SOC residence time in IMLs is controlled by the interactions between crops, microbes, soil, topography, management, and weather which collectively affect reaction times and the transformation of plant C and N to microbial necromass, SOM storage, and $CO_2$ exchange. Aggregate dynamics (i.e., breakdown, stabilization, and aggregation) control carbon release and storage inside soil aggregates, thereby affecting the abundance and distribution of SOC (section 5.1).

### 3.2. Hillslope and topographic depression controls

Microtopographic features and human modifications to drainage (Figs. 3,5) are dominant controls on streamflow generation (Dunne et al., 1991; Frei et al., 2010), soil moisture dynamics (Simmons et al., 2011), and vegetation patterns. This is primarily due to the altered persistence and variability of moisture dynamics in the system (Le and Kumar, 2014). For example, the hydrologic residence time of moisture in topographic depressions is significantly longer than the travel time of overland flow or channel flow in a similar landscape setting without depressions, thus increasing surface-subsurface interaction. Additionally, SOC concentrations were found to be 18–27% higher in depressions than surrounding areas due to the combination of increased deposition and decreased decomposition, indicating that microbial decomposition of SOC is likely suppressed under elevated soil moisture and anoxic conditions in those areas (H. Li, 2020). This results in a multimodal distribution of SOC with twice the spatial variability relative to a more sloping landscape with few depressions. The control of landscape topography on SOC distribution patterns across the landscape contribute to variable areas of $CO_2$ releases from the soil. While topographic depressions retain moisture and lead to higher SOC concentrations in soils, channelization in IMLs increases hydrologic connectivity and water transport, and tile drains quickly remove excess moisture and thus reduce soil moisture residence time. Further, preferential flow paths through soil fractures create subsurface channelization to tile drains, which provide rapid transport pathways and enhance surface-subsurface connectivity. Tile drains considerably modify the age of water and nutrients and their spatial heterogeneity within the system relative to the pre-settlement landscape (Woo and Kumar, 2016, 2017). Studies on the USRB have shown that the removal of water and nutrients from the subsurface through tile drains reduced the water and nutrient ages by ~700 days and nitrate age by ~500 days, respectively, compared to cases without tile drains (Woo and Kumar, 2019). In other words, water and nutrient transport processes have been accelerated and intensified due to subsurface drainage.

Geomorphic micro-features at the near-surface interface, such as surface seals and crusts, headcuts, and incision/depositional zones, develop and disappear during rainfall-runoff events due to combinations of roughness and erosion mechanisms that vary in space and time. These transient features in IMLs alter flow-pathway connectivity, enhancing unsteadiness in runoff and sediment fluxes. Micro-headcuts also affect the distribution of soil wetness and "regulate" SOM redistribution through preferential enrichment and deposition along a hillslope, with implications to the vertical distribution of SOM and the resulting soil porous structure. Our studies have found that the evolution of transient geomorphic features, which occurs predominantly during the initial, unsteady parts of a rainfall-runoff event, can contribute as much as one-third to the observed fluxes of water and sediment (Blair et al., 2021). Headcut genesis and retreat result from the combination of flow concentration, turbulence, high upstream sediment supply, and low transport capacity of flow. Discontinuities in bed elevation due to headcuts are mostly seen at the rill initiation locations, where there is a transition from rainsplash to flow-dominated transport. Drainage network self-organization through the genesis and evolution of headcuts gives rise to a temporal lag between flow and sediment and a hysteretic behavior in the sediment rating curve that reflects the dominance of distinct sediment entrainment mechanisms between unsteady and pseudo-steady timescales (Blair et al., 2021).

### 3.3. Landscape heterogeneity and drainage network controls

Topographic features such as hillslope gradient, curvature (Dunne et al., 1991), and size distribution of depressions exert significant control on the partitioning of rainfall into surface runoff and infiltration. In this way, topography influences SOC heterogeneity through transport, or erosion and deposition, and transformation, or stabilization and decomposition. This is well illustrated in two of our study watersheds that differ substantially in topographic characteristics (Fig. 2). The Clear Creek watershed has a rolling topography and well-connected drainage environment. The runoff exhibits high stream power and enhances erosion-induced carbon mobilization, which translates to more SOC mobilization and mixing of soils from different areas. This mixing leads to a more uniform SOC signature across the landscape. In contrast, the USRB is a low-relief, poorly connected drainage environment, where the number of upland depressions and their areal density exceed those in Clear Creek by an order of magnitude. This high density of upland depressions impedes the connectivity of surface runoff. The surface water and transported sediment deposit accumulate in the depressions, leading to large differences in soil moisture and carbon between depressions and surrounding areas.

Microtopographical and larger-scale landscape features are blanketed by a patchwork landscape of rotating maize and soybean row-crop agriculture in the midwestern US (Fig. 2). We refer to this landscape feature as "organized land cover heterogeneity" (Hernandez Rodriguez et al., 2023), where annually shifting spatial configurations of crops combined with variable planting and harvesting dates and agricultural practices contribute to ecosystem-scale fluxes of water, energy, and $CO_2$. We consider this organized heterogeneity to be a large-scale control of fluxes at the near-surface critical interface. In our research, observations from a tall eddy covariance flux tower (Fig. 5a) together with ecohydrological modeling (Drewry et al., 2010) show how the flux footprint (Kljun et al., 2015) or the upwind contributing area of the tower observation, captures this aspect of landscape variability (Fig. 5b,c). The patchwork of maize and soybean fields surrounding the tower results in fluxes that differ from what would be observed in either a monoculture landscape or a random distribution of crop types. In this way, annual changes in crop rotations in addition to constantly shifting atmospheric properties exert partial controls on observed land-atmosphere fluxes.

## 4. Role of root zone and shallow subsurface critical interfaces in nutrient dynamics

The shallow subsurface root zone, the zone of soil between the land surface and phreatic surface (natural or engineered), experiences unique patterns of fluid infiltration, movement, and drainage in concert with episodically changing vegetation root structures and processes that influence and optimize the soil microbiome in intensively managed landscapes. It is therefore identified as a critical interface. Tile drains quickly remove moisture from the shallow subsurface, carrying excess fertilizer, nutrients, and weathered solutes to receiving bodies of water. Residence times during which transformative processes like microbially-facilitated nitrogen fixation and decomposition occur are greatly reduced. Plant roots fundamentally regulate microbial activity and the movement and transformation of moisture and nutrients (Roque-Malo et al., 2020; Roque-Malo et al., 2022), and periodic land cover change with each crop season alters the shallow subsurface soil microbial biomass and its functioning depending on the vegetation present.

### 4.1. The role of tile drains

Tile drains create a highly altered sub-surface moisture environment by modifying hydrologic connectivity. In watersheds with limited anthropogenic influence, runoff patterns can generally be understood given knowledge of precipitation events and antecedent soil moisture conditions. However, in tile-drained landscapes, runoff events are influenced by antecedent shallow soil moisture, antecedent below-tile soil moisture, and precipitation (Cain et al., 2022). Cain et al. (2022) found that subsurface nitrate transport is generally dependent on runoff, while within-event concentration-discharge relationships are driven by precipitation intensity and duration as well as antecedent tile flow.

While we recognize that residence times in tile-drained systems are greatly reduced, residence time estimates are better suited for systems in quasi-equilibrium. For transient systems, examining solute spatial distribution and age helps elucidates more complex pathways taken by reactive constituents like nitrogen whose chemical species (i.e. nitrate, ammonia, and ammonium) vary in solubility, mobility, and reactivity through the soil matrix (Woo and Kumar, 2016). For example, Woo and Kumar (2017) determined through nitrate concentration-age simulations that low-lying areas classified as topographic depressions are hotspots for denitrification and leach more nitrate than other areas of the landscape. In topographic depressions, the age and concentration of nitrate are low. However, this does not remain true for mobile ammonium, which exhibits low concentrations and higher age. This difference between nitrogen species is due to cation exchange, which partitions ammonium into mobile and immobile pools, increasing the age of mobile ammonium while nitrate is lost through leaching and denitrification. Furthermore, Woo and Kumar (2019) demonstrated that tile drains reduce the age of nitrate in the soil. Like the case of topographic depressions, the age of mobile ammonium in the soil is higher than nitrate but when considering tile drain efflux, a different pattern emerges. They determined that nitrate in drainage flow is initially younger, most likely freshly derived from fertilizer and mineralization. However, after the peak of tile discharge, the drainage flux carries away older nitrate (Fig. 6). This older nitrate is likely a product of nitrification when mobile or immobile ammonium, the latter of which is the oldest among nitrogen species, is converted to nitrate. The age of nitrate in drainage flow ranges from 1 to 3 years, while that of mobile ammonium is less than a year. This unexpected result from age analysis reveals a built-in time lag in nitrogen dynamics that can be used to improve nitrogen loading

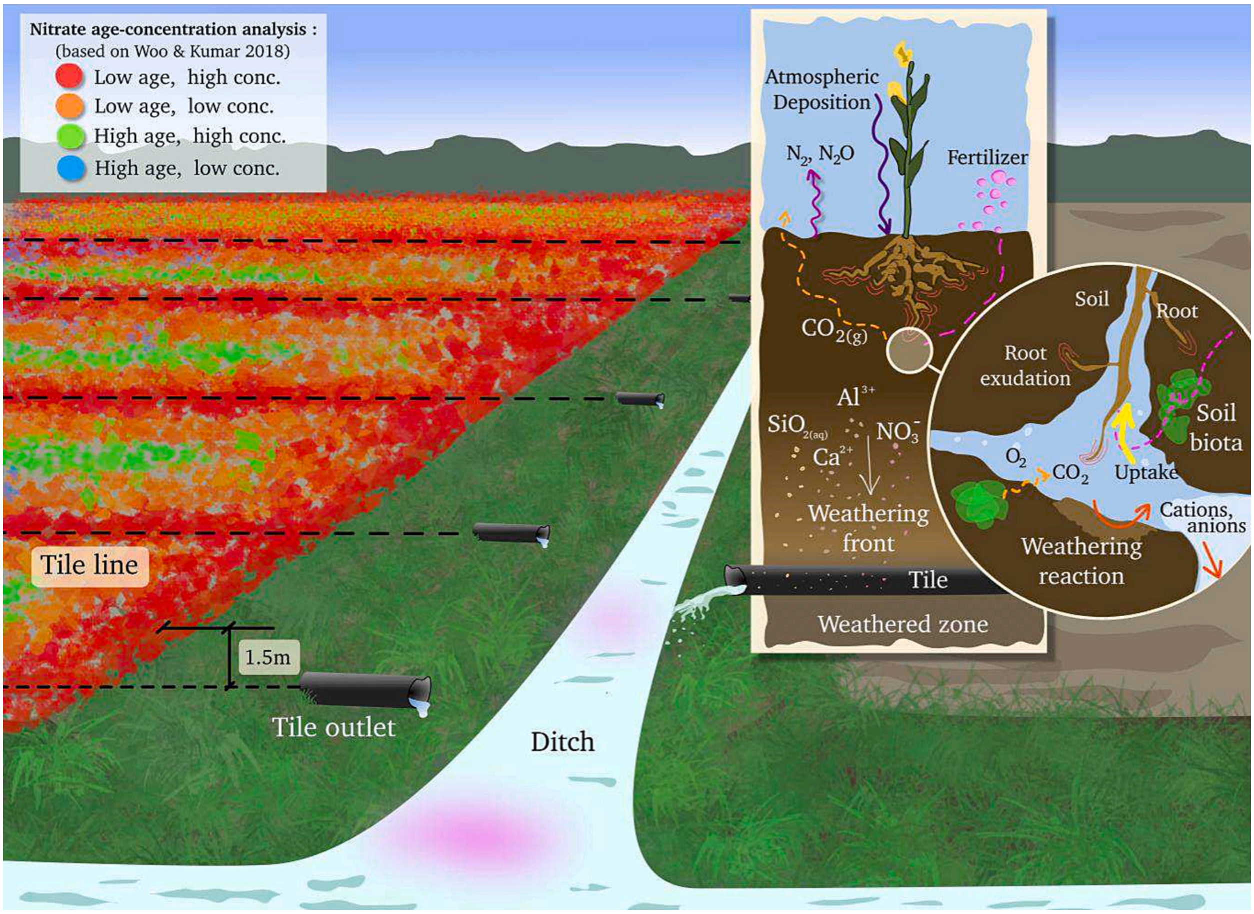


**Fig. 6.** Illustration of nutrient dynamics influenced by tile drains (left) and root exudates (right). Tile drains alter the moisture and associated flow patterns across the landscape which affects the spatial variability of age and concentration of nitrate (and other nitrogen species, not shown). Root exudates alter the microbial dynamics and sub-surface biogeochemistry and transport of solutes.

mitigation plans. While nuanced concentration-age analyses shed light on nitrogen dynamics that may not otherwise be captured, the data necessary to validate such simulations are not yet available and presents a frontier to be explored.

### *4.2. Root zone processes*

Vegetation helps modulate solute dynamics and influences microbial action through root exudation, the process by which plants secrete a variety of organic compounds to influence and optimize their immediate geochemical environments. These compounds vary widely depending on vegetation type and the plant's nutritional or other needs. Roque-Malo et al. (2020) modeled the transport dynamics of root exudates including glucose, a polysaccharide that directly fuels microbial biomass growth, and flavonoids, a type of biological nitrification inhibitor. They developed the REWT (Root Exudation in Watershed-scale Transport) model, the first of its kind to offer prognostic capabilities regarding vegetation-driven hydrobiogeochemical dynamics. These simulations indicated that the explicit consideration of root exudation in shallow subsurface biogeochemistry can result in dramatic differences in the estimation of both microbial biomass and solute export. For example, these simulations indicated that flavonoid exudation can reduce the concentration of nitrate that reaches tile drains by up to 16% when corn crops are present and 14% when soybean is present (Roque-Malo et al., 2020).

Because root zone processes vary depending on the type of vegetation that is present, land cover changes can result in consequential changes in long-term soil health and soil formation through weathering and ultimately influence the chemistry of streams draining watersheds. This is important when considering historical land cover change from native prairie to intensively managed agriculture and to higher-frequency crop rotation patterns. Coupled simulation of REWT to reactive transport using CrunchFlow (Steefel et al., 2015) demonstrated that root-sourced reactive C can augment or reduce solute concentrations in the soil by several orders of magnitude and over time influence the formation of weathering fronts. Direct measurements of soil porewater chemistry in CCW revealed higher concentrations of Ca and Mg in the upper 1 m of agricultural soils compared to restored prairie soils, likely due to enhanced weathering in the agricultural soils (Dere et al., 2019). Not only were similar solute patterns observed in agriculture and restored prairie soils at a comparable (but slightly drier) study site in Eastern Nebraska, but higher Ca and Mg concentrations were also measured in streams draining the different land uses, highlighting that land management effects in the shallow subsoil critical interface can influence stream chemistry (Dere et al., 2019). Furthermore, the prairies studied in CCW and Eastern Nebraska were restored from agriculture ~20–50 years ago, indicating that vegetation and management changes in the root zone can significantly impact soil and stream chemistry on relatively short timescales in these dynamic landscapes.

## 5. Carbon dynamics across the critical interfaces

There have been substantial debates on the role of organic carbon (OC) redistribution during land use as a net atmospheric source or sink, global estimates of which range from $-1$ Pg C $yr^{-1}$ to 1 Pg C $yr^{-1}$ (Doetterl et al., 2016; Lal, 2004; Van Oost et al., 2007). The substantial uncertainty in the land use C budget stems from the temporal-spatial complexity of landscape processes as described in previous sections in combination with the chemical complexity of carbon. Carbon is unusually flexible in its molecular bonding properties relative to other elements allowing it to exist in a myriad of molecular species and in all fundamental physical states, gases, liquids, and solids under environmental conditions. Its elemental permanence in its stable isotope forms ($^{13}C$, $^{12}C$) contrasts greatly with its ability to be seen aging by virtue of its radioisotope, $^{14}C$. Molecular species can thus be soluble or insoluble, young or old, reactive or nonreactive, all characteristics that contribute to diverse behaviors and fates. Our simplistic reference to C as a single or fully integrated entity (as in the "C-cycle") omits details that can provide constraints on budgets. The analogy that we use is that we tend to view C as an integrated or 'white light' form composed of its many spectral (molecular) constituents. A more nuanced picture is attained with the resolution of the constituents, as nature often does, to reveal the "rainbow" of characteristics and behaviors. The C-rainbow concept provides a means by which to tease apart critical interface processes. In this section, examples are provided of how C-mixture components are separated (the "prism" effect), mixed and transformed via interactions with critical interfaces.

### 5.1. C-erosion from the hillslope near surface interface

Soil erosion by rain splash and overland flow on the loess mantled hillslopes under tillage is a major factor controlling soil OC redistribution and loss in the Upper Mississippi River Basin (Papanicolaou et al., 2015a). The downslope erosional flux of soil OC, while a critical parameter to measure (Berhe et al., 2012; Doetterl et al., 2016; Kleber and Johnson, 2010), is not the only factor to consider when describing the fate of eroded materials. Most of the current biogeochemical models for soil C flux and distribution, to some extent, successfully simulate soil OC fluxes (Papanicolaou et al., 2015a; Van Oost et al., 2007; Yan et al., 2019). However, hillslope erosion processes typically are considered passive pathways where delivered materials are thought to remain chemically and/or structurally the same as their source and decay at a certain rate (Doetterl et al., 2016). A new perspective is to view hillslope erosion processes as a *"prism"* that resolves or filters OC compositions (Fig. 7, upper left), which results in the preferential transport of specific soil aggregates possessing differing OC compositions.

In addition to direct mechanical fragmentation of the aggregates by tillage, soil aggregates in IMLs are at increased risk of disaggregation by runoff and raindrop impacts, as soil lacks plant cover for over half of the year (Hu et al., 2013). This raindrop-induced disruption of aggregates can result in local depletion of soil organic matter as organic fragments, both free and clay/silt-bound, are detached from the larger protective aggregate structures, redistributed across the landscape, and exposed to microbial-driven degradation (K. Wacha et al., 2014). The physicochemical differences between the liberated and mobilized material and the residual raindrop-stable soil aggregates can be a critical factor in controlling landscape-level heterogeneity in soil biogeochemical reactivity. The results from artificial rainfall experiments on Clear Creek soils indicate that exposed soils from landscapes that are under long-term prairie restoration will produce particles roughly reflecting the mean geochemistry of the surface soil, while soils from landscapes under intensive tillage will liberate relatively more particles that are depleted in soil OC (SOC), total nitrogen (TN), and with organic geochemistry reflective of compounds that have undergone relatively greater microbial processing compared to the initial soil (T Hou et al., 2018; Hou et al., 2020a). The difference between the two scenarios reflects

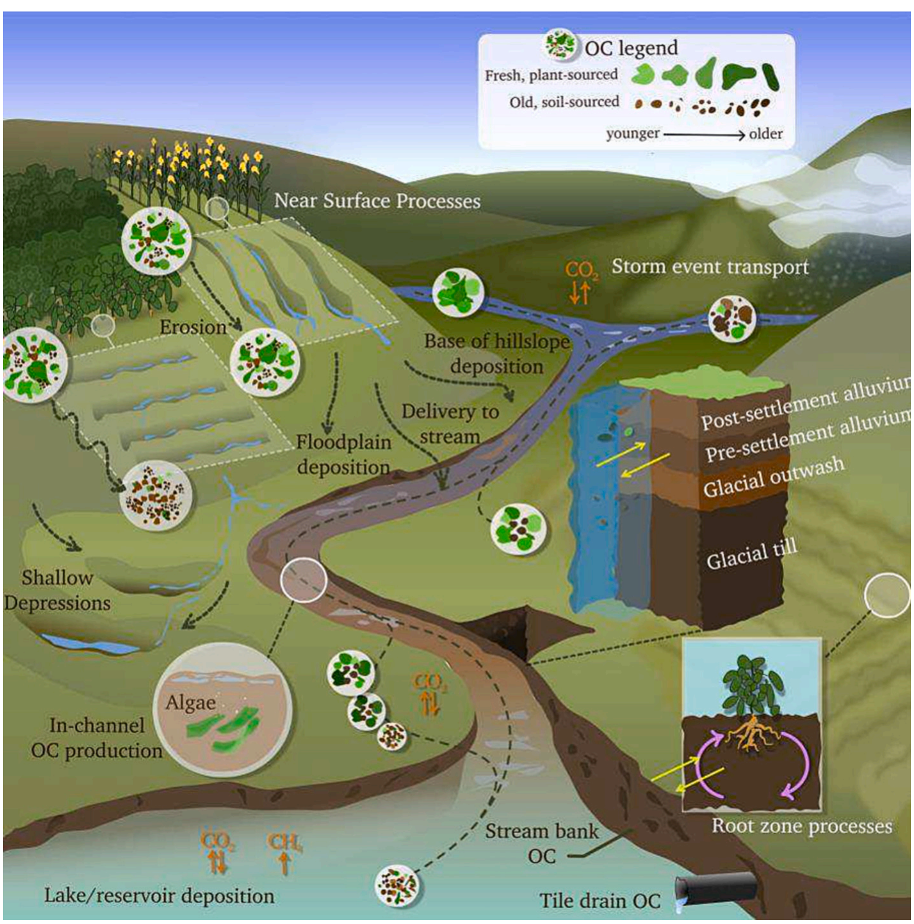


**Fig. 7.** Carbon's rainbow from a landscape perspective. The various forms of organic C, including relatively fresh plant debris and highly degraded soil OC, are resolved and re-integrated by processes within a watershed. Microtopographic processes, such as associated with tillage perpendicular to the hillslope (upper left), can hydrodynamically sort particles thereby filtering out the larger and fresher plant fragments. Floodplains trap fluvial materials, promote reaction (primary and secondary production/weathering/diagenesis), and then release them over timescales reaching millennia. The Root Zone is an important reactor that transforms OC across the landscape.

preferential transport of fines that contained more degraded OC by till-roughened surfaces.

The rainfall simulation experiments also revealed that tillage-induced, oriented roughness controls the amount and organic geochemistry of soil particles mobilized downhill (B. Abban et al., 2016; Hou et al., 2020b; K. M. Wacha et al., 2018). The average discharge rate of mobilized sediment was nearly 30-fold higher when the tillage orientation was parallel to the runoff direction compared to when the tillage orientation (i.e., contour tillage) was perpendicular to the runoff direction. Mobilized particles under contour tillage were higher in organic carbon (OC) content and were relatively less decomposed, based on lignin chemistry, compared to analogous particles under the parallel tillage orientation (Hou et al., 2020b). Contour tillage increased the deposition of denser particles within the furrows and increased the release of the finer, lighter, and organic-rich material during over-spilling and contour breach (Fig. 7) (Papanicolaou et al., 2018).

The mechanical mixing due to tillage reshapes the vertical profiles of soil OC and therefore alters the rates of biogeochemical transformation. The reshaped profiles affect the heterotrophic carbon loss, defined as the carbon loss in soils through microbial decomposition, by reducing the amount at erosional sites and increasing the amount at depositional sites (Yan and Kumar, 2021). The reason is that after homogenizing the near-surface soil OC content, at upland erosional zones, the surface soil OC content is reduced, but below-surface soil OC contents are increased. The burial of more soil OC slows down the decomposition rate. However, at downslope depositional zones, before mechanical mixing, the surface soil OC content would be lower than values below-surface due to rapid burial of soils removed from erosional sites (Yan et al., 2019), then after the mechanical mixing, the surface soil OC content could increase and therefore, increase the decomposition rate. In general, the mechanical mixing reduces the heterotrophic carbon loss and favors the OC storage in erosional zones but increases the heterographic carbon loss and reduces the OC storage in depositional zones.

### 5.2. The downslope near surface interface – the balance between OC erosion and deposition

Over a broad range of time scales, surface soil organic C processes are strongly influenced by soil erosion, deposition, and the development of landscape macro/microtopography (Papanicolaou et al., 2018; Papanicolaou et al., 2015a). Through the natural coevolution of geomorphic, pedogenic, and ecological processes in the critical zone or by punctuated changes in these processes as a result of intensive management, dynamic landscapes establish characteristic hierarchies of physicochemical controls on organic matter stability (Kumar et al., 2018; Wilson et al., 2018). These processes have been studied with investigation of the spatial patterns of static surface soil properties to document how the organic geochemistry of hillslopes, under land managements from row crop to restored prairie, are currently evolving, and how they might have evolved during management of the early to middle 20th century and pre-settlement. For a watershed with rolling topography like Clear Creek, hillslope gradient was negatively correlated with soil organic C and accounted for most of the variation. Through erosion and deposition, lower SOC concentrations were found near the summits and higher levels were at the toe slopes. In depositional zones, SOC vertical profiles are found to have a 'nose'-like shape below the surface due to the accelerated soil deposition since the European Settlement (Yan et al., 2019). This contrasts with a generally accepted exponential decrease along soil depth in natural areas. In low-relief fields pocketed with depressions (i.e. Upper Sangamon River, IL), soil moisture and bulk density were positively correlated with SOC (M. Li et al., 2020; K. M. Wacha et al., 2018).

A Dynamic Wetness Index (DWI) that accounts for the persistence of soil moisture over time at the microtopographic scale shows a positive correlation with indicators of lignin oxidation, indicating that wetter soils have higher potential for lignin decomposition (M. Li et al., 2020). Both lignin and substituted fatty acid concentration and their molecular ratios highlighted differences in $C_3/C_4$ (soy/corn) management activities in surface soils while over 40 years of prairie restoration dramatically altered surface soil profiles. For example, a general pattern in static baseline samples was an $^{15}$N-enrichment of soil particulate N down slope and an opposite pattern of accumulation/loss of lignin and carboxyl-substituted fatty acids (SFA) in topographic highs and lows (T Hou et al., 2018).

Biogeochemical transformation shows opposing behaviors in erosional and depositional zones. A process-based quasi three-dimensional modeling provided insights into the evolution of soil OC from eroding hillslopes to depositional settings (Yan et al., 2019) successfully illustrating the importance of connectivity within a system. This model couples surface runoff, soil moisture dynamics, biogeochemical transformation, and landscape evolution; and provides a depth-resolved simulation of the SOC cycle. The balance between OC accumulation and loss via microbial oxidation varied with location. The rate of soil organic C decomposition is slower than gain from plant residues in erosional zones which also serves as a net atmospheric C sink, and vice versa for depositional zones, which is generally a net C source with respect to the atmosphere (Yan et al., 2019). Trapping eroded material at the base of hillslopes could create a carbon sink. Moreover, in depositional zones, the influx of carbon includes local plant inputs as well as soils eroded from upslope, which exceeds decomposition of OC (regarded as heterotrophic carbon loss) by a greater amount than in erosional settings. Even so, the heterotrophic carbon loss exhibits the highest rates in topographic settings where net soil erosion and depositional rates are small, but the influx and efflux are high (Yan and Kumar, 2021). The rapid soil OC redistribution driven by soil erosion and deposition increases the land surface spatial heterogeneity of not only soil OC stock; but also, soil-atmospheric carbon exchange rate, and heterotrophic carbon loss. These results elucidate the nature of the control of buried soil C in floodplains across the Midwest and determine, in part, the burial and preservation of soil C versus its conversion to atmospheric $CO_2$.

### 5.3. C-transport across the river corridor interface

Rivers and their tributaries have been portrayed in the C-cycle as both reactors that foster in-channel primary and secondary production, and conduits that transport material (Bouillon et al., 2009; Cole et al., 2007; Raymond et al., 2016). Rivers also integrate organic C (particulate, POC, and dissolved, DOC) with different ages and reactivity from in-channel production and the adjacent landscape. The mixture is then delivered to downstream depocenters and ecosystems, such as floodplains, lakes, and the ocean for further reaction and/or sequestration (Blair and Aller, 2012; Wohl, 2017). This network of processes operating within the river corridor is particularly susceptible to perturbation in terms of transformer-transporter balances (Kumar et al., 2018) and as such, has been identified as a key interface within the greater C-landscape and critical zone.

Storm events and land use greatly accelerate the integration and transport of POC and DOC. The C-cycle response to a storm is transitory in both time and space and is thus difficult to capture in detail (Blair et al., 2021; Kim et al., 2020). As part of the IML-CZO effort, the Clear Creek watershed was sampled at a nested series of stations through storm events to determine how POC and DOC change as functions of transport downstream and time. In acknowledgment of the inherent compositional complexity of the OC, a broad-spectrum approach was employed to characterize it, which included elemental and isotopic analyses (C/N, $^{13}C/^{12}C$, $^{15}N/^{14}N$) and compound-level measurements (lipids, lignin phenols, soil biomarkers). A temporal sequence of POC and DOC inputs was identified (Blair et al., 2021; Hassanpour et al., 2022; Hou et al., 2020b; Hou et al., 2023; Kim et al., 2020). Prior to the storm and during the early stages of precipitation, OC from in-channel algal production was dominant. This source was fueled via the eutrophication of this agricultural stream and is a good example of the system operating in transformer or reactor mode. The first indication of the transition to transporter mode occurred during peak precipitation when row crop surface soils, recognized by their $C_4$ plant (corn) C-isotopic signature, appear in the channel. A third and the most dominant peak of OC is closely correlated with discharge. This material is an integrated product from upstream (Fig. 8). Similar discharge-dependent and -independent behaviors for suspended sediment transport have been seen in the small agricultural watershed of Plum Creek, Wisconsin (Rose and Karwan, 2021).

The envelope of the OC peaks became more complex as the storm pulse moved downstream due to the additive contributions of multiple tributaries and the hypothesized increasing importance of alluvial bank erosion (Fig. 8) (Kim et al., 2020). This increasing bank contribution is attributed to a systematic transition in basin geomorphology from a V-shape in the upper reach to a wider box-shaped valley in the lower reach as described in section 2.3.3 (Yan et al., 2018). Storm intensity and trajectory, along with seasonal factors appeared to induce variability in the particulate organic C sources, concentrations, and yield from the landscape (Blair et al., 2021).

### 5.4. C-sequestration and emissions in the river corridor interface

Humans have accelerated the erosion of the critical zone by 3 to 5-fold, and in doing so have perturbed nearly half of the land surface globally (Amundson et al., 2015; Hooke, 2000; Wilkinson and McElroy, 2007). Most of the disturbance has been driven by deforestation and tillage and these activities often lead to substantial local losses of OC (Lal, 2003; Papanicolaou et al., 2015b). The eroded material is redistributed across the landscape to depositional sites broadly characterized as 1) colluvium and alluvium deposited at the base of hillslopes or in closed depressions, 2) sediments transported fluvially and deposited in channels or on floodplains as alluvium, and 3) sediments trapped by lakes and reservoirs (Meade et al., 1990; Stallard, 1998). <10% of the eroded soil and its C is thought to escape the continental land mass to be exported to the ocean (Meade et al., 1990; Stallard, 1998). The distribution of OC, and thus potentially its subsequent behavior, is highly uncertain because there have been few comparable studies of depositional rates within the three general environments (Blair et al., 2018).

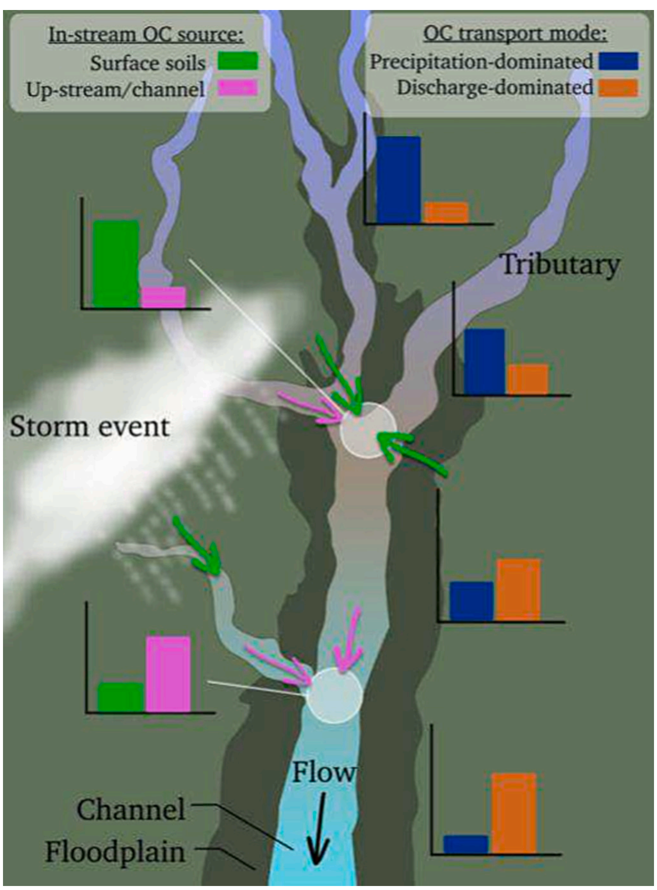


**Fig. 8.** Conceptual representation of the evolution of storm pulse OC from uplands to downstream. OC delivery and transport are closely associated with precipitation in areas where uplands are well-connected with the channel (blue bars). This is especially true when there is an ample supply of easily erodible surface soils, such as row-crop fields (green bars). OC transport is more closely tied to fluvial discharge downstream (orange) as material is delivered from upstream and bank erosion accumulates (pink). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

A preliminary assessment of the post-European settlement (~1850) depositional OC fluxes in downslope depressions, valley floodplain alluvium, designated as post-settlement alluvium or PSA (Grimley et al., 2017), and lacustrine reservoir sediments of the Upper Sangamon River Basin (USRB), has been performed for the first-ever comparison of the depocenters in one watershed (Blair et al., 2018, 2022), In general, OC accumulation fluxes support the hypothesis and prevailing view that deposition of eroded materials occurs primarily near to the source and attenuates with transport distance. Approximated 60% of the sequestered OC resided in glacial-derived depressions at the base of hillslopes, 34% on floodplains and 6% in Lake Decatur, a reservoir at the terminus of the watershed. The depositional record within the Lake Decatur reveals the episodic nature of the transport (Blair et al., 2018, 2022). Deposition intervals most dominated by row crop OC correlated with multi-year rainy periods. This illustrates one aspect in which the near-surface environment, and the various controls on erosion and deposition, serve as another critical interface within the critical zone C-cycle.

The fate of the OC does not end with deposition in Lake Decatur. Oxidation of the OC in the lakebed to dissolved inorganic C (DIC) results in either the burial and sequestration of that product or its escape to the overlying water (Blair et al., 2018). The anaerobic conditions of the lakebed facilitate methanogenesis as well. OC burial fluxes and methane formation rates positively correlate, which explains the spatial variability of methane concentrations and provides a predictive capability for methane emissions as reservoir sediment trapping and deposition change over time.

## 6. Dynamic connectivity, uncertainty, and predictability across scales

The scale-dependent controls that mediate relationships between drivers and fluxes of energy, water, and other material also have implications for predictability and uncertainty within and across scales. For example, variability observed in SOC concentrations within and around a micro-topographic depression may or may not be reflected in land-atmosphere carbon fluxes observed at the landscape scale. Through our research, we have framed questions related to predictability, uncertainty, and the propagation of fluctuations through a system in an information-theoretic context. Information theory is based on Shannon Entropy (Shannon, 1948), which quantifies the uncertainty of a random variable, such as a measured or modeled time-series. Mutual information, which can be estimated in lagged, multivariate, and conditional forms, measures reductions in uncertainty of target variables given the knowledge of sources and provides a mechanism to determine causal interactions within time series variables (Goodwell et al., 2020). Moreover, these "information flows" indicate a level of predictability of the target, given knowledge of a source variable, its lagged history, or multiple histories of multiple source variables.

Our studies have used information-based analyses to characterize interactions in several critical zone systems. At a weather station in a restored prairie site in the USRB, lagged interactions between weather variables, measured as joint mutual information, exist at very short timescales on the order of several minutes. These interactions take the form of unique, or individual, redundant, or overlapping, and synergistic, or joint, types of dependencies, which vary with weather conditions, with the diurnal cycle, and over a growing season (Goodwell and Kumar, 2017a, 2017b). In a cross-CZO study of eddy covariance flux tower sites along two elevation transects, we detect unique, synergistic, and redundant drivers of latent (LE) and sensible (H) heat fluxes (Goodwell et al., 2018). At the Reynolds Creek CZO in Idaho, flux magnitudes and associated drivers shift due to a summer rainfall event in a typically dry period, where increased information flows are observed during and after rainfall events. At the Southern Sierra CZO in California, a site that had a more extreme response to the 2012 drought, measured as reduction in LE, diverged from a second site in terms of dominant drivers of LE as the drought progressed. Specifically, LE at the site with a more extreme drought response became disconnected from variability in atmospheric drivers, while LE at the higher elevation site became disconnected from soil moisture and temperature variability. A causal history approach, which involves highly multivariate information measures in an directed acyclic graph, was applied to study stream chemistry dynamics, and showed that solute dynamics are driven by self-feedbacks at a short timescale, but cross-variable dependencies at longer lag times (Jiang and Kumar, 2019). Further development of "bundled causal histories" was used to reveal how cations and anions in a stream quality dataset synergistically and uniquely inform pH dynamics (Jiang and Kumar, 2020). Daily precipitation persistence, or patterns in space and time, has also been explored for watersheds throughout the continental US using a range of information-theory based measures (Goodwell, 2020; Goodwell and Kumar, 2019). High-frequency (10 Hz) eddy covariance multivariate observations collected at a flux tower, including wind speed, air temperature, and $H_20$ and $CO_2$ densities were used to investigate the causal structure of turbulence resulting from variable interactions and to gain insight into its evolution and functionality (Hernandez Rodriguez and Kumar, 2023a, 2023b). These information-based studies present novel methods to characterize different levels of causal interactions at critical interfaces in critical zones.

## 7. Summary

Our studies have highlighted the importance of critical interfaces in shaping landscape processes. Critical interfaces are transition areas between different landscape components and can include interfaces between the atmosphere and land surface, between hillslopes and river channels, and between the biotic-abiotic interfaces in the root zone. Critical interfaces serve multiple functions, including acting as transition areas for the transmission of material and gaseous fluxes, regulating the connectivity between material fluxes across the critical zone, functioning as loci of biogeochemical transformations, amplifying, or attenuating the strength of flux signals, controlling the time variability of material fluxes and biogeochemical activity, and synchronizing the co-evolutionary dynamics of different parts of the landscape. These interfaces can be natural, such as near land-surface depressions and floodplains, or human-made, such as tile networks and riparian buffers.

Anthropogenic modifications of the landscape related to agricultural development have fundamentally altered the structure and functional nature of critical interfaces due to changes in the spatial arrangement and increased spatial density of flow pathways, resulting in fast response times and strong coupling between water, sediment, and carbon fluxes, in some cases on decadal timescales. Sediment fluxes and sediment storage have increased as sediment mobilized in headwaters through runoff from tilled farm fields, effects of cattle grazing, and channel bank erosion moves downstream through roadside ditches, drainage ditches, and headwater streams into large rivers, where fine material accumulates on floodplains. Rates of overbank deposition on floodplains have increased 10-fold in comparison to pre-agriculture period, with both the absolute amount of floodplain deposition as well as the subsequent tendency for channel incision into accumulating floodplain deposits being directly dependent on landscape relief, loess thickness, and drainage density.

Sources of sediment in these IMLs vary in relation to landscape relief, the associated degree of dissection of the landscape by streams, and event magnitude. Upland soil erosion and bank erosion contribute sediment in highly dissected landscapes over a range of events, whereas near-channel sources, such as bank erosion associated with meander migration and cattle grazing, contribute the majority of sediment in low-relief landscapes, at least for high and moderate frequency events. Midwest landscapes, particularly those glaciated most recently, were characterized prior to intensive management by high-resistance, poorly defined, or even disconnected flow pathways that limited export of fluxes of water, sediment, and carbon. Occasionally, low-frequency, high-magnitude events overcame flux-limiting thresholds, resulting in large episodes of export through integration of flow pathways. Overall, however, landscapes included ample storage areas for water and sediment, which in turn served as bioreactors for facilitating biogeochemical transformations.

Root exudates from agricultural crops alter the rates of nitrification, respiration, and release of solutes through soil weathering. Topographic depressions, tile drain networks, and macropores in the soil structure the spatial variability of age-concentration dynamics of the sub-surface nitrogen cycle. Low concentration and age are associated with nitrate in areas of topographic depression even when tile drains are present, even though high concentration and low age for nitrate are expected in the areas near the tile drains. The age of inorganic nitrogen in the fracture, which is associated with rapid transport, is not always lower than that in the matrix. This is primarily due to cation exchange between ammonium and clay minerals, which is important in influencing the retention of inorganic nitrogen in the soil. Intensive agriculture can increase soil solute concentrations and consequently alter the chemistry of the streams draining the landscape.

The interdependencies between critical interfaces are crucial for understanding landscape dynamics. For example, the interface between hillslopes and river channels is critical for sediment and carbon fluxes, with the rate of sediment and carbon export being regulated by the degree of connectivity between these two interfaces. Similarly, the interface between the atmosphere and land surface is critical for the exchange of gases and water vapor, which in turn can impact the biogeochemical cycles in the soil and vegetation.

Furthermore, the interface between the biotic and abiotic components of the soil in the root zone plays a critical role in nutrient cycling and storage. This interface is influenced by factors such as root exudates from vegetation and the presence of microbes, which can facilitate or impede nutrient uptake by plants. The critical interface between the soil and the atmosphere is also important for nutrient cycling, as it is a site for biogeochemical transformations that can influence the availability of nutrients for plant uptake.

Overall, the critical interfaces in a landscape are interconnected and play a crucial role in governing the movement of materials, energy, and water through the landscape. Understanding the interdependencies between critical interfaces is key to predicting the response of landscapes to changing environmental conditions and human activities, and to developing effective management strategies for sustaining ecosystem services.

**Declaration of Competing Interest**

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Praveen Kumar reports financial support was provided by National Science Foundation. Praveen Kumar reports financial support was provided by Advanced Research Projects Agency-Energy.

## Data availability

No data was used for the research described in the article.

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