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Riparian land-use impacts on bank erosion and deposition of an incised stream in north-central Iowa, USA

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ABSTRACT

Stream bank erosion and deposition are complex phenomena because of the many factors that influence them. These factors can be spatial such as bank aspect, height and slope or temporal such as seasonal and yearly precipitation and streamflow events. Riparian land-use also has a major influence. This study investigated for two years, spatial and temporal patterns and dominant geomorphologic processes of stream bank erosion and deposition along a 10 km reach of Bear Creek in north-central Iowa, USA. The channel sub-reaches used were adjacent to a riparian forest buffer, a perennial grass filter and a continuously grazed pasture. Two plots were placed in each sub-reach; one on a north-facing outside bank (north-bank) and the other on a south-facing outside bank (south-bank). Each plot had two photo-electronic erosion pins (PEEPs) placed at 1/3 of the bank height (bottom-bank) and the other at 2/3 of the bank height (top-bank). PEEP daily measurements were compared to daily precipitation and streamflow. The continuously grazed pasture banks had the highest erosion rates. The grass area banks had approximately equal rates of erosion and deposition. The riparian forest buffer banks had high erosion rates during the second year. In the continuously grazed pasture, fluvial entrainment was the dominant erosion process, although minor mass failures also caused erosion. In the riparian forest buffer most erosion was recorded after moderate streamflows removed the bank soil loosened by freeze–thaw cycling. This occurred in late winter/early spring, when trees provide primarily mechanical but not hydraulic reinforcement to stream banks and on the lower part of the banks that have less extensive root networks. Overall, stream bank erosion and deposition in each sub-reach occurred during different time periods and under different processes and conditions. This indicates the need for continuous erosion and deposition measurements along with continuous soil moisture, soil temperature and streamflow measurements to fully comprehend these erosion phenomena.

1. Introduction

Accelerated and extensive stream bank erosion can have detrimental effects on aquatic and terrestrial ecosystems. An understanding of stream bank erosion is necessary to efficiently and effectively manage streams, rivers and their riparian areas. Many studies of stream bank erosion have been conducted during the last decades (Bull, 1997; Couper and Maddock, 2001; Lawler, 1993, 2005; Pollen, 2007; Pollen-Bankhead and Simon, 2010; Wynn et al., 2008) but, many facets of stream bank erosion processes are still not well understood, because of their high temporal and spatial complexity (Langendoen et al., 2009; Lawler, 2005; Wynn et al., 2008).

The agricultural land-use changes for the last 200 years in the Midwestern United States have had a greater impact on fluvial geomorphology than any natural disturbance in the last 10,000 years (Knox, 2006). Most of the natural vegetation of the region has been converted into annual row-crops and cool-season grass pastures (Burkhart et al., 1994). Row-crop agriculture and continuous grazing decrease biodiversity and overall vegetation cover, lower surface roughness and rates of evapotranspiration (Hoffman and Ries, 1991), and reduce soil porosity which decreases water infiltration (Bharati et al., 2002; Marquez et al., 1999). These alterations increase surface runoff, total annual and peak streamflows, stream scouring potential and sediment transport capacity (National Research Council, 2002). Since the beginning of the twentieth century it is estimated that surface runoff and peak streamflows in Iowa agricultural watersheds have increased by 2–3 times and 10–50 times, respectively (Piest et al., 1977).

Stream channelization or straightening has been practiced extensively in the region to make fields more rectangular and easier to farm. This practice increases channel incision by increasing the stream

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gradient by up to an order of magnitude and reducing its roughness (Simon and Rinaldi, 2000). Artificial drainage efforts including the installation of subsurface tile drainage and surface drainage ditches have increased the total length, drainage density and channel frequency of intermittent streams by more than 50% in most Iowa headwater watersheds (Andersen, 2000).

All the aforementioned land cover and stream channel changes have led to hydrologic disequilibrium conditions of streams and caused incision. Incised channels have undergone or are undergoing excessive channel erosion which causes many environmental, human and economic problems (Erskine, 1999). Stable channels that develop disequilibrium conditions move through five phases before they re-establish equilibrium: I) stable, II) incising (degradation), III) widening, IV) aggrading and V) quasi-equilibrium (Schumm et al., 1984).

Most of Iowa streams are in the widening (III) or aggrading (IV) phases (Hadish, 1994). Both phases are associated with accelerated and excessive stream bank erosion that is exacerbated by current riparian land-uses (Schumm et al., 1984). The lack of perennial plant cover and its associated root mass along many stream banks of row-crop fields, further increases susceptibility to stream bank erosion (Pollen-Bankhead and Simon, 2010; Wynn and Mostaghimi, 2006). In riparian areas used as pastures the direct effect of livestock trampling and treading results in the mechanical breakdown and erosion of stream banks (Trimble, 1994). The indirect effects are the results of cattle tendencies to remove the protective vegetation on the top of the banks (Trimble and Mendel, 1995). Odgaard (1987) and Schilling and Wolter (2000) estimated that 45–50% of the sediment in several Iowa streams originated from bank erosion while Wilson et al. (2008) reported an even higher percentage of 80%. The establishment of undisturbed perennial riparian vegetation with high root mass development increases the flow resistance on most fluvial surfaces including stream banks (Schultz et al., 2004).

Three major natural stream bank erosion processes have been identified (Couper and Maddock, 2001; Lawler et al., 1997; Wynn and Mostaghimi, 2006): i) fluvial entrainment, ii) mass wasting or failure and iii) subaerial preparation or processes. Fluvial entrainment is the direct removal of soil particles or aggregates from the stream bed or bank by streamflow (Table 1). When the height and angle of the bank have increased to the point that the gravitational forces exceed the shear strength of the bank material, mass wasting or failure can occur (Table 1). Finally, subaerial preparation is a physical process that reduces soil strength by weakening and loosening of the bank material by climatic factors (Table 1). In most studies, subaerial processes dominate upstream reaches (headwater streams), fluvial entrainment midstream reaches and mass failure downstream reaches (larger rivers) (Couper and Maddock, 2001; Henshaw et al., 2012).

While many studies in the Midwestern United States have investigated the impact of riparian land-use on stream bank erosion rates (Lyons et al., 2000; Sekely et al., 2002; Zaimes et al., 2004, 2006, 2008) there has not been the same emphasis on identifying the timing of stream bank erosion or deposition and which processes cause them. Understanding the processes that drive stream bank erosion is essential for selecting the most appropriate measures to enhance stream bank stability (Simon and Collison, 2002).

The focus of this study was to identify when stream bank erosion and deposition actually occur and the erosion processes that dominate under different riparian land-uses. To achieve this, the following were investigated on three sub-reaches adjacent to different riparian land-uses (riparian forest, grass filter and continuous pasture): i) temporal changes;—when stream bank erosion or deposition events occur; (ii) spatial changes;—the impacts of bank aspect (north and south-facing) and position (top and bottom part of the bank) on erosion and deposition; and (iii) stream bank erosion processes;—which processes are dominant in these types of streams.

2. Methods

2.1. Study area

The research was conducted along a 10 km, second order reach of Bear Creek in north-central Iowa, USA (coordinates of the most southern point of the reach are 42°18′82″ N, 93° 49′ 52″ W- and of the most northern point are 42°23′82″ N, 93° 47′ 63″ W) (Fig. 1). Bear Creek has been designated as a National Restoration Demonstration Watershed by the interagency team implementing the Clean Water Action Plan (1999) because of the extensive stream corridor research conducted over the last 24 years (Berges et al., 2010; Bharati et al., 2002; Lee et al., 2003; Marquez et al., 1999; Schultz et al., 2004; Simpkins et al., 2002; Tufekcioglu et al., 2003; Zaimes et al., 2004, 2006). The study reach is typical of streams in the relatively flat, intensive row-cropping landscape of the Midwestern United States. Channels are deeply incised and experience accelerated stream bank erosion (phase III widening) due to anthropogenic disturbance associated with intensive row-crop agriculture (e.g. land-uses changes, channelization and artificial drainage) (Hadish, 1994). The watershed area of the study reach is 52 km^2 from the most southern point of the 10 km reach. The majority of the watershed is in row-crop agriculture with occasional pastures (typically in the riparian area), homesteads and small pockets of forest. Row-crop fields, pastures and well-established conservation practices (riparian forest buffers and grass areas) are adjacent to the stream in the study reach.

The study reach has an average of 17.3 days/year with snowfall of at least 0.25 cm with most occurring in January (4.4 days) (NOAA, n.d.). The stream channel is covered with snow for many days and experiences frequent freeze–thaw cycling. The average precipitation is 91.0 cm/year, with June being the wettest month (12.6 cm) (NOAA, n.d.). The average annual high temperature is 14 °C while the average low is 4 °C (NOAA, n.d.). July is the hottest month with an average high of 29 °C and an average low of 16 °C and January is the coldest month with an average high of −1 °C and an average low of −11 °C (NOAA, n.d.). The average annual relative humidity is 69% for the region and ranges from 80% in the morning to 56% in the afternoon (NOAA, n.d.).

Table 1
The three major natural stream bank erosion processes and their major characteristics (Couper and Maddock, 2001; Lawler et al., 1997; Simon et al., 2000; Wynn and Mostaghimi, 2006).

Name	Process	Characteristic conditions	Types
Fluvial entrainment	Hydraulic	Occurs during the rising limb of a storm flow hydrograph	a) Lateral erosion b) Basal scour c) Undercutting
Mass wasting or failure	Geotechnical	Common along deeply incised channels. Occurs during the recessional limb of a storm flow hydrograph	a) Slab failures, b) Rotational slips c) Pop-out failures
Subaerial preparation or processes	Preparatory	Rain splash, freeze–thaw cycling during fall, winter and spring, desiccation associated with wetting and drying cycles during summer	a) Creep erosion b) Loosened material on the bank removed by subsequent streamflow

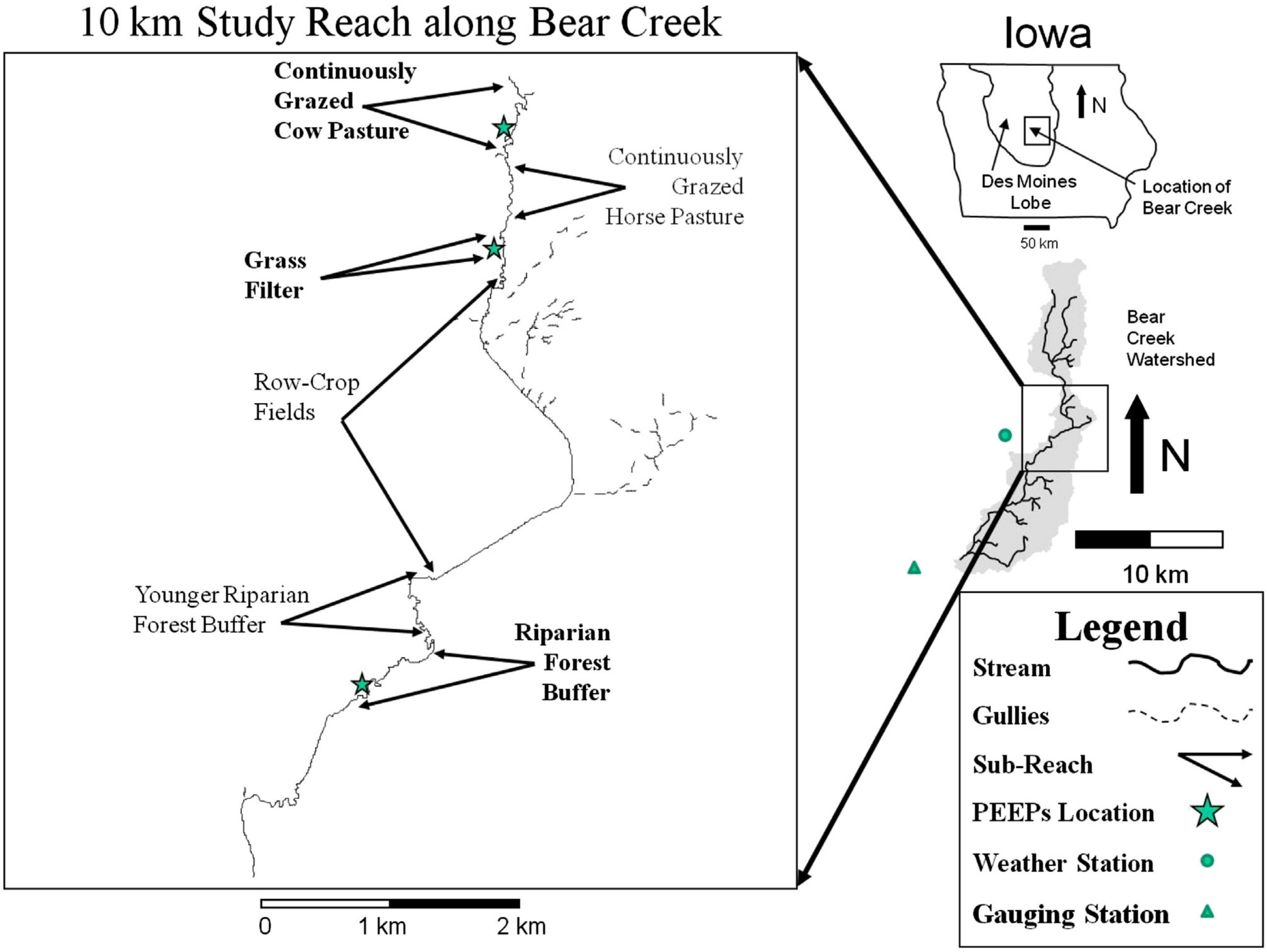

Fig. 1. The 10 km study reach of Bear Creek in north-central Iowa, USA. Photo-electronic erosion pins (PEEPs) were installed on three sub-reaches (in bold). The riparian land-use along each study sub-reach was: a riparian forest buffer, a grass filter and a continuously grazed pasture. The locations of the gauging station and the weather station are also indicated.

Streamflow is perennial with frequent flashy high flow events particularly during spring and early summer. The lowest flows occur in late summer and early fall. The baseflow of Bear Creek, as with most headwater streams in central Iowa, is the result of subsurface tile drainage. In the 10 km study reach the channel is deeply incised (channel depth ranging from 1.6 to 2.5 m) and has no major tributaries, only some contributing ephemeral gullies. The Spillville (fine-loamy, mixed, mesic Cumulic Hapludolls) and Coland (fine-loamy, mixed, mesic Cumulic Haplaquolls) series are the dominant soils adjacent to the channel (DeWitt, 1984). Both Coland and Spillville are alluvial soils, on 0 to 2% slopes, that are moderately permeable, although Coland is deeper, finer in texture and more poorly drained than Spillville (DeWitt, 1984). With similar weather, streamflows, channel dimensions, topography and soils, riparian land-use is the primary variant of stream bank erosion.

2.2. Riparian land-uses

Erosion measurement plots were placed on cohesive stream banks along meandering sub-reaches adjacent to a riparian forest buffer, a grass filter and a continuously grazed pasture (Fig. 2; Tables 2 and 3). The same riparian land-use was present on both sides of these sub-reaches. The stream is channelized upstream of all three sub-reaches; specifically it is channelized for a length of 0.8 km immediately upstream from the pasture sub-reach, and at distance of ~2.4 km from the grass filter sub-reach and channelized for a stream length ~3.6 km and at a distance of ~1.7 km from the riparian forest buffer sub-reach.

The 20 m wide, re-established riparian forest buffer consists of three vegetation zones parallel to the stream course (Fig. 2a) (Schultz et al., 2004). The vegetation was established 12 years prior to the start of the study. The first zone (10 m wide), is located nearest to the stream and is composed of trees that stabilize the stream bank and provide long-term nutrient storage (Schultz et al., 2004). The main tree species along the stream bank are willows (*Salix* spp.), hybrid poplar (*Populus* spp.), silver maple (*Acer saccharinum* L.), and green ash (*Fraxinus pennsylvanica* Marsh.). Slower growing species such as northern red oak (*Quercus rubra* L.), bur oak (*Quercus macrocarpa* Michx.), and black walnut (*Juglans nigra* L.) were planted further from the stream bank, where conditions permitted. The second zone (3.6 m wide) includes shrubs that increase habitat diversity, reduce floodwater velocities and trap floodwater debris (Schultz et al., 2004). The shrub species include redosier dogwood (*Cornus stolonifera* Michx.), gray dogwood (*Cornus racemosa* Lam.), common chokecherry (*Prunus virginiana* L.), nannyberry (*Viburnum lentago* L.), ninebark [*Physicarpus opulifolius* (L.) Maxim.], nanking cherry (*Prunus tomentosa* Thunb.), silky dogwood (*Cornus amomum* Mill.) and highbush cranberry (*Viburnum trilobum* Marsh.). The third zone (6.4 m wide) consists of warm-season grasses and forbs that intercept and reduce the sediment load and chemicals in overland flow (Schultz et al., 2004). Pure switchgrass (*Panicum virgatum* L.) or combinations of big bluestem (*Andropogon geraldii* Vitman), Indian grass (*Sorgastrum nutans* L.) Canada wild rye (*Elymus canadensis* L.) and up to 15 different native forbs were planted.

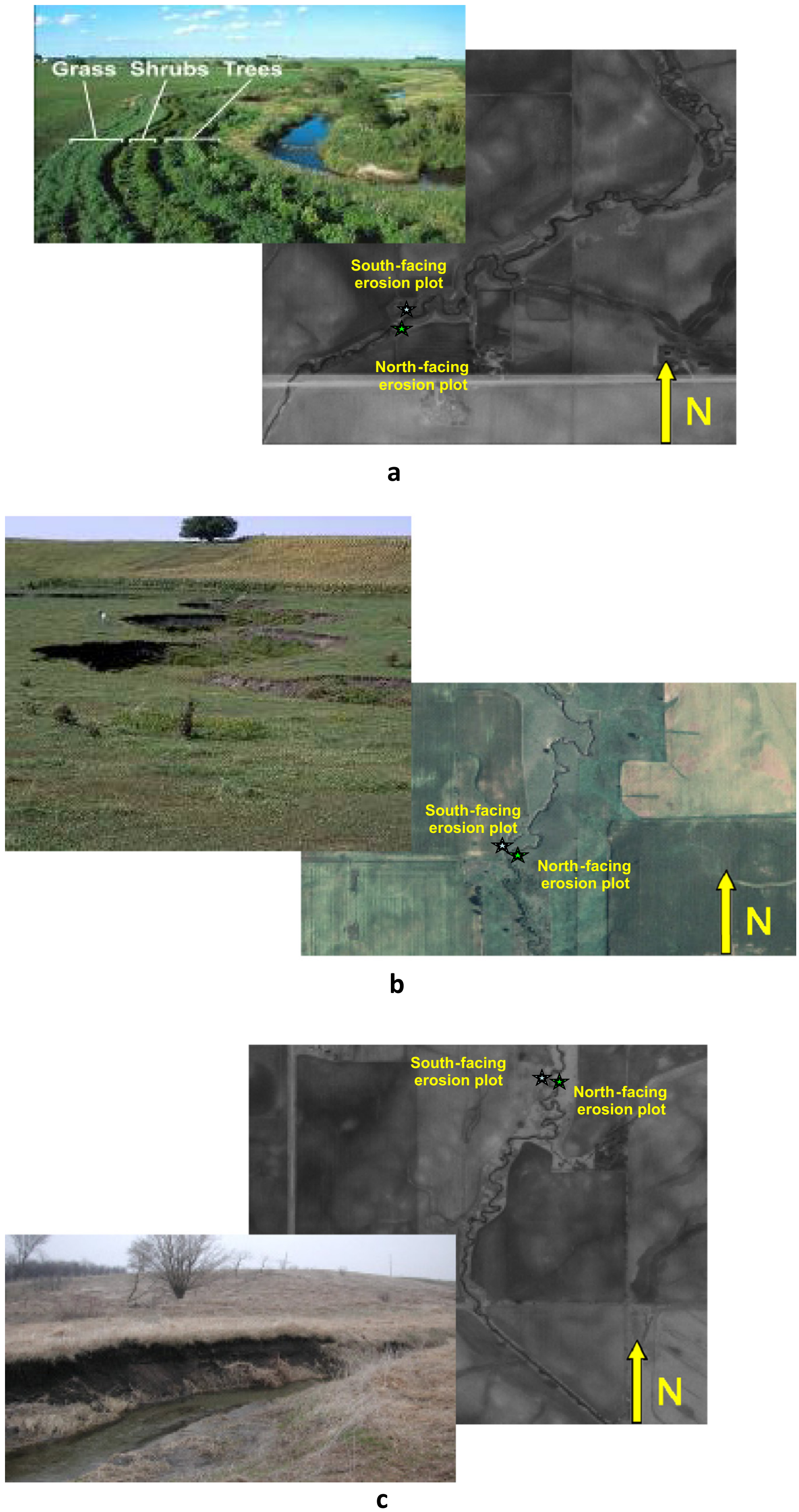

Fig. 2. An aerial photograph of each study sub-reach (Iowa State University GIS Facility, n.d.) and a close-up of its vegetation cover: a) riparian forest buffer, b) continuously grazed pasture and c) grass filter.

Table 2
Stream characteristics of the three study sub-reaches of Bear Creek in north-central Iowa, USA.

Sub-reach	Stream pattern	Length (km)	Average slope (%)	Sinuosity	Average bank height (m)
Riparian forest buffer	Meandering	1.8	0.13	1.8	1.8
Continuously grazed pasture	Meandering	1.1	0.19	1.5	2.1
Grass filter	Meandering	0.6	0.17	1.4	2.3

The pasture consists primarily of cool-season grasses [primarily Kentucky bluegrass (*Poa prantensis* L.)] and is confined to the riparian zone and backslope of the narrow stream valley (Fig. 2b). Beef cattle have access to the whole pasture and stream channel during the entire grazing season that typically starts in late April or early May and ends in October. The stocking rate during the study was 2.6 cow-calves per hectare. The grass filter was a pasture until 1992 when it was abandoned and left unmanaged (Fig. 2c). The grasses are primarily brome (*Bromus* spp.) with some reed canary grass (*Phalaris arundinacea*) near the stream channel. While this is not a true grass filter, at the time the study started it was the site, within the 10 km study reach, that was most similar to re-established grass filters in the region.

2.3. Stream bank erosion measurements

Each sub-reach had two erosion plots (Table 4; Fig. 2). The plots were on severely eroding outside bends (cut-banks) since the focus was to study the processes of accelerated erosion. Severely eroding stream banks are defined as bare of vegetation, with slumps, vegetative overhang and/or exposed tree roots (USDA-NRCS, 1998). The plots selected had similar radius of curvature and channel geometry. One of the plots in each sub-reach was on a north facing bank (north-bank) and the other on a south facing bank (south-bank).

To study the temporal scale of stream bank erosion, photo-electronic erosion pins (PEEPs) were used since they can record erosion and deposition continuously during the daytime (Lawler, 1992). Photo-electronic erosion pins (PEEPs) provide semi-continuous bank erosion measurements of discrete and episodic stream bank erosion events (Lawler, 2005). Each plot included two PEEPs placed at 1/3 (bottom-bank) and 2/3 (top-bank) of the bank height measured from the bottom. The PEEPs were also placed at the apex of the outside bend. The slope of the top part of all banks selected (>80%) were substantially steeper than the bottom part of the banks (<60%) where deposition could often be encountered (Table 4).

The total of six plots with no replication per riparian land-use and the spatial measurements at only two bank height locations (total of 12) were limited and are a concern since stream bank erosion experiences high spatial variability (Zaimes et al., 2006). To meet the objectives of this study an emphasis was given to the high temporal resolution (15 min measurements) instead of the number of plots. Most stream bank erosion studies utilize pins or cross-sections that are measured typically once a month or even less frequently (Lawler, 2005). These methods do not provide the temporal resolution needed to capture individual stream bank events that are typically discreet and episodic (Lawler, 2005).

This study used the PEEP 200 model that has 20 photovoltaic cells and measures up to 20 cm of erosion (momentarily) when fully exposed to sunlight (Fig. 3a and b). When initially installed in the field the PEEP was inserted perpendicularly into the stream bank face with only the first two cells exposed (Fig. 3b and c). The PEEP output voltage was recorded every 15 min by a Campbell Scientific CR10X data logger, but the data were lumped into daily measurements. This was done to compare the PEEP data with the streamflow data that had a coarser temporal scale (daily). The PEEPs have been used extensively in various fluvial systems with good results especially for stream bank erosion (Bull, 1997; Couperthwaite et al., 1998; Lawler et al., 1997; Mitchell et al., 2003; Prosser et al., 2000). To our knowledge this was the first study that had so many PEEPs placed on different land-uses and on different bank positions.

Data from the PEEPs were collected for the Water Year of 2003 (October 2002–September 2003) and 2004 (October 2003–September 2004) in the riparian forest buffer and continuous pasture and only for the Water Year of 2004 (October 2003–September 2004) in the grass filter. The Water Year of 2003 will be referred to as 2003 and the Water Year of 2004 as 2004. The PEEP measurements provided two variables: i) the number of erosion and deposition events (#) and ii) the erosion or deposition rate (cm). These two variables were estimated daily, yearly and for the entire study period. When estimating the rate both erosion and deposition were included. For these timescales the two variables were estimated for each PEEP individually and for all four in each sub-reach.

The measuring accuracy reported for PEEPs is 2–4 mm, although low light levels can reduce the accuracy (Lawler, 1992). The authors accepted an accuracy of 5 mm of erosion and deposition per event for the PEEPs. Smaller changes could have been the result of soil expansion, poor sunlight conditions, stream water covering the PEEPS or other reasons. Based on extensive, presently unpublished data from other streams in the area, the authors considered the daily erosional rates greater than 3 cm as major erosion events and daily depositional rates greater than 2 cm as major deposition events. An emphasis during the analysis of the results was given to these major erosion and deposition events.

2.4. Rainfall and streamflow data

The hourly precipitation data (cm) were obtained from the National Oceanic and Atmospheric Administration (NOAA) weather station from Story City, Iowa (# 7985) (NOAA, 2002–2004) that is approximately 5 km from the riparian forest buffer site of our study (Fig. 1) (42.2°N 93.59°W). The daily streamflow data (m^3/s) were obtained from the United States Geological Survey (USGS) gauging station (# 05470000) (42°03′59″, 93°37′11″) on the South Skunk River near Ames, Iowa (HUC # 07080105) (USGS, nd). Bear Creek is a tributary to the South Skunk River. This station was approximately 10 km from the riparian forest buffer site (Fig. 1).

2.5. Stream bank processes

The daily precipitation and streamflow data were compared to the daily erosion and deposition data to establish the potential erosion

Table 3
Soil characteristics of the three study sub-reaches of Bear Creek in north-central Iowa, USA.

Sub-reach	Soil series	Bank texture	Clay (%)	Silt (%)	Sand (%)	Bulk density (g/cm^3)
Riparian forest buffer	Coland	Clay loam	29	28	43	1.24
Continuously grazed pasture	Spillville–Coland	Clay loam	31	32	37	1.33
Grass filter	Spillville–Coland	Clay loam	32	29	39	1.33

Table 4
Characteristics of the stream banks and erosion plots established in the three study sub-reaches of Bear Creek in north-central Iowa, USA. All stream banks are on the outside bend, concave and severely eroding.

Sub-reach	Plot (#)	PEEPs[a] (#)	Aspect	Height (m)	Slope (%)
Riparian forest buffer	1	2	N-NW	1.5	Top—83 Bottom—41
	1	2	S	1.6	Top—90 Bottom—55
Continuously grazed pasture	1	2	N-NE	2.3	Top—85 Bottom—56
	1	2	S	2.3	Top—74 Bottom—55
Grass filter	1	2	N	2.4	Top—88 Bottom—44
	1	2	S-SW	2.3	Top—Cantilever Bottom—45

[a] Photo-electronic erosion pins.

processes responsible for each event. We used the characteristic conditions that other scientists have reported for the three major erosion processes (Table 1). Specifically, if the erosion occurred a day or two after a large daily precipitation event and as streamflow increased or peaked (rising limb of the hydrograph), fluvial entrainment was considered as the main process (Lawler et al., 1997). If erosion occurred during the recessional period of streamflow (recessional limb of the hydrograph), mass failure was considered as the main mechanism (Simon et al., 2000). Finally, if a stream bank experienced several depositional events (particularly on the bottom-bank) and afterwards moderate streamflow removed this material, subaerial processes were considered dominant (Wynn and Mostaghimi, 2006). Since this was a second order, headwater reach, subaerial processes were expected to be the dominant process (Couper and Maddock, 2001).

3. Results

The erosion rates and the number of erosion and deposition events varied among the different riparian land-uses (Table 5). The continuous pasture banks had the highest erosion rates in both years except for the bottom banks of the riparian forest buffer of both aspects which had the highest erosion rates in 2004. The riparian forest buffer banks had the most erosion (41 in 2003; 57 in 2004) and deposition events (30 in 2003; 64 in 2004). The continuous pasture banks had more events in 2003 (erosion 36; deposition 35) than in 2004 (erosion 28; deposition 31). The south-banks of the riparian forest buffer had the most stream bank erosion and deposition events while the north-banks of the continuous pastures in 2003 (Table 5). In 2004, most riparian forest banks had the most erosion and deposition events. The grass filter

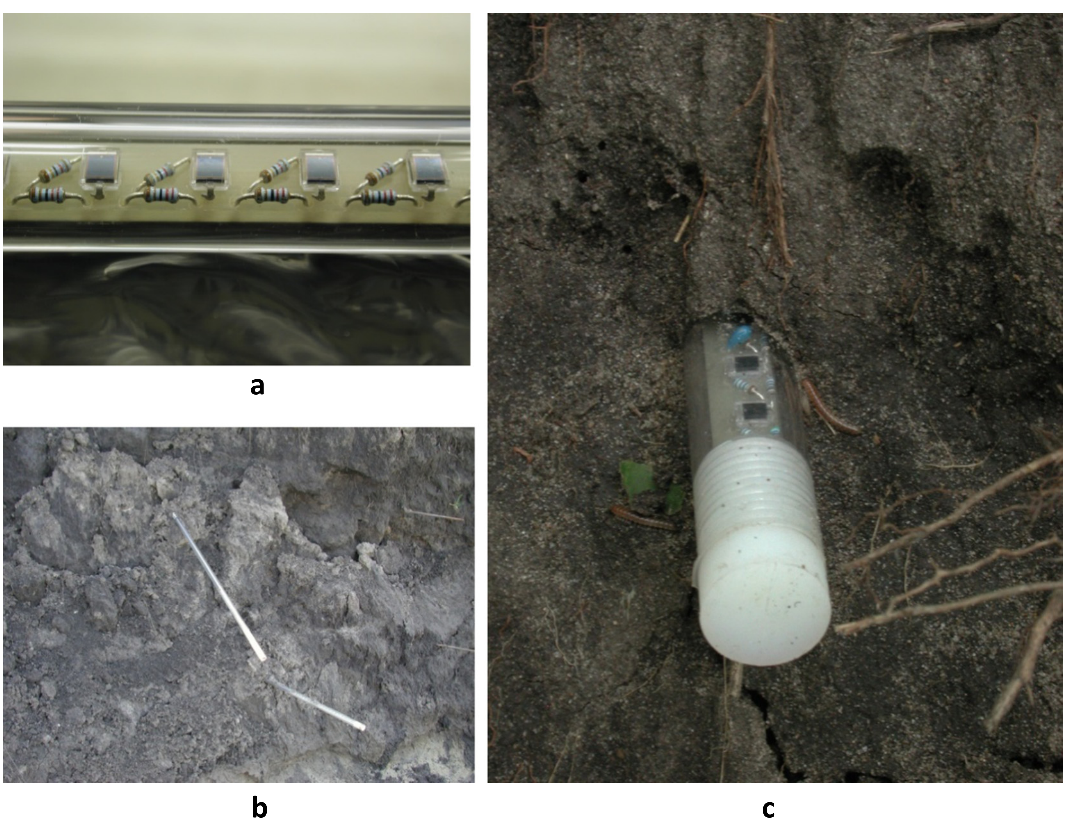

Fig. 3. Photo-electronic erosion pins (PEEPs): a) close-up of the photo-voltaic cells, b) completely exposed because of stream bank erosion and c) how they were initially installed.

Table 5
The top- and bottom-stream bank erosion rates and erosion and deposition events of the north- and south-facing banks. The measurements are based on the four PEEPs[a] on banks along the riparian forest buffer, continuously grazed pasture and grass filter study sub-reaches of Bear Creek in north-central Iowa, USA. The yearly precipitation and maximum daily streamflow are also presented.

Sub-reach	Aspect	Top-bank			Bottom-bank			Yearly precipitation (cm)	Maximum daily streamflow (m3/s)
		Erosion rate[b] (cm)	Erosion events (#)	Deposition events (#)	Erosion rate[b] (cm)	Erosion events (#)	Deposition events (#)		
	2003								
Riparian forest buffer	North	6.5	10	3	0.5	2	4	73	54.7
	South	3	12	8	2	17	15		
Continuously grazed pasture	North	107	11	4	26.5	5	7		
	South	4.5	7	7	23	13	10		
	2004								
Riparian forest buffer	North	−3.5	16	19	−6	2	10	100.4	66.8
	South	11.5	19	14	23	20	21		
Continuously grazed pasture	North	23.5	13	3	12.5	7	7		
	South	5	6	6	11	9	16		
Grass filter	North	2	4	0	−3.5	4	10		
	South	4	3	1	−4	4	11		

[a] Photo-electronic erosion pins.
[b] Positive numbers of rate indicate the rate of the erosion events rate was greater than the deposition events while negative the opposite.

banks were the most stable with the lowest erosion rate and least erosion events in 2004. Despite the very low erosion rate of the grass filter banks in 2004 these banks had more than 35 erosion and deposition events (Table 5).

The yearly precipitation (Table 5) and daily maximum streamflow events in 2004 were larger and more frequent than in 2003. Still, in the continuously grazed pasture, the stream bank erosion rates recorded by three PEEPs were substantially higher in 2003 than in 2004 (Table 5). In addition, in the continuously grazed pasture all bank locations, except the south-top bank, had less than half the erosion rates in 2004 than in 2003 (Table 5). The banks of the riparian forest buffer had a different trend. The south-bank PEEPs recorded a substantially higher erosion rate in 2004 than in 2003. In contrast the north-banks had deposition in 2004.

The continuous pasture banks had the largest number of major erosion events (>3 cm) (Table 6) while the riparian forest buffer banks had the largest number of major deposition events (>2 cm) (Table 7). The grass filter banks did not have any major events. These major events showed some seasonal variations although they differed between the two years since climatic conditions differed. In the riparian forest buffer there were major erosion events only in 2004. Specifically the highest erosion rates were at the end of February and beginning of March 2004. The other events occurred in December 2003 and in May and June 2004. The first major erosion event in the continuous pasture was in October 2002. The other major erosion events in 2003 occurred from the middle of April until early July. May and July had the highest erosion rates. In 2004, the major erosion events were for a similar period (4 months) but started (mid March) and ended (mid June) earlier. In the riparian forest buffer major deposition events occurred primarily in the winter months (December 2003, January and February 2004) with some events also in August (2003) and May (2004). In the continuous pasture most major deposition events occurred in May and June 2003 while the highest rate occurred in March (2004).

The north- and south-banks of the riparian forest buffer had different trends in 2003 (Table 5). Specifically on the north-bank, the top bank had double the erosion of the bottom bank while on the south-bank the bottom bank had three-times the erosion of the top. In 2004 the pattern was very different with both north-bank positions having deposition while the south-banks had substantial erosion. Overall most of the major erosion and deposition events occurred on the south-bank. Only two major erosion and three major deposition events occurred on the north-bank.

In the continuously grazed pasture the north-bank had a higher yearly erosion rate in both years compared to the south-bank with the differences more substantial on the top-banks (Table 5). In 2003 the south-bank had slightly more major erosion events although the fewer major events on the north-bank had substantially higher erosion rates (Table 6). In 2004 each bank had the same number of major erosion events. Each aspect had two major depositional events (Table 7) in 2003 and only the north-bank had a major deposition event in 2004.

Finally, for the grass filter the south bank had a slightly higher erosion rate on the top-bank and a slightly higher deposition rate on the bottom-bank. Neither banks experienced any major erosion or depositional events.

Looking at bank position out of all the six banks investigated, only the two in the grass filter showed a consistent pattern (Table 5). The steeper top-banks were eroding and this eroded material accumulated on the more gradual bottom-banks. The banks of the other two riparian land-uses did not reveal specific patterns among top- and bottom-banks (Table 5). In the riparian forest, the north-top-bank experienced erosion in 2003 but deposition in 2004 while the bottom-bank accumulated eroded material during both years. The south-bank of the riparian forest buffer experienced approximately the same erosion rates in 2003 on both top- and bottom-banks. In 2004 the pattern was very different, with both parts of the bank experiencing substantially greater erosion than in 2003 and the bottom-bank having twice as much erosion as the top-bank. In the continuously grazed pasture, the top-bank of the north-bank had a substantially higher erosion rate than the bottom-bank in both years (Table 5). On the south-bank the trend was opposite with the bottom-bank having a higher erosion rate in both years.

Finally an attempt was made to identify the main processes of stream bank erosion along these banks. To identify the processes the major events were correlated to daily precipitation and streamflow based on the characteristics described in Table 1.

In the riparian forest buffer on February 29th in 2004, a moderate streamflow (Fig. 4) eroded and transported the loosened material deposited by freeze–thaw cycling (Fig. 5a and b) only on the south-bank. The erosion rate was larger than the deposition rate indicating also erosion by fluvial entrainment (Fig. 5c and d). Approximately a week later, on March 5th in 2004, another major erosion event occurred a day after a precipitation event and as streamflow started to increase. This indicated fluvial entrainment and specifically basal scour since the erosion occurred on the south-bottom-bank. The following day, despite the largest streamflow in March, minimal erosion occurred only on the north-bank. On May 8th in 2004, a small precipitation event and the associated streamflow washed away the friable material that had accumulated on the south-bottom-bank. This material had accumulated during the previous months. During the next month, on June 1st 2004 the north-top-bank had an erosion event during

Table 6
The major erosion events (>3 cm per event) and responsible bank erosion processes in each study sub-reach of Bear Creek in north-central Iowa, USA. For each event, the daily erosion rate, precipitation and streamflow during the event and the day before the event are presented. The grass filter experienced no major erosion events during the study period.

Sub-reach	Event (#)	Date	Bank aspect—position	Daily erosion (cm)	Daily precipitation (cm)	Daily streamflow (m^3/s)	Stream bank processes
Riparian forest buffer		23/12/03	–	–	0.0	0.3	
	1	24/12/03	North—top	3.0	0.0	0.2	Not determined (potentially snowpack effects)
		27/12/03			0.5	0.3	
	2	28/12/03	South—top	4.0	0.0	0.4	Not determined (potentially snowpack effects)
			South—bottom	2.5			
		28/02/04	–	–	0.0	15.3	
	3	29/02/04	South—top	7.0	0.0	12.2	Fluvial entrainment enhanced by freeze and thaw
			South—bottom	11.0			
			North—top	0.5			
		04/03/04	–	–	1.8	5.8	
	4	05/03/04	South—bottom	9.0	0.8	16.9	Fluvial entrainment (basal scour)
		06/03/04	North—top	0.5	0.3	26	Fluvial entrainment
	5		North—bottom	0.5			
		07/05/04	–	–	0.0	4.3	
	6	08/05/04	South—bottom	5.0	0.8	4.3	Freeze and thaw material eroded
	7	19/05/04			0.0	8.4	
		20/05/04	South—bottom	4.0	0.0	8.9	Not determined
		31/05/04	–		0.3	33.4	
	8	01/06/04	North—top	4.0	0.0	23.1	Minor mass failure
Continuously grazed pasture		25/10/02			0.6	5.9	
	1	26/10/02	South—bottom	4.0	0.0	6.0	Not determined
		11/04/03			0.0	4.5	
	2	12/04/03	North—top	7.0	0.0	4.1	Not determined
		04/05/03			3.3	13.3	
	3	05/05/03	North—top	50.0	0.0	32.3	Fluvial entrainment
			North—bottom	31.5			
			South—top	4.0			
			South—bottom	1.5			
		04/06/03			0.0	4.6	
	4	05/06/03	South—bottom	4.0	0.0	4.4	Not determined
		06/06/03			1.8	4.7	
	5	07/06/03	South—bottom	5.0	0.0	7.6	Fluvial entrainment (basal scour)
		12/06/03			0.0	7.6	
	6	13/06/03	South—bottom	5.0	0.0	6.9	Minor mass failure
		25/06/03			8.4	6.4	
	7	26/06/03	South—bottom	5.5	0	18.2	Fluvial entrainment (basal scour)
		08/07/03			1.5	8.0	
	8	09/07/03	North—top	51.5	4.6	35.1	Fluvial entrainment
		04/03/04	–	–	1.8	5.8	
	9	05/03/04	North—bottom	7.0	0.8	16.9	Fluvial entrainment (basal scour)
			South—bottom	6.0			
	10	06/03/04	North—top	1.0	0.3	26	Fluvial entrainment
			South—top	3.0			
			South—bottom	3.0			
		24/03/04			0.0	3.2	
	11	25/03/04	North—top	6.5	5.1	3.1	Minor mass failure (high soil moisture)
		29/03/04			0.0	12.3	
	12	30/03/04	North—top	3.0	0.0	8.5	Minor mass failure
		30/04/04			0.0	5.7	
	13	01/05/04	North—top	5.0	0.0	5.4	Not determined
		22/05/04			3.6	9.3	
	14	23/05/04	North—bottom	14.0	1.5	41.9	Fluvial entrainment (basal scour)
	15	24/05/04	North—top	3.0	2.5	56.1	Fluvial entrainment
		27/05/04			0.0	33.7	
	16	28/05/04	South—bottom	3.0	0.0	24.3	Minor mass failure
		12/06/04			1.0	29.2	
	17	13/06/04	South—bottom	8.0	0.3	51.8	Fluvial entrainment (basal scour)
		18/06/04			0.3	39.6	
	18	19/06/04	South—bottom	7.0	0.0	21.6	Minor mass failure

streamflow recession. This suggests that mass failure (Fig. 5e) was the dominant process, especially since the top of the bank eroded. The rate of this erosion event was substantially smaller than a typical mass failure event. So this event and similar ones are called minor mass failures by the authors. Finally, the processes responsible for the December 24th, and 28th 2003 and May 20th in 2004, could not be determined. The major deposition events occurred mostly during winter (freeze and thaw cycles) (Fig. 5a and b), once at the end of summer (desiccation events) and once in late spring (undetermined) (Table 7).

On the continuously grazed pasture banks fluvial entrainment (Fig. 5c and d) was the most frequent process (Table 6). On May 5th in 2003, the north-bank experienced extensive erosion by fluvial entrainment. The top- and bottom-south-banks also had erosion that was substantially less. On March 5th in 2004, erosion occurred on both bottom-banks. This is similar to the basal scour that the bottom-banks of the riparian forest buffer experienced on the same date. The following day, had the largest streamflow of the month, but the erosion rates were less. Basal scour were also the main erosion process on June 7th and 26th in 2003 and June 13th in 2004 on the south-bottom-bank.

On May 23rd in 2003, basal scour eroded the north-bottom-bank that increased the bank's slope. This slope increase which destabilized the bank and the streamflows of the next day eroded the north-top-bank. Finally on July 9th in 2003, the increased streamflows resulted in an excessive erosion rate of 51.5 cm on the north-top-bank by fluvial entrainment.

On June 13th in 2003, the erosion event on the south-bottom-bank occurred during streamflow recession indicating minor mass failure (Table 6). Minor mass failures also occurred on the south-bottom-bank on May 28th and June 19th in 2004 and on the north-top-bank on March 25th and 31st in 2004. Overall, with regard to aspect, the north-bank of the continuously grazed pasture had the most erosion by fluvial entrainment while the south-bank experienced both fluvial entrainment and minor mass failure. The processes responsible for the major erosion events on the continuously grazed pasture banks on October 26th, April 12th, June 5th in 2003, and May 1st in 2004, could not be determined. The major deposition events occurred in March, May and June (Table 7) when deposition was not anticipated.

The grass filter banks had no major erosion or deposition events (Tables 6 and 7). In most cases, the eroding material from the steeper top-banks accumulated on the more gradual bottom-banks indicating subaerial processes.

4. Discussion

Land-use and the condition of the associated riparian vegetation play a very important role in many fluvial geomorphologic processes including stream bank erosion and deposition (Gurnell, 2014). In this study the grass area banks were the most stable. Another study by the authors (Zaimes et al., 2008) found that riparian forest buffers were more effective in reducing stream bank erosion than grass filters. There is an ongoing debate on the most effective vegetation type for bank stabilization, with some supporting trees (Langendoen et al., 2009; Wynn and Mostaghimi, 2006), while others support grasses (Lyons et al., 2000). Perennial plant communities with vigorous root systems, regardless of whether they are trees or grasses, increase stream bank stability, especially in headwater streams (Zaimes et al., 2008; Malkinson and Wittenberg, 2007). In contrast, overgrazed pastures lead to excessive stream bank erosion. Cattle are attracted to riparian areas and tend to spend a lot of time in and around the stream (Trimble and Mendel, 1995). Overgrazing of plants leads to less developed root systems that provide less support to stream bank stability while the increased soil compaction leads to increased surface runoff and peak streamflows (Dunaway et al., 1994). Just removing the cattle from the riparian area 10 years prior to the study (e.g. the grass filter of this study) stabilized the stream banks. This corresponds well with results of other studies (Laubel et al., 2003; Zaimes et al., 2008).

The yearly erosion rate of the grass area banks in 2004 was almost 0 cm, despite the fact that more than 35 erosion and deposition events occurred (Table 5). Even on relatively 'stable' banks (grass filter), small erosion and deposition events can still occur especially on banks that have slopes of 75–90%. To capture these erosion or deposition events and to comprehend the processes of stream bank erosion, high temporal resolution (daily or even better continuous) measurements like those provided by the PEEPs, are necessary.

Precipitation and streamflow, in addition to riparian land-use, are also major drivers of stream bank erosion (Zaimes et al., 2006). The lower erosion rate on the continuously grazed pasture banks in 2004 compared to 2003 was not expected because of the higher annual precipitation and streamflows in 2004. This exhibits the complexity and 'apparent' randomness of stream bank erosion and deposition (Pizzuto, 2009) because of the many different factors that influence them. We suspect that these responses may have been the result of the re-shaping and stabilization of the banks due to the widening of the channel that took place in 2003 on the banks of the continuous pasture. According to Schumm et al. (1984) when the widening of the channel reaches a certain width, bank erosion will decrease and the aggradation phase will start. Long-term data collection on the same bank is necessary to fully understand the high temporal complexity of stream bank erosion.

Differences in riparian land-uses can also influence the timing of the major erosion and deposition events. In the continuous pastures major erosion rates occurred in the spring and early summer months when precipitation (cm) and streamflow (m^3/s) were greatest (Table 6). This is a period when the majority of the study watershed soils are still fallow or the row-crop plants are relatively young with most precipitation becoming surface runoff and leading to peak streamflows. In contrast on the riparian forest buffer banks, erosion did not occur during the large streamflow events. The banks of the riparian forest vegetation appear more susceptible to fluvial entrainment by moderate streamflows that occur in early spring, even though these flows were not peak streamflows. These streamflows were aided by freeze–thaw cycling events that loosened the bank soil prior to the major erosion events. In addition, these banks might have been more susceptible to fluvial entrainment during this period because of high bank soil moisture from the infiltrating water of the melting snowpack. Pre-wetted banks erode more easily (Lawler et al., 1997).

In regard to the major deposition events in the riparian forest buffer these primarily occurred during two periods. The first period was in August and September, when minimal rainfall and streamflow (baseflow) occurred. More importantly during these months the high temperatures and low soil moisture caused desiccation that loosened the soil on the bare stream banks. The second period occurred during November and the winter months. This is also a period of minimal rainfall and streamflow (baseflow conditions). The diurnal temperatures of this period caused freeze–thaw cycling events (Fig. 5a) that also loosened the soil particles (Fig. 5b). Desiccation and freeze–thaw cycling along with low baseflow were the main causal agents for the deposition of eroded bank soils. Wynn and Mostaghimi (2006) found that deciduous forest buffers provided little protection against freeze–thaw cycles on stream banks. They also found that forested stream banks experienced diurnal temperature ranges two to three times greater than stream banks under dense herbaceous cover and underwent as many as eight times the number of freeze–thaw cycles (Wynn and Mostaghimi, 2006). In contrast, stream banks with herbaceous vegetation had higher soil temperatures and a greater diurnal temperature range during the summer (causing desiccation) compared to forested stream banks (Wynn and Mostaghimi, 2006). On the continuously grazed pasture banks the major depositional events occurred from March to June, a period with multiple precipitation events and increased streamflows. A probable cause could have been cattle trampling and treading (Fig. 5f). One of the PEEPs in this study was broken by cattle.

The potential amount of solar radiation a bank receives is highly dependent on its aspect. Higher solar radiation on the south-banks during the summer will cause more desiccation on the bank face (Wynn et al., 2008). South-banks are also more exposed to higher diurnal temperature variation during the winter leading to more freeze–thaw cycling events (Wynn et al., 2008). This suggests that south-banks should have more friable material (Fig. 5b) on their banks that is easily eroded by even moderate streamflows (Fig. 4). Simon and Rinaldi (2000) reported that south-banks were generally more unstable than north-banks in the same reach. In this study, it is likely that the trees and perennial grasses along the banks of the conservation practice sub-reaches provided shade that dampened the sunlight effects (Wynn and Mostaghimi, 2006). In the continuously grazed pasture cattle impacts were probably more important for stream bank erosion than freeze–thaw cycling and desiccation.

The shape and slope of the bank influence whether erosion or deposition are the dominant processes (Lawler et al., 1999). The banks of this study were concave with the top-banks having much steeper slopes (greater than 80%) than the bottom-banks (ranged

Table 7
The major deposition events (>2 cm per event) and responsible deposition processes in each study sub-reach along Bear Creek in north-central Iowa, USA. For each event, the daily erosion rate, precipitation and streamflow during the event and the day before the event are presented. The grass filter experienced no major deposition during the study period.

Sub-reach	Event (#)	Date	Bank aspect—position	Daily deposition (cm)	Daily precipitation (cm)	Daily streamflow (m^3/s)	Stream bank processes
Riparian forest buffer		12/08/03	–		0.0	0.6	
	1	13/08/03	South—bottom	3.5	0.0	0.5	Desiccation
		02/12/03			0.0	0.3	
	2	03/12/03	South—top	2.5	0.0	0.3	Freeze–thaw
		08/12/03			0.0	0.3	
	3	09/12/03	South—top	2.5	0.5	0.3	Freeze–thaw
			South—bottom	1.0			
		31/12/03			0.0	0.4	
	4	01/01/04	North—top	3.0	0.0	0.4	Freeze–thaw
		02/02/04			0.5	0.5	
	5	03/02/04	South—top	3.5	0.0	0.5	Freeze–thaw
			South—bottom	1.5			
			North—top	1.5			
		22/05/04			3.6	9.3	
	6	23/05/04	North—top	4.0	1.5	41.3	Eroded material from higher bank parts
			North—bottom	2.0			
Continuously grazed pasture		07/05/03			0.3	27.7	
	1	08/05/03	South—bottom	3.0	1.5	22.9	Eroded material from higher bank parts
			South—top	2.0			
		14/05/03			0.8	20.3	
	2	15/05/03	North—bottom	3.5	0.3	20.2	Eroded material from higher bank parts
		27/06/03			0.3	14.3	
	3	28/06/03	North—top	2.5	1.3	11.0	Eroded material from higher bank parts
		15/03/04			0.5	3.1	
	4	16/03/04	North—bottom	5.5	0.5	2.9	Eroded material from higher bank parts

from 41–56%) (Table 3). Steeper slopes are typically more unstable. In addition, the microclimatic condition along the stream bank profile can also play a very important role. Freeze–thaw cycling and soil desiccation are greater on the top-banks because of the greater thermal and moisture regulation on the bottom-banks (Wynn and Mostaghimi, 2006). The bottom-banks are also more frequently exposed to streamflow and consequently to basal scour since the top-banks are exposed to only the few peak streamflow events in a year (particularly in deeply incised channels). Laubel et al. (2003) found that bottom-banks had more erosion than the top-banks because of basal scour. Researchers have found contradicting results regarding erosion rates of the top- and bottom-banks (Kronvang et al., 1997; Laubel et al., 2003; Lawler et al., 1999). In addition, the dominant stream bank erosion processes on the top- and bottom-banks may also differ (Lawler et al., 1999). In this study no consistent patterns among top and bottom banks were found (except for the grass area banks). Overall the aspect and bank position had different impacts on stream bank erosion plots among the different land-uses. This again indicates the complex nature of stream bank erosion and that different processes are occurring both spatially and temporally.

On the riparian forest buffer banks all three bank erosion processes caused erosion. Still the banks appear to be more susceptible to late winter and early spring moderate streamflows (e.g. February and March) after the subaerial processes during winter prepare the soil of the bank face for erosion. During peak streamflows, such as May and July of 2003 and June of 2004, only minimal erosion occurred. This was associated with tree root reinforcement of the banks that varies in space and time (Pollen, 2007). During winter, tree roots reinforce

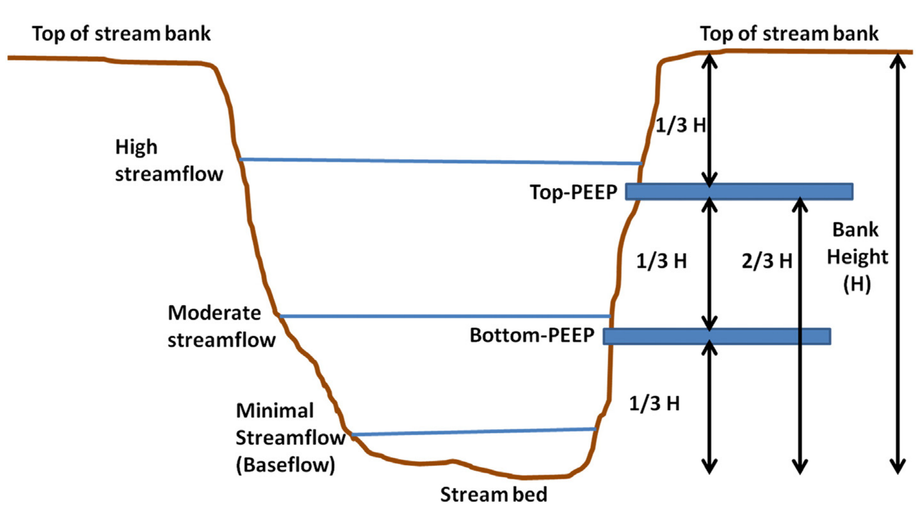

Fig. 4. The potential levels of the streamflows in an idealized stream bank cross-section. The location of the PEEPs is also indicated along the stream bank cross-section. Minimal streamflows are the baseflows that indicate the lowest level of water throughout the year and are always below the bottom PEEP. Moderate streamflows are when the water flow is above the bottom PEEP and can reach the middle of the stream bank. During high streamflows the water flow covers both PEEPS and in some cases causes overbank flows.

Fig. 5. Pictorial overview of stream bank erosion processes along the study reach of Bear Creek in north-central Iowa, USA: a) freeze–thaw cycling, b) loosened soil because of freeze–thaw cycling, c) flooding can cause fluvial entrainment, d) the exposed pins (indicated by yellow arrows) show the substantial erosion due to fluvial entrainment, e) mass failure causes large amounts of soil erosion, f) erosion caused by cattle trampling and treading and g) the movement of snowpack in early spring, while it is melting along the stream bank, can cause erosion and deposition. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

banks primarily mechanically (Pollen-Bankhead and Simon, 2010). In contrast, during the summer months' trees reinforce banks both mechanically and hydraulically because of the tree's transpiration (Pollen-Bankhead and Simon, 2010). This hydraulic mechanism can increase the stability safety factor by more than 50% (Pollen-Bankhead and Simon, 2010) and provide greater resistance to erosion despite larger streamflows with greater scouring potential.

Fluvial entrainment, due to peak streamflows, was the dominant process of most large erosion events on the continuously grazed pasture banks. The lack of an extensive root system in the continuously grazed decreases the shear strength of the pasture banks and makes them more susceptible to the scouring potential of the peak streamflows. Still some erosion events in the continuously grazed south-banks also occurred during streamflow recession indicating minor mass failures. During minor mass failures snow cover can also play a very important role. An example is the snowfall in the middle part of March of 2004. Snow had completely covered the ground and stream banks. Such extensive snow events are not common in Iowa during March. As the snow melted, it increased the soil moisture levels of the stream banks, particularly on the top parts of the banks increasing its erosion susceptibility promoting mass failure (north-top-bank on March 25th in 2004).

The authors observed additional impacts by snowpack. Specifically, as the snowpack melted it moved slowly down along the bank carrying soil particles with it (Fig. 5g). As a result the top-bank eroded while the bottom-bank accumulated material (deposition). This could have been the case for the erosion events of December 24th (north-top bank) and 28th (south-top-bank) in 2004, in the riparian forest buffer. This is a process that to our knowledge has not been reported in the literature. Its importance to stream bank erosion needs to be studied in areas where the banks are deeply incised and have large amounts of snow accumulated for long periods of time. As a process it acts like creep erosion since it has much slower rates and erodes smaller amounts of material compared to the other stream bank erosion processes.

5. Conclusions

Riparian land-use can play a major role in stream bank erosion and influence temporal and spatial patterns and processes. Overall vigorous vegetation with deep and extensive root systems on stream banks can reduce erosion as demonstrated by the small total rate of erosion on the grass filter banks. The continuously grazed pasture banks had the highest erosion rates with most erosion occurring in mid spring to early summer when cattle were present on the banks. The riparian forest banks experienced the most erosion in early spring when trees provide only mechanical reinforcement. On the continuously grazed pasture banks fluvial entrainment was the dominant process although minor mass failures also contributed. In contrast on the riparian forest banks, fluvial entrainment by moderate flows aided by freeze and thaw events caused most erosion.

The continuously grazed pasture and forest buffer banks also had the highest variation in erosion rates between the top and bottom banks. In the continuously grazed pasture the top-banks had more than double the erosion rate of the bottom-banks. In contrast the bottom-banks of riparian forest buffer had the highest erosion rate. The resistance to erosion by the tree root system is one of the main reasons for the large difference in erosion rates between the top and bottom of the forest buffer banks.

In some cases, the process and cause of stream bank erosion could not be determined. In the continuously grazed pasture this could have been because of cattle trampling and treading. Another cause could be snowpack cover that appears to influence stream bank erosion in this region. When the snowpack cover starts melting its physical movement along the bank can cause erosion and deposition events. More extensive investigation of the erosion caused by snowpack movement along the stream bank should be conducted.

The different processes that can cause erosion and deposition along with the many factors that influence them make it extremely difficult to predict and understand stream bank erosion and deposition events. Even though all our plots were within a 10 km reach, with similar channel and bank characteristics and riparian vegetation the major changing variable, substantial differences in erosion and deposition were found. High temporal (e.g. continuous) erosion measurements (e.g. PEEPs) along with high temporal (e.g. continuous) soil moisture and temperature and streamflow measurements will provide more insights on the conditions that cause stream bank erosion and deposition.

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