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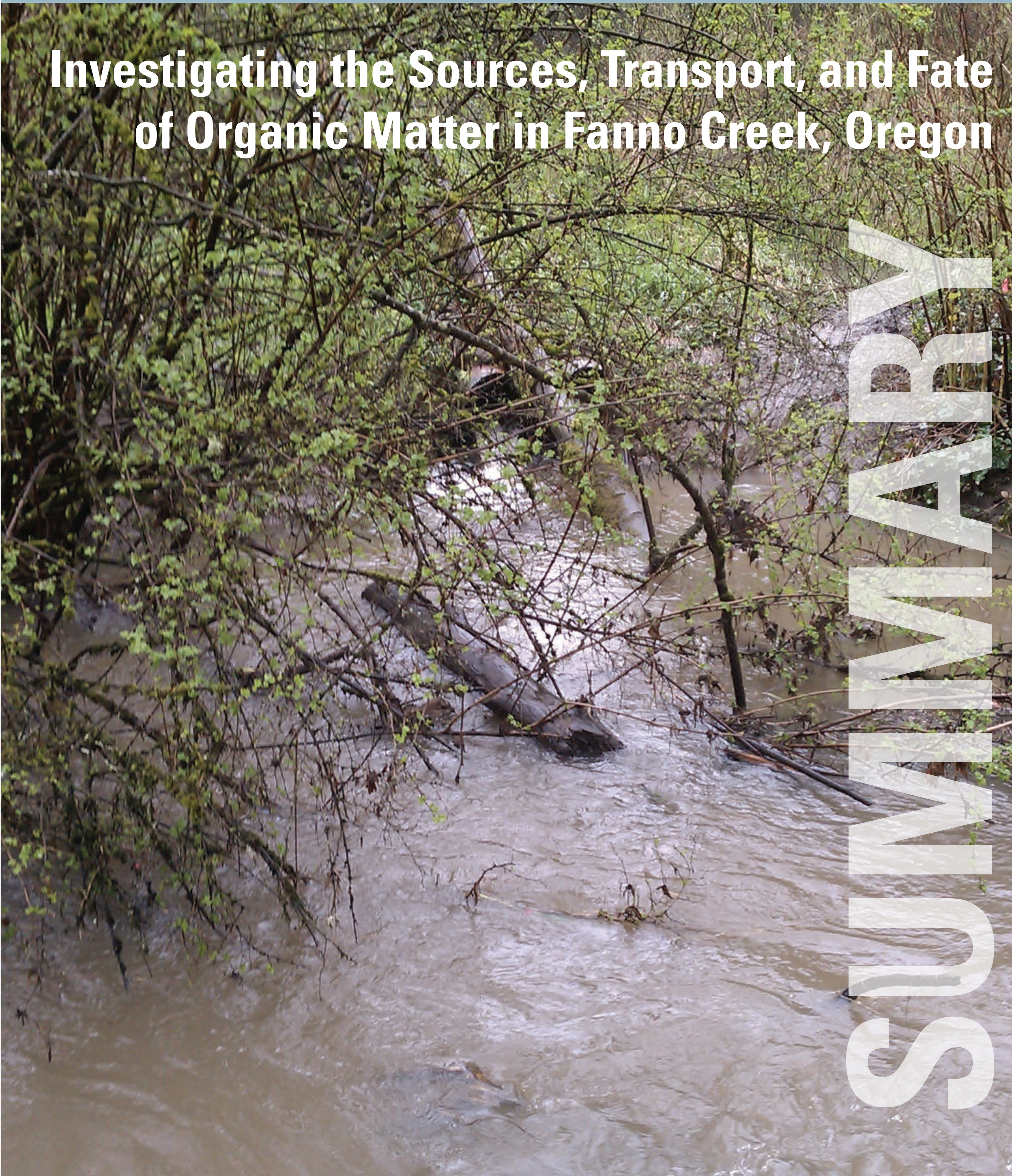
Investigating the Sources, Transport, and Fate of Organic Matter in Fanno Creek, Oregon

SUMMARY



USGS
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Prepared in cooperation with Clean Water Services

Organic Matters

Investigating the Sources, Transport, and Fate of Organic Matter in Fanno Creek, Oregon

The term *organic matter* refers to the remnants of all living material. This can include fallen leaves, yard waste, animal waste, downed timber, or the remains of any other plant and animal life. Organic matter is abundant both on land and in water. Investigating organic matter is necessary for understanding the fate and transport of carbon (a major constituent of organic matter).

Organic matter is necessary for maintaining a healthy ecosystem. It participates in a wide range of ecological functions, such as supplying food to the microbes that are part of the foundation of the food chain. Organic matter also plays a role in many other natural functions, including the binding and transport of some trace metals and controlling how light is absorbed in the water column. Organic matter in a stream can be found in many places, such as in the leaves that have fallen from a tree (termed “leaf litter”), in algae floating in the stream or attached to rocks, as part of the soil, or even suspended or dissolved in the water.

The U.S. Geological Survey (USGS), in cooperation with Clean Water Services, recently completed an investigation into the sources, transport, and fate of organic matter in the Fanno Creek watershed. The information provided by this investigation will help resource managers to implement strategies aimed at decreasing the excess supply of organic matter that contributes to low dissolved-oxygen levels in Fanno Creek and downstream in the Tualatin River during summer. This fact sheet summarizes the findings of the investigation.

Figure 1. Location of Fanno Creek, Oregon.

Organic Matter and the Environment

Organic matter plays a vital role in the environment, especially in the ecological health of a river system. It provides food for animals to eat. It supplies nutrients to the soil that plants need to grow. However, in some situations it can adversely affect the health of a river. When microbes break down organic matter in a stream, they use some of the oxygen that is dissolved in the water. This decreased dissolved oxygen in the water can stress fish and other aquatic animals that depend on oxygen to breathe.

Some streams such as Fanno Creek in the Portland, Oregon, metropolitan area (fig. 1) are listed as impaired waterways

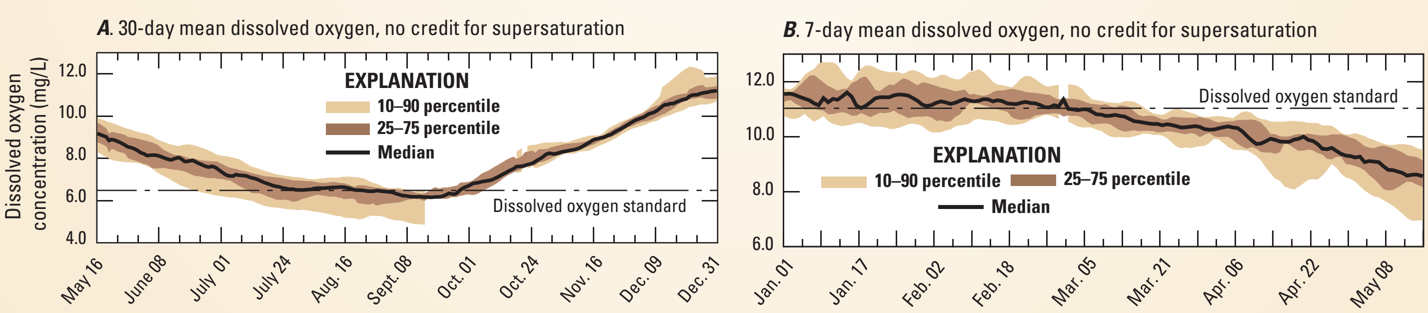

Figure 2. Dissolved oxygen (DO) concentration in Fanno Creek between 2003 and 2014. The DO standard line indicates two of the minimum thresholds to protect fish at different times in their life: (*A*) 6.5 mg/L—30-day average of daily mean DO (minimum criterion for rearing and migration period of May 16 to December 31) and (*B*) 11 mg/L—7-day average daily mean DO (minimum criterion for spawning period of January 1 to May 15).

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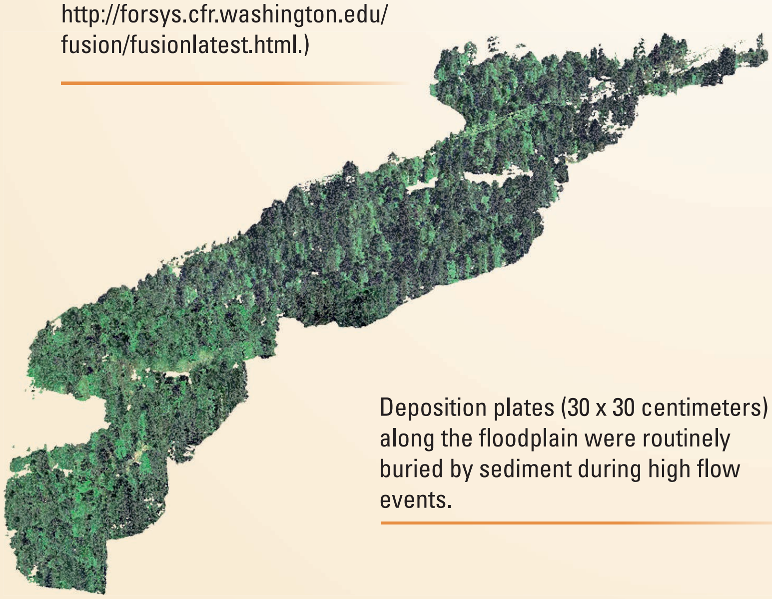
Sediment erosion was observed using metal stakes hammered into the streambanks and measured after high flow events.

by the Oregon Department of Environmental Quality and require active management in order to improve dissolved-oxygen conditions and meet State standards. The standards vary seasonally and are based on whether fish are rearing or spawning (fig. 2). For Fanno Creek, the primary sources of organic matter are terrestrial (land based), such as leaf litter and soils, rather than aquatic, such as algae. So, how much terrestrial organic matter is available along the stream? To find the answer, USGS scientists began by measuring the amount of leaf litter, or foliage, available.

Organic matter in Fanno Creek comes mostly from terrestrial sources, such as leaf litter.

Figure 3. Three-dimensional (3-D) view of tree canopy as represented by remotely sensed data (light detection and ranging [lidar]) near Durham City Park, Oregon. Lidar from Fusion software available at http://forsys.cfr.washington.edu/fusion/fusionlatest.html.)



Leaf Litter (Foliage) Biomass

To estimate how much leafy material exists along Fanno Creek, USGS scientists used a combination of field measurements and remotely sensed data to calculate the *foliage biomass*, or the total dry weight of all leaf material (fig. 3). The annual leaf litter biomass was determined for two areas: (1) all foliage across the entire floodplain, and (2) only foliage overhanging the stream. Based on this analysis, an estimated 990 metric tons (t) of organic matter is produced annually above the Fanno Creek floodplain, with about 140 t present directly over the channel. The amount of leaf material that falls along the floodplain varies depending on the size and age of the trees, and the density of the tree canopy. Because forest-dominant reaches along Fanno Creek contain more mature deciduous trees with broader tree canopies than either wetland or urban-dominant reaches, they typically generate more leafy biomass in any given year.

USGS research explored organic matter "above, around, and in" Fanno Creek.

Organic Matter Transport with Fine Sediment

USGS scientists also assessed the organic matter (and carbon) contribution in the fine sediments along the floodplain and streambanks of Fanno Creek (fig. 4). Based on the carbon content of samples collected from the streambanks and measured rates of erosion and deposition, it was estimated that streambanks supplied between 50 and 120 t of organic matter annually during the study period. Generally, the organic matter stored in topsoil floodplain deposits was 2–5 times richer in carbon than that sampled directly from the subsoil of the streambanks. Comparatively, the streambanks supplied less organic matter to Fanno Creek than that measured from the foliage above.

Deposition plates (30 x 30 centimeters) along the floodplain were routinely buried by sediment during high flow events.

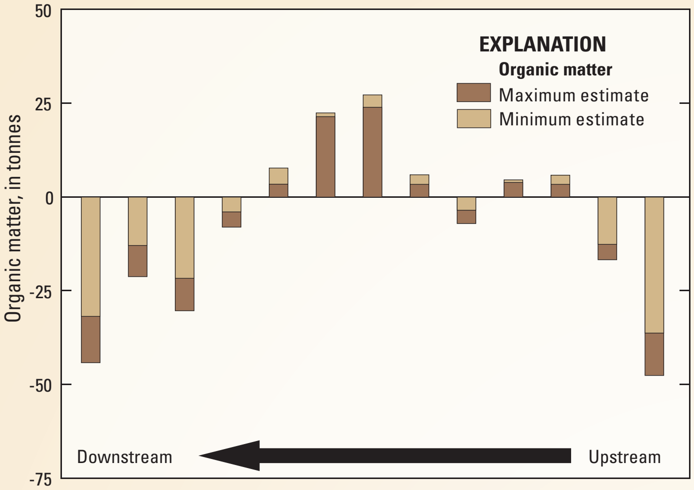
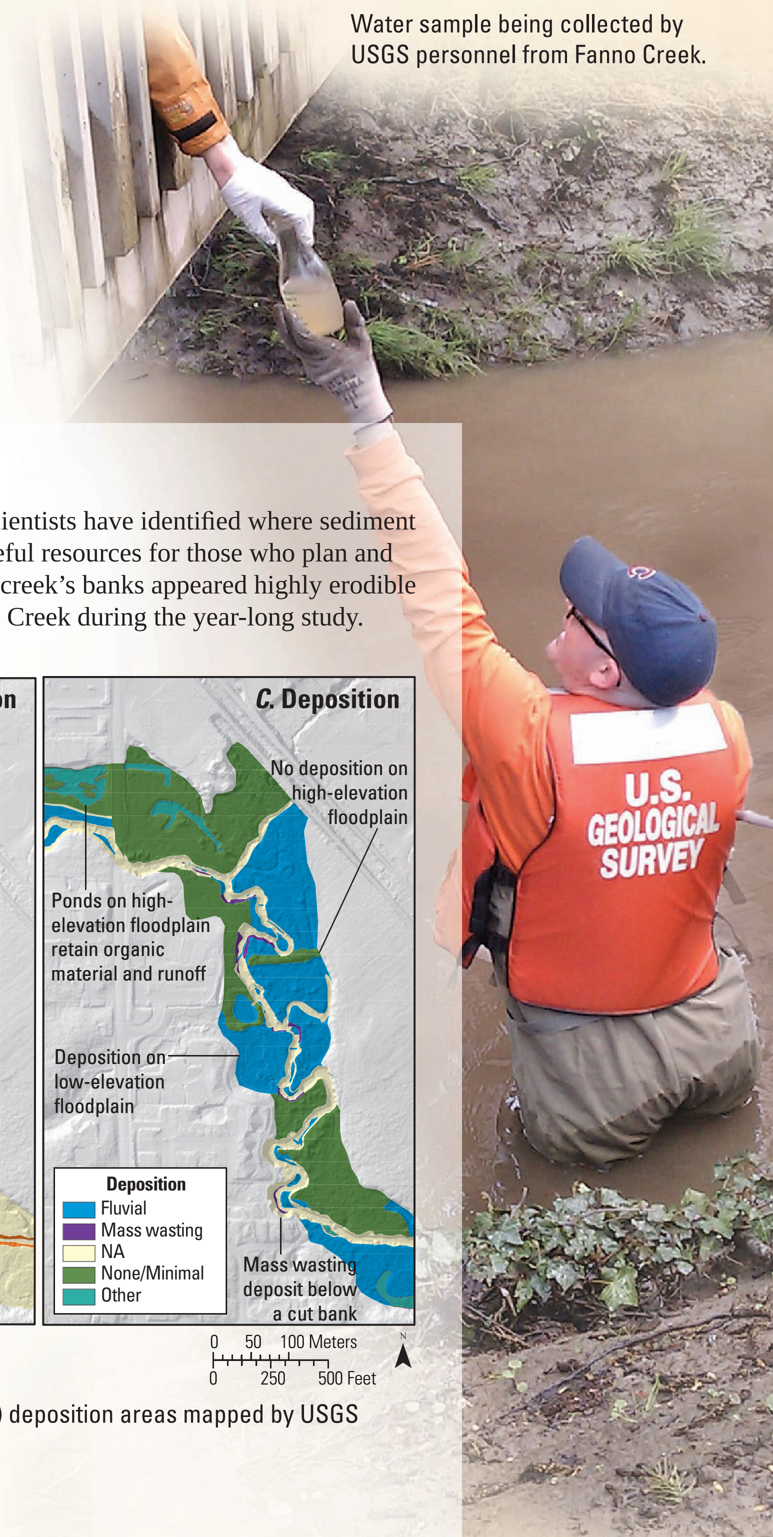


Figure 4. Organic matter contribution from fine sediments along Fanno Creek. Positive values indicate overall deposition or storage; negative values indicate erosion or export. Net deposition is greatest along the middle sections of Fanno Creek where wetlands have been restored

Organic Matter as Instream Carbon

In addition to estimating organic matter contributions from above and along Fanno Creek, USGS scientists also assessed the instream movement and characteristics of organic matter.

Using cutting-edge instream water-quality instruments (optical fluorescence sensors) and laboratory analyses (fluorescence spectroscopy and isotope chemistry), investigators estimated the amount and characteristics of dissolved, particulate, and total organic carbon in the stream. Each year, about 320 t of organic carbon floats or flows through Fanno Creek, with about 70 percent of organic carbon dissolved in the water. The concentration of the dissolved organic carbon varies throughout the year, but generally amounts to at least 3–4 milligrams per liter (mg/L) during most of the year. The instream and laboratory analyses confirm previous findings that the carbon in the stream predominantly originates from terrestrial organic matter, such as from leaf litter or other surface-soil runoff.



Water sample being collected by USGS personnel from Fanno Creek.

Mapping Erosion and Deposition

Based on geomorphic maps of the floodplain (fig. 5), USGS scientists have identified where sediment is being eroded and deposited along Fanno Creek. The maps are useful resources for those who plan and restore wetlands or riparian areas. Approximately 70 percent of the creek's banks appeared highly erodible and resulted in 550–3,300 t of sediment being exported from Fanno Creek during the year-long study.

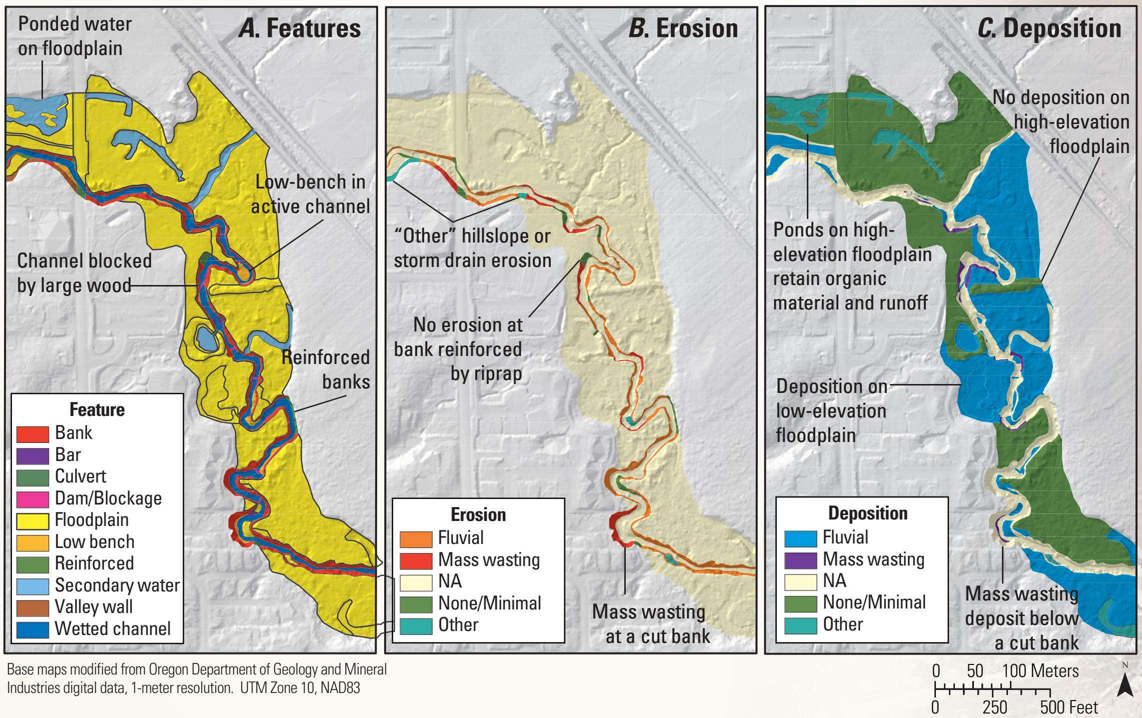


Figure 5. Examples of (*A*) channel features, (*B*) erosion areas, and (*C*) deposition areas mapped by USGS scientists near Fanno Creek Park in Tigard, Oregon.

Organic Matter Transport Following the First Storm of Autumn

In mid-October 2012, the first autumn storm swept across the Fanno Creek watershed. This first rain disturbed fine particulate materials that had been accumulating during spring and summer along the streambed and washed some materials into the stream from nearby storm systems and soils (fig. 6). Real-time water-quality monitoring equipment recorded the event (fig. 7). Due to the mobilization of this accumulated material, a large part of the annual supply of organic matter was transported during this storm, despite the fact that bigger storms occurred later in the year. Not only was the proportion of the organic matter greater during this first storm, but the transported material also was characteristically different than other storms. The organic matter showed more decomposition through microbial activity, reinforcing the conclusion that easy-to-mobilize sediment and decomposing organic matter had accumulated in the streambed during the dry summer months. Downstream in the Tualatin River, this storm plume containing decomposing organic matter resulted in a measurable and significant decrease in dissolved oxygen, a condition that tends to occur with the first autumn storms in most years and is a potential water-quality concern for resource managers.

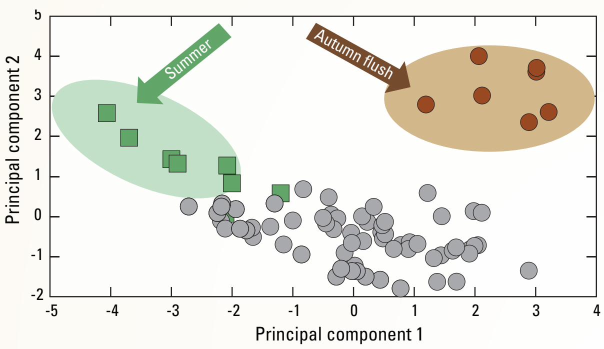


Figure 6. Statistical analysis of water-quality samples collected from Fanno Creek. The two sample periods (summer low flow and the first autumn storm) were characteristically different from other samples collected.

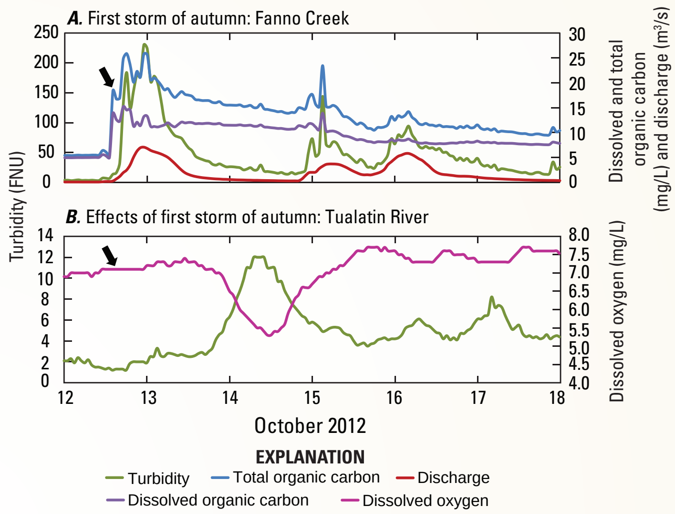


Figure 7. First autumn storm readings for Fanno Creek and downstream in the Tualatin River. (*A*) Turbidity, total organic carbon, discharge, and dissolved organic carbon patterns in Fanno Creek in October 2012. Arrow indicates the beginning of the storm. (*B*) Dissolved oxygen and turbidity in the Tualatin River. The effects of the storm plume show up downstream about 1.5 days later.

Implications for Watershed Management

Fanno Creek flows through a heavily urbanized part of the Portland, Oregon area. As such, the watershed has many interested stakeholders, including municipalities, counties, utility providers, conservation groups, and private citizens. The health and safety of the creek has implications to more than just the aquatic life in the stream, but also to people who live and play along the creek. Therefore, it is useful to understand the critical water-quality issues in Fanno Creek and provide the maps, data, and insights necessary to assist resource managers to make decisions regarding management and restoration activities to maintain and enhance the stream environment.

Full Results of the Study

The results of the Fanno Creek study have been published in the Journal of Hydrology as a series of three articles. Figures presented in this fact sheet were modified from these articles.

Sobieszczyk, Steven, Keith, M.K., Rounds, S.A., and Goldman, J.H., 2014, Investigating organic matter in Fanno Creek, Oregon, part 1 of 3—Estimating annual foliar biomass for a deciduous dominant urban riparian corridor: Journal of Hydrology, v. 519D, p. 3001–3009, *http://dx.doi.org/10.1016/j.jhydrol.2014.06.054*.

Keith, M.K., Sobieszczyk, Steven, Goldman, J.H., and Rounds, S.A., 2014, Investigating organic matter in Fanno Creek, Oregon, part 2 of 3—Sources, sinks, and transport of organic matter with fine sediment: Journal of Hydrology, v. 519D, p. 3010–3027, *http://dx.doi.org/10.1016/j.jhydrol.2014.07.027*.

Goldman, J.H., Rounds, S.A., Keith, M.K., and Sobieszczyk, Steven, 2014, Investigating organic matter in Fanno Creek, Oregon, part 3 of 3—Identifying and quantifying sources of organic matter to an urban stream: Journal of Hydrology, v. 519D, p. 3028–3041, *http://dx.doi.org/10.1016/j.jhydrol.2014.07.033*.

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Investigating organic matter in Fanno Creek, Oregon, Part 1 of 3: Estimating annual foliar biomass for a deciduous-dominant urban riparian corridor

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SUMMARY

For this study, we explored the amount, type, and distribution of foliar biomass that is deposited annually as leaf litter to Fanno Creek and its floodplain in Portland, Oregon, USA. Organic matter is a significant contributor to the decreased dissolved oxygen concentrations observed in Fanno Creek each year and leaf litter is amongst the largest sources of organic matter to the stream channel and floodplain. Using a combination of field measurements and light detection and ranging (LiDAR) point cloud data, the annual foliar biomass was estimated for 13 stream reaches along the creek. Biomass estimates were divided into two sets: (1) the annual foliage available from the entire floodplain overstory canopy, and (2) the annual foliage overhanging the stream, which likely contributes leaf litter directly to the creek each year. Based on these computations, an estimated 991 (±22%) metric tons (tonnes, t) of foliar biomass is produced annually above the floodplain, with about 136 t (±24%) of that foliage falling directly into Fanno Creek. The distribution of foliar biomass varies by reach, with between 150 and 640 t/km^2 produced along the floodplain and between 400 and 1100 t/km^2 available over the channel. Biomass estimates vary by reach based primarily on the density of tree cover, with forest-dominant reaches containing more mature deciduous trees with broader tree canopies than either wetland or urban-dominant reaches, thus supplying more organic material to the creek. By quantifying the foliar biomass along Fanno Creek we have provided a reach-scale assessment of terrestrial organic matter loading, thereby providing land managers useful information for planning future restoration efforts.

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1. Introduction

The link between terrestrial sources of organic matter and their effect on instream processes is well established (Abelho, 2001; Benfield, 1997; Meyer et al., 1998). Foliage from the surrounding canopy falls as leaf litter, enters the channel and begins to decompose, consuming oxygen from the stream. Due to the relation of allochthonous litterfall and instream organic matter, resource managers are increasingly interested in knowing the location and the amount of available canopy foliage, or foliar biomass, which supplies material to their managed streams. Thus, quantifying terrestrial biomass provides meaningful insight about potential instream organic matter and the associated water-quality issues, such as low dissolved oxygen concentrations that may propagate downstream from known source areas.

The amount of foliar biomass a tree canopy supplies varies significantly depending on the environmental setting and predominant land use. For example, successfully quantifying the amount of foliar biomass available in an urban, primarily deciduous environment can be challenging (Nowak, 1996). For years, classic forestry texts have demonstrated ways to quantify available biomass in forested areas by measuring tree canopy characteristics, such as canopy cover and canopy fuel load, through either destructive (Brown, 1978; Snell and Little, 1983) or nondestructive field-based techniques (Bunce, 1968; Scott and Reinhardt, 2005). Modern forestry practices focus more on methods that use remotely sensed data, such as light detection and ranging (LiDAR) data, to produce spatially accurate estimates of tree canopy metrics and biomass loads (Anderson et al., 2005; Erdody and Moskal, 2010; Li et al., 2008). However, these different techniques have varying success when applied to a mixed deciduous urban setting.

Paralleling forestry professionals, ecologists and biologists have also developed numerous techniques for determining foliar biomass, leaf area, litterfall rates, and leaf litter decomposition

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through either remotely sensed (Popescu et al., 2004; Zheng and Moskal, 2009) or field-based methods (Abelho, 2001; Swan and Palmer, 2004; Edmonds and Tuttle, 2010; Hladyz et al., 2010; Roberts and Bilby, 2009). Researchers utilized these techniques to determine the relation between in channel processes and above channel vegetation. These studies demonstrate a greater applicability to deciduous dominant setting, but still do not fully account for variations in land cover. Thus, we are testing whether a hybrid remotely sensed and field-based technique can successfully quantify foliar biomass production along a variable land use, primarily deciduous-dominant riparian corridor at a suitable scale for land restoration decisions to be made. With this approach we can provide land resource managers information about where leaf litter originates, the amount of the material produced, how much of the material will enter the stream in any given year, as well as provide beneficial insight into how different land uses drive biomass production.

1.1. Background

Once terrestrial organic matter, such as leaf litter, enters a stream, microbes begin to decompose and break down the material. During decomposition oxygen is consumed from the water column through the process of biochemical oxygen demand (BOD) and sediment oxygen demand (SOD). BOD and SOD are two of the main drivers of low dissolved oxygen (DO) concentrations found in streams. Low DO is considered a water-quality impairment by U.S. Environmental Protection Agency (2006) and is regulated by the ODEQ; Oregon Department of Environmental Quality (2001). To combat low DO in streams, total maximum daily loads (TMDLs), or the maximum amount of a pollutant a stream can carry while still meeting a water-quality standard, have been established by ODEQ for much of the Tualatin River basin, including Fanno Creek (Oregon Department of Environmental Quality, 2001). In the case of Fanno Creek, a TMDL has been established for total volatile suspended solids—essentially the organic matter that decomposes instream and uses DO from the water column.

Instream organic matter comes from a variety of terrestrial and aquatic sources, including leaf litter, algae, organic-rich soils, bed sediments, and stormwater. Bonn and Rounds (2010) indicate that it is the terrestrial, rather than aquatic sources of organic matter, which lead to low DO conditions found in Fanno Creek and downstream in the Tualatin River. Therefore, this study was designed to explore the predominant terrestrial organic matter source by estimating available foliar biomass and computing how much of this foliage is available as litterfall to Fanno Creek and its floodplain. Measurements of other terrestrial sources of organic matter to the creek, such as bank erosion, bed-sediment transport, and stormwater are also evaluated independently in this issue (Goldman et al., 2014; Keith et al., 2014).

For the purpose of this study, foliage refers to all the leafy components of the tree canopy structure, such as leaves, flowers, needles, seeds, cones, and fruits (Benfield, 1997) that blossom and shed annually as litter. This material is comparable to the leaf litter components used for canopy fuel load estimators, such as FARSITE (Keane et al., 1998), and other canopy metric calculators (McGaughey, 2009; Rebain et al., 2011; Scott and Burgan, 2005). Foliar biomass estimates do not include dense woody materials like tree branches or trunks. Although these woody sources are a component of terrestrial biomass and play a vital role in the ecological health of a stream (Abelho, 2001), their contribution to seasonal stream BOD and SOD is small compared to the more labile leaf litter (Meyer et al., 1998) that is the focus of this study.

1.2. Study area

1.2.1. Location

Fanno Creek is an urban stream that originates in the West Hills of Portland, Oregon (Fig. 1). The watershed drains 82.4 km^2 of predominately residential land within the southwestern metropolitan area. The creek flows 27 km through a riparian corridor comprised of a series of intermittent wetlands, parks, and small forests before entering the Tualatin River in the city of Durham. The study area (Fig. 1) extends along the Fanno Creek geomorphic floodplain and is divided into 13 reaches (Table 1). A geomorphic floodplain is not a recurrence interval-type (e.g., 100-year or 500-year) flood delineation boundary, like that used by the Federal Emergency Management Agency for flood insurance, but rather represents the extent where the stream system has flowed and created landforms over the last 10,000 years (i.e., Holocene Epoch). Within the Fanno Creek floodplain (Sobieszczyk, 2011b), each reach is separated by a major roadway or bridge and is discrete in design and management. For example, the reaches in the upper section of the Fanno Creek floodplain are heavily urbanized and consist of a narrow, riparian buffer that weaves through residential neighborhoods, business areas, and a golf course. Much of the area in the middle section of Fanno Creek is designated as parks and wetlands complete with restoration projects and reintroduction of native

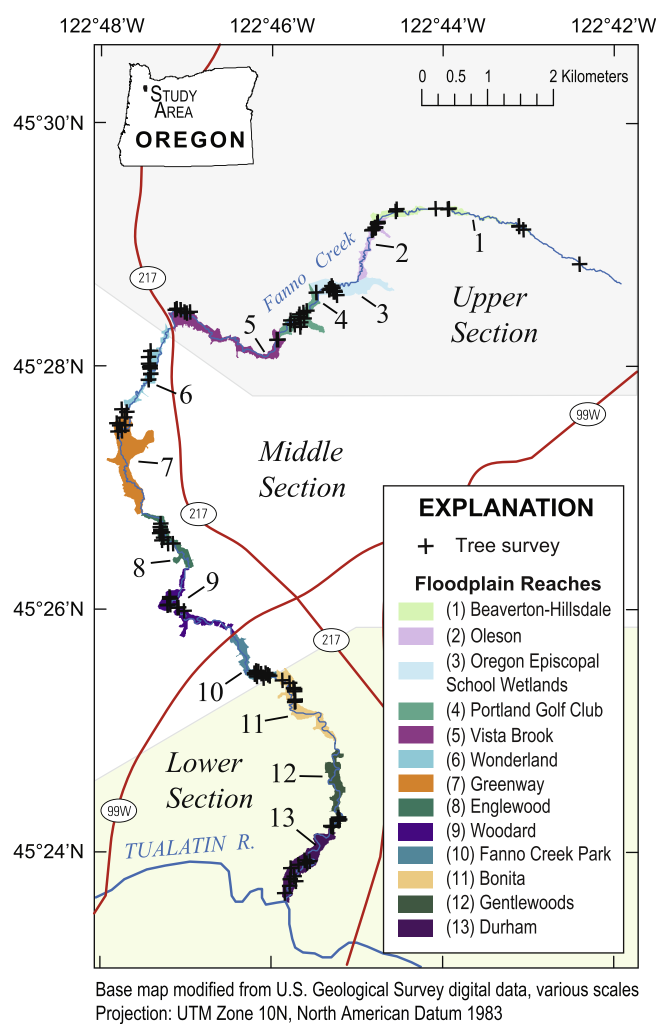

Fig. 1. Location of Fanno Creek, Oregon, including reach extents and tree inventory sites.

Table 1
Land cover percentages for 13 stream reaches of the Fanno Creek floodplain, Oregon (Sobieszczyk, 2011b,c). **Bold** values represent dominant land cover type. *Italic* values represent subdominant land cover type that covers at least one-third of the floodplain. Shading represents demarcation between upper, middle, and lower sections.

Reach Information			Dimensions		
Reach	Name	Section	Floodplain	Stream	
			(km^2)	(km)	(km^2)
1	Beaverton-Hillsdale	Upper	0.17	4.7	0.021
2	Oleson	Upper	0.12	1.5	0.009
3	Oregon Episcopal School Wetlands	Upper	0.22	1.0	0.006
4	Portland Golf Club	Upper	0.16	1.1	0.005
5	Vista Brook	Upper	0.28	2.9	0.020
6	Wonderland	Middle	0.15	1.8	0.009
7	Greenway	Middle	0.41	2.3	0.010
8	Englewood	Middle	0.14	1.5	0.002
9	Woodard	Middle	0.22	2.4	0.016
10	Fanno Creek Park	Middle	0.14	1.4	0.008
11	Bonita	Lower	0.22	2.2	0.014
12	Gentlewoods	Lower	0.18	2.1	0.012
13	Durham	Lower	0.26	2.4	0.027

wetland plants and animals. The lower section of the floodplain is dominated by older deciduous and mixed deciduous-conifer forests. Deciduous trees are found along most of the floodplain, although the largest and most mature trees grow in the lowest reaches, such as Reach 13.

1.2.2. Common tree species

The Fanno Creek floodplain contains a diverse community of plant species. In wetland areas plants species include willow (*Salix* spp.), cottonwood (*Populus* spp.), Oregon ash (*Fraxinus latifolia*), and red alder (*Alnus rubra*). In forested areas woody deciduous plant species are dominant, such as red alder, Oregon ash, cottonwood, American aspen (*Populus tremuloides*), bigleaf maple (*Acer macrophyllum*), and Oregon oak (*Quercus garryana*), with sparsely distributed coniferous plots of Douglas-fir (*Pseudotsuga menziesii*) and western hemlock (*Tsuga heterophylla*). Invasive plants like English ivy (*Hedera helix*), Himalayan blackberry (*Rubus armeniacus*), and reed canary grass (P*halaris arundinacea*), have overtaken large swaths of the upper section.

1.3. Concurrent research

The research presented in this article summarizes the first component of a three part investigation. The overall project goal was to identify and quantify sources of organic matter found in and around Fanno Creek that decompose and deplete oxygen from the stream. The research presented here was designed to investigate terrestrial riparian sources of organic matter, such as foliar or leaf litter biomass. The remaining components of the study, which are also presented in this issue, focus on floodplain soils and sediment-related sources and sinks of organic matter (Keith et al., 2014) and associated instream water-quality characteristics, such as dissolved and particulate carbon, organic matter fluorescence, and suspended-sediment concentrations (Goldman et al., 2014). Together, these concurrent research efforts provide a comprehensive overview of the origin, transport, and fate of organic matter in Fanno Creek.

2. Methods

2.1. Canopy metrics

2.1.1. Canopy metric definitions

Unlike forestry professionals who are interested in the relation of canopy metrics to forest fuel loads (Anderson, 1982; Erdody and Moskal, 2010; Keane et al., 1998; Reinhardt et al., 2006) or other timber-production costs (Forest Products Laboratory, 1999; Harrison et al., 2009; Koerper and Richardson, 1980; Rebain et al., 2011), this research explores how canopy metrics can be used to estimate what foliage falls down, rather than what combusts. Metrics (Table 2) like canopy base height (CBH), canopy height (CH), canopy length (CL), and canopy bulk density (CBD) can be computed from field-based measurements (Fule et al., 2001; Hoffman et al., 2007) or through remotely sensed methods (Anderson et al., 2005; Erdody and Moskal, 2010; Keane et al., 2005; Li et al., 2008). The approach employed for this research supplements LiDAR-derived canopy metrics (e.g., CBH, CH, and CL) with field-based measurements of CBD.

2.1.2. LiDAR-derived canopy metrics

Tree canopy metrics were calculated from available LiDAR point cloud data (Puget Sound Lidar Consortium, 2004; Oregon Department of Geology and Mineral Industries, 2009) using the software package FUSION (McGaughey, 2009). Using the CLOUDMETRICS feature and all LiDAR returns, the software generated a suite of canopy characteristics, including CH, CBH, and percent canopy cover for all plots of coniferous and deciduous trees taller than 3 m. A 3 m threshold was established to eliminate ground return surfaces and other potential near-surface errors originating from the LiDAR data. The difference between the CH and the CBH was used to determine CL (height component for calculating canopy volume).

2.1.3. Deciduous and coniferous plot classification

Next, using available land cover data (Sobieszczyk, 2011c) coniferous and deciduous tree plots were separated, by reach, for both tree types. In this case, a plot refers to the area mapped as either deciduous or coniferous within each reach. Therefore, canopy metrics were produced for 26 discrete plots (i.e., coniferous and deciduous plots for each of the 13 reaches) along the Fanno Creek floodplain. Areas classified as urban, water, shrub, farm, and wetland in the land cover data set were removed from the analysis because the associated vegetative features were either below the tree height threshold (i.e., <3 m) or did not produce foliar biomass (e.g., asphalt). All canopy metric calculations were assumed to have a homogeneous, anisotropic distribution of data across each reach (i.e., canopy varied laterally by tree type, however each type remained consistent vertically). By assuming a uniform vertical distribution, we eliminated the known bias in the point cloud data toward the upper canopy due to the higher density of first return points (Lim et al., 2003). Also, by assuming a single vertical value, this approach can be reproduced elsewhere where more detailed elevation/height data may be limited. The mapped areas for the different tree types provided the areal extent used in conjunction with the CL to estimate reach-based canopy volumes. With a canopy volume calculated, the only remaining requirement was a foliar CBD to compress the volume into an actual biomass load.

2.2. Field-based measurements

2.2.1. Tree inventory

Field surveys focused on seven common tree species (i.e., alder, ash, aspen, maple, oak, willow, and Douglas fir) found in the study area (Table 3), as other deciduous or coniferous species not identified were assumed to share similar crown structures and crown bulk densities as those listed. A total of 130 trees (i.e., 10 trees per reach) were selected, identified, and measured along the Fanno Creek floodplain (Fig. 1). All trees selected were taller than 3 m, were in close proximity to the creek, and were chosen to represent species diversity within each reach. Measurements from the tree inventory included location, tree species type, diameter at breast height (DBH), crown height, crown base height, and crown base width (radius). Crown metrics were measured in the field using an inclinometer and tape measure. Additional metrics, such as crown length and crown volume, were also calculated from the field measurements. Crown length equaled the distance between crown height and crown base height. Crown volumes were calculated based on a generalized tree shape, where the volume equation for a dome (Eq. (1)) was used for all deciduous trees and the volume equation for a cone (Eq. (2)) was used for all coniferous trees.

$$V = \frac{\pi h}{6}(3r^2 + h^2) \tag{1}$$

$$V = \frac{1}{3}(\pi r^2 h) \tag{2}$$

where V is tree crown volume (m^3), r is radius at crown base (m), and h is crown length. After determining the crown volume, allometric equations were used to calculate foliar biomass and crown bulk densities.

2.2.2. Allometric equations

Due to an established correlation between DBH and tree crown biomass (Brown, 1978; Brown et al., 1982; Snell and Little, 1983), it was possible to calculate crown biomass and crown bulk density using field measurements and tree-specific allometric equations (Eq. (3)). Allometric equations have proven effective for decades at relating relative sizes of plant parts, such as DBH to tree height or DBH to crown biomass. The base equation used for calculating crown foliage was (Ter-Mikaelian and Korzukhin, 1997):

$$M = a(DBH)^b \tag{3}$$

where M is oven-dry weight biomass for foliage (kg), DBH is diameter at breast height (cm), and a and b are tree species-specific coefficients (Table 3). Once the crown biomass (kg) was calculated, the measured crown volume (m^3) was converted into a crown bulk density (kg/m^3). The crown bulk density for an individual tree was calculated using the equation:

$$c = \frac{M}{V} \tag{4}$$

where c is the crown bulk density (kg/m^3), M is oven-dry weight biomass for foliage (kg), and V is crown volume (m^3). Hence, allometric equations were used to calculate individual tree crown bulk density and crown foliar biomass for the inventoried trees. Once individual tree crown bulk densities were calculated, they were converted into a canopy bulk density (CBD) by averaging all deciduous tree crown bulk densities together and averaging all coniferous tree crown bulk densities together. Crown measurements refer to a single tree, whereas canopy values represent the generalized structure of all trees in a specific plot.

2.2.3. Calculating annual foliar biomass

Annual floodplain and over-stream foliar biomass was calculated for each reach using the LiDAR-derived canopy metrics and field-derived CBD values (Eq. (5)). Floodplain (Sobieszczyk, 2011b) and over-stream (Sobieszczyk, 2011a) spatial extents were mapped previously. The over-stream extent was based on the 2-yr streamflow recurrence flow interval channel width. Biomass values represented the available annual foliar biomass produced, assuming that deciduous trees shed their entire foliage each year (1-year lifespan). Coniferous plot biomass contributions were scaled to one-fifth of their measured canopy as the inverse fraction of their 5-year foliage lifespan (Rebain et al., 2011). Therefore, the foliar biomass annually available for each reach was calculated as:

$$\sum_i (CL_i * A_i * CBD_i) * \frac{1}{y} \tag{5}$$

where CL is the canopy length (m), A is tree canopy plot area (m^2), CBD is the canopy bulk density (kg/m^3), y is the vegetation lifespan, and i is tree type. The final floodplain foliar biomass was calculated for deciduous and coniferous plots and then summed along each reach to produce a total foliar biomass load. Annual over-stream foliar biomass was calculated using a similar methodology, except the spatial extent was truncated to areas directly over the mapped channel.

2.2.4. Uncertainties in biomass estimates

Uncertainties exist in every level of data collection and processing. For example, uncertainties were present in the LiDAR data collection, the post-processing of the data, and in the final manipulations and computations. Likewise, there were uncertainties and assumptions made for tree inventory field measurements and for the accuracy of the allometric equation calculations that were used. To address these potential errors, each of the sources

Table 2
Canopy metric definitions.

Canopy metric	Acronym	Description	Units
Canopy base height	CBH	Mean height for bottom of tree canopy unit	m
Canopy height	CH	Mean height for top of tree canopy unit	m
Canopy length	CL	Length or height of tree canopy unit (CH – CBH = CL)	m
Biomass	–	Mass of material	kg
Canopy fuel	CF	Mass of material, per tree canopy unit area	kg/m^2
Crown bulk density	–	Mass of crown material, per crown volume (individual tree)	kg/m^3
Canopy bulk density	CBD	Mass of tree canopy material, per tree canopy unit volume (group of trees)	kg/m^3

Table 3
Tree species-specific coefficients used in the allometric biomass equations of Ter-Mikaelian and Korzukhin (1997).

Name	Allometric Coefficients		Source
	a	b	
Red alder (*Alnus rubra*)	0.010	1.940	Snell and Little (1983)
Cottonwood/aspen (*Populus* spp.)	0.016	1.693	Ker (1980)
Oregon ash (*Fraxinus latifolia*)	0.004	2.148	Koerper and Richardson (1980)
Bigleaf maple (*Acer macrophyllum*)	0.022	1.617	Gholz et al. (1979)
Oregon oak (*Quercus garryana*)	0.048	1.455	Perala and Alban (1994)
Willow (*Salix* spp.)	0.030	1.692	Young et al. (1980)
Douglas-fir (*Pseudotsuga menziesii*)	0.046	1.701	Gholz et al. (1979)

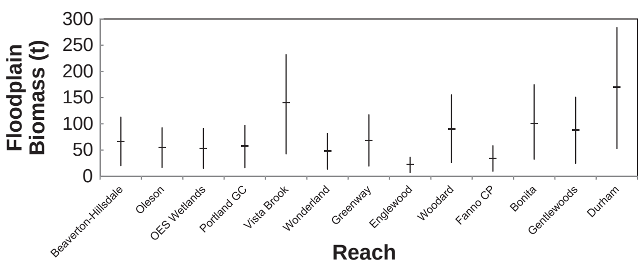

Fig. 2. Annual foliar biomass (t), by reach, for the floodplain along Fanno Creek, Oregon. Data variability shown as one standard deviation from mean.

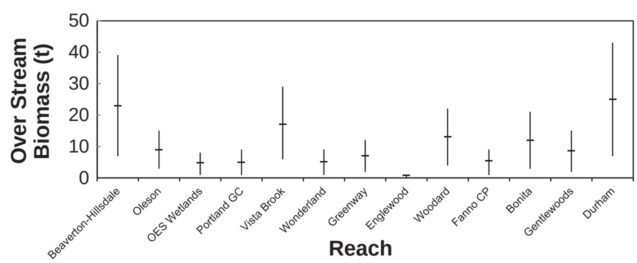

Fig. 3. Annual foliar biomass (t), by reach, for the over-stream extents along Fanno Creek, Oregon. Data variability shown as one standard deviation from mean.

of error used to compute foliar biomass was assessed and a potential magnitude of error was estimated. Based on a combination of variances for each of the independent sources, an uncertainty was calculated for both the floodplain and over-channel biomass estimates using the root mean square error propagation method outlined by Topping (1972) and Harmel et al. (2006):

$$E_p = \sqrt{E_1^2 + E_2^2 + \cdots + E_n^2} = \sqrt{\sum_i E_i^2} \qquad (6)$$

where E_p is the probable error of a calculated quantity, n is the number of sources of error, and E_1 through E_n are the errors from each source. Based on the error analysis, a resultant range of values was applied as a percentage error for the total foliar biomass values. Individual potential distributions of biomass for each reach are also shown in Figs. 2 and 3 as one standard deviation.

3. Results

3.1. Canopy bulk densities

Before canopy biomass could be calculated, the CBD for deciduous and coniferous plots was determined. Based on field measurements the crown bulk densities for all deciduous trees ($n = 109$; two outliers removed from analysis) were averaged to generate a mean CBD of 0.05 kg/m^3 (range: 0.01–0.11 kg/m^3) for deciduous tree plots. Since Douglas-fir trees ($n = 19$) were the only coniferous trees inventoried, their average crown bulk density was used for a CBD of 0.12 kg/m^3 (range: 0.04–0.19 kg/m^3). These values were comparable to other CBD values published in the scientific literature, such as by Keane et al. (1998, 2000) for broadleaf riparian forest (0.01 kg/m^3) and Douglas-fir (0.10–0.25 kg/m^3).

3.2. Foliar biomass available in floodplain

About 991,000 kg (±22%) or 991 metric tons (tonnes, t) of foliar biomass is annually available to the Fanno Creek floodplain as potential leaf litter (Table 4). A large percentage of this source of organic matter is located in reaches where there is an abundance of large deciduous trees, especially those with a dense canopy cover. For example, the two reaches with the largest percentage of forested deciduous land cover (Reaches 5 and 13) generate 31% of all foliage available in the floodplain (Table 1). The amount of leaf litter organic matter present varies considerably (Fig. 2) depending on the location and dominant land use of the reach, with Reach 8 producing the least foliar biomass at only 22 t, while Reach 13 generates the most at 170 t (Table 4). A comparison of reach yield (Table 4) highlights the disparity in production. The heavily forested Reach 13 produces 640 t/km^2, considerably more foliage than the next two most productive streams, Reach 12 (500 t/km^2) and Reach 5 (500 t/km^2). The two wetland-dominant reaches (Reach 7 and 8) yield the lowest amount of foliar biomass with 170 t/km^2 and 150 t/km^2, respectively.

Based on dominant land cover (Table 1), there are certain overall trends in biomass production in the upper, middle, and lower sections. The upper section of Fanno Creek (Reaches 1–5) produces a floodplain biomass proportional to its area, with 37% of the total foliage available over 36% of the total floodplain area. This distribution becomes less consistent downstream, as the middle section (Reaches 6–10) produces only 26% of the foliar biomass over 39% of the floodplain area. The lower section (Reaches 11–13) produces 36% of the foliar biomass over 25% of the area. Therefore, even though the largest amount of foliage is generated in the upper section compared to the middle and lower sections (371 t compared to 262 t and 358 t, respectively), when normalized by area, the yield is much greater in the upper (540 t/km^2) and lower sections (570 t/km^2) than the middle section (210 t/km^2). The biomass distribution relates strongly to the dominance of forested areas in the upper and lower reaches and the prevalence of wetland or grassy park-land areas in the middle reaches.

3.3. Foliar biomass available over the stream

Only a fraction (about 14%) of the overall floodplain foliage falls directly into Fanno Creek, with about 136 t (±24%) of the overall annual foliar biomass present above the active stream channel in any given year (Table 4). This ratio of over-stream to floodplain biomass is generally reflected in each reach, where 4–16% of the floodplain foliage overhangs the stream. The only noticeable exception is Reach 1, where 35% of the floodplain foliage is located directly above Fanno Creek. This above average ratio is related to

Table 4
Annual foliar biomass (t), by reach, for both the floodplain and over-stream extents along Fanno Creek, Oregon.

Reach	Name	Annual foliar biomass				
		Floodplain		Over stream		
		(t)	(t/km^2)	(t)	(t/km)	(t/km^2)
1	Beaverton-Hillsdale	66	380	23	4.9	1100
2	Oleson	55	460	9	6.1	1,000
3	Oregon Episcopal School Wetlands	53	240	5	5.0	830
4	Portland Golf Club	57	350	5	4.7	950
5	Vista Brook	140	500	17	6.0	860
6	Wonderland	48	320	5	2.8	580
7	Greenway	68	170	7	3.0	730
8	Englewood	22	150	1	0.5	400
9	Woodard	90	410	13	5.5	820
10	Fanno Creek Park	34	250	6	3.8	700
11	Bonita	100	450	12	5.6	870
12	Gentlewoods	88	500	9	4.2	740
13	Durham	170	640	25	10.4	940
x		991 (±22%)		136 (±24%)		

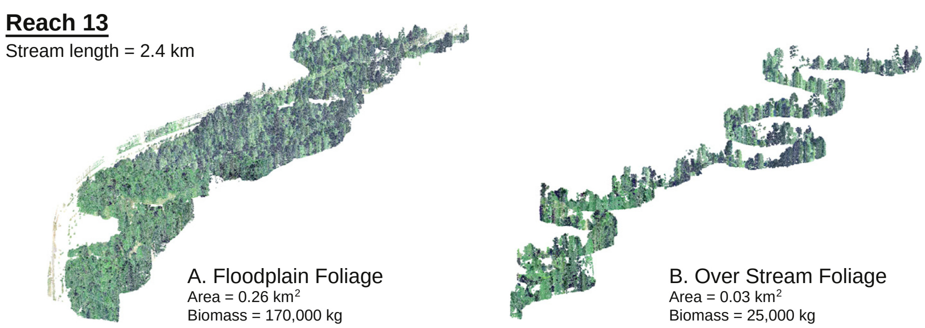

Fig. 4. Example of LiDAR point cloud data used to calculate foliar biomass for both floodplain and over-stream extents for Reach 13. Data viewed with LiDAR Data Viewer extension of FUSION software (McGaughey, 2009).

the shape of the floodplain along this reach (Fig. 1), which is narrow but heavily forested. Reach 1 produces the second largest amount (Fig. 3) of total annual over-stream foliage (23 t), slightly less than the largest forested reach, Reach 13 (25 t). The rate of production for Reach 1 is by far the largest, with 1100 t/km^2, demonstrating how dense the overhanging vegetation is along the reach. Comparatively, Reach 13 produces 940 t/km^2 of material directly to the stream each year. Fig. 4 illustrates the LiDAR point cloud data comparison of canopy cover and potential biomass production between the floodplain and over-stream for Reach 13.

Wetland-dominant reaches (Reaches 3, 6, and 8) have very little overhanging vegetation; therefore, their available foliar biomass is much less (Table 4). Typically, wetland biomass production is restricted to shrub and ground-based vegetation. When normalized by area, the rates of foliar biomass production are similarly small, with Reach 8 yielding only 400 t/km^2 of leaf litter to the stream, less than half of the most productive reaches. Unlike the floodplain estimates that are dependent on the tree type (e.g., deciduous), over-channel biomass estimates appear to be controlled more by the length of stream and its relative stream area. Reach 13 supplies the largest amount of organic matter per length of channel (10.4 t/km), nearly twice as much as the next largest contributor. The smallest contribution per reach is Reach 8, where only 0.7 t/km falls annually.

4. Discussion

4.1. Implications for stream management

Resource managers are responsible for maintaining the quality of the water and ecosystems in streams in their jurisdiction. Due to the interaction of streams with the surrounding environment, often times the best way to address an instream issue is to focus on the adjacent landscape. A classic example of this relation is the reduction of instream temperatures through tree plantings and improved canopy shading along the riparian area. In Fanno Creek, one of the major water-quality issues is the seasonal drop in dissolved oxygen concentration. ODEQ standards for DO (when adequate data exist) require that DO concentrations between 16 May and 31 December not fall below any of three established criteria for cool water aquatic habitats in Oregon: (1) the 30-day mean DO without credit for supersaturation must remain above 6.5 milligrams per liter (mg/L); (2) the 7-day average of the daily minimum DO must remain above 5.0 mg/L; and (3) there shall be no instantaneous DO readings that fall below 4 mg/L (Oregon Department of Environmental Quality, 2014). Between 01 January and 15 May DO concentrations for salmon spawning are 11.0 mg/L as a 7-day mean, with no credit for supersaturation. Throughout the year DO concentrations near or do not meet these criteria for Fanno Creek (Fig. 5). Therefore, it has become paramount for resource managers to address the sources, processes, and system dynamics that drive DO concentrations below these established water-quality standards.

Decreases in DO concentration can be caused by many factors, such as increases in stream temperature, lack of turbulent flow and aeration, sediment oxygen demand (SOD), and biochemical oxygen demand (BOD), among others. The type and amount of riparian vegetation greatly affects many of these causes. Trees provide shade to cool the stream, they supply organic matter directly to the stream (leads to SOD and BOD), and they supply organic matter to the floodplain that breaks down into soil (leads to SOD). Therefore, the more information managers have about where

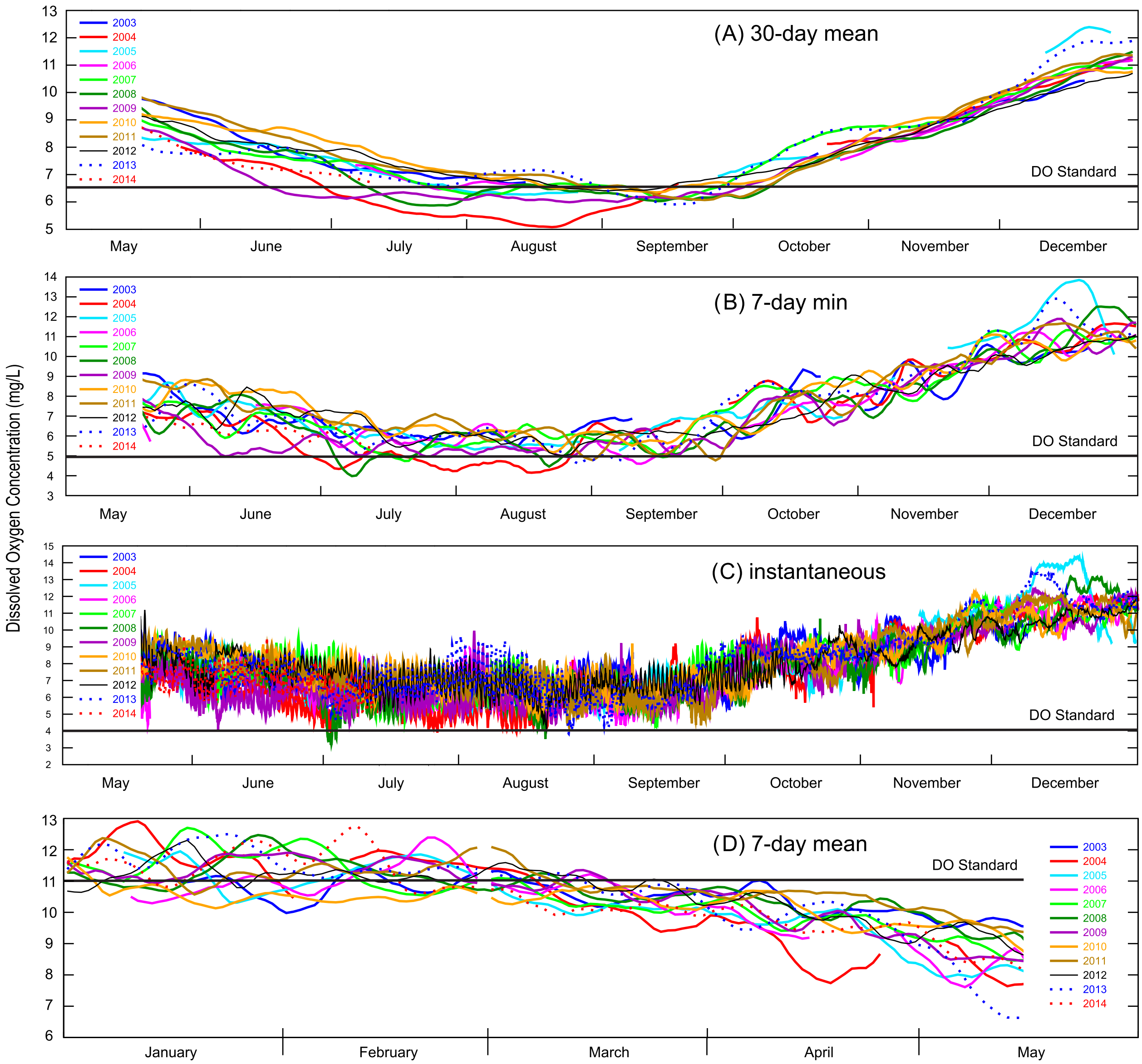

Fig. 5. Continuous monitored dissolved oxygen (DO) concentration for Fanno Creek between 2003 and 2014. ODEQ standards are set for cool water aquatic life criteria (Oregon Department of Environmental Quality, 2014). DO Standard line indicates minimum criteria threshold for: A) 30-day average of daily mean DO, with no credit for supersaturation (minimum allowed – 6.5 mg/L); B) 7-day average of daily minimum DO (minimum allowed – 5.0 mg/L); C) instantaneous DO for entire period of record (minimum allowed – 4 mg/L); and D) 7-day average daily mean DO, with no credit for supersaturation (minimum allowed – 11 mg/L). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the trees are, the size and density of the tree canopy, and the type of tree (e.g., deciduous or coniferous), the better they will be able to make critical management and restoration decisions.

4.2. Application of hybrid approach

4.2.1. Integrating field measurements into LiDAR estimates

Foliar biomass can be estimated at a reach scale for an urban riparian corridor by incorporating both field measurements and remotely sensed data. By integrating field-based measurements of CBD (kg/m^3) with the volumetric canopy measurements (m^3) from LiDAR data, it becomes possible to reliably estimate the foliar biomass (t) in the floodplain tree canopy. This approach provides greater flexibility for exploring large areas of deciduous-dominant forest with greater ease than previous approaches that used only field observations (Roberts and Bilby, 2009). It also provides a solution for calculating CBD values, something that is difficult for deciduous forests using only LiDAR (Li et al., 2008). In addition, since some studies, such as those by Anderson et al. (2005) and Naesset and Bjerknes (2001), have shown a strong correlation between LiDAR-derived and field-based measurements, integrating the two has become more common. Lastly, this approach alleviates the time and expense of a solely field intensive effort, while still retaining the accuracy of large scale empirical measurements from high-resolution remotely sensed data.

4.2.2. Benefits

One major benefit of this approach is that it can be applied at a variety of scales, from individual tree, to reach, to watershed scale. However, by focusing on a reach-scale the results directly compare to reach-level estimates of fine sediment (Keith et al., 2014) and instream organic matter (Goldman et al., 2014) published by others studying Fanno Creek. Although this method does not address terrestrial organic matter contributions from other sources (e.g., contribution from tributaries and stormwater runoff), it does provide a better understanding of the relative magnitude of the terrestrial sources of organic matter in Fanno Creek and downstream in the Tualatin River. And only by beginning to characterize the magnitude of these sources can appropriate and targeted management strategies be crafted.

The greatest advantage of this approach is that it can be applied anywhere LiDAR data are available. Also, since CBD values are measured in the field, local tree species variability is accounted for in the specific study area of interest. This approach is applicable for coniferous forests, deciduous forests, or even urban parks. One ideal environment where this approach can be applied is in orchard-dominant agricultural areas. The large areas of alternating plots of similar trees can be easily quantified and their associated biomass loads estimated. In addition, if there are water-quality data for pesticides or fertilizers associated with runoff from these areas, combining those data with the organic matter loads could prove rather useful.

4.3. Limitations to study design

The goal of this research was to test whether (and with what accuracy) a hybrid method using field measurements and remotely sensed data can be used to estimate how much foliage is produced along Fanno Creek in any given year. With this information, land resource managers can derive insights into the source areas, and subsequently the delivery mechanisms, of terrestrial biomass material that may enter the system, break down, and cause issues instream. This research does not address all terrestrial biomass delivery mechanisms (e.g., erosion, overland flow), nor how, when, and where organic matter is retained and broken down on the land. Keith et al. (2014) addresses some of those questions by exploring organic matter contribution from bed and bank sediments. Similarly, this method does not address seasonal variation in the litterfall contribution, but it could be adapted to that time period if the spatial extents of the river and respective canopy volumes were determined. Generally, by focusing on the floodplain and channel extents, we tried to best address the potential maximum annual contribution (i.e., floodplain), as well as the expected single year (i.e., active channel) contribution of leaf litter for the stream system. This approach provides results at a scale where real-world decisions can be made.

5. Conclusions and summary

The results from this study demonstrate that remotely sensed data can be used in conjunction with field measurements to successfully estimate annual foliar biomass in a deciduous-dominant riparian area. Landscape characteristics of the floodplain have a strong effect on the delivery of organic matter to streams. The wide range in production between the different stream reaches demonstrates this. Based on the available data, foliar biomass production in the floodplain varies significantly by stream reach (22–170 t). Biomass production is greatest in reaches where densely populated mature deciduous forest plots are present. Most of the heavily deciduous forested areas are found in the lower sections of the study area (Reaches 11–13), with a few exceptions (Reaches 1 and 5). Foliar biomass production is far less in the densely urban and sparsely vegetated wetland areas. In fact, the wetland-dominant reaches (Reaches 6, 7, 8, and 10) produce significantly less annual canopy foliage than the forested reaches.

Generally, the fraction of foliage overhanging the stream in relation to foliage in the floodplain is consistent among reaches (4–16%), regardless of land use and deciduous versus coniferous tree canopy type. It appears that reaches with the longest stream segments, and thus greatest stream area, tend to have the most over-stream biomass loading (Reaches 1, 5, 9, and 13). Inputs of foliar biomass from tributaries to Fanno Creek, or from vegetation outside of the floodplain, were not included in this study. Of the 991 t (±22%) of foliar biomass produced annually along the Fanno Creek floodplain, only 136 t (±24%) of the foliage falls directly into the stream channel. This component of the terrestrial source material is likely to be a large and important contribution to the organic matter found in the stream that breaks down and leads to low dissolved oxygen concentrations found in Fanno Creek.

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Investigating organic matter in Fanno Creek, Oregon, Part 2 of 3: Sources, sinks, and transport of organic matter with fine sediment

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SUMMARY

Organic matter (OM) is abundant in Fanno Creek, Oregon, USA, and has been tied to a variety of water-quality concerns, including periods of low dissolved oxygen downstream in the Tualatin River, Oregon. The key sources of OM in Fanno Creek and other Tualatin River tributaries have not been fully identified, although isotopic analyses from previous studies indicated a predominantly terrestrial source. This study investigates the role of fine sediment erosion and deposition (mechanisms and spatial patterns) in relation to OM transport. Geomorphic mapping within the Fanno Creek floodplain shows that a large portion (approximately 70%) of the banks are eroding or subject to erosion, likely as a result of the imbalance caused by anthropogenic alteration. Field measurements of long- and short-term bank erosion average 4.2 cm/year and average measurements of deposition for the watershed are 4.8 cm/year. The balance between average annual erosion and deposition indicates an export of 3,250 metric tons (tonnes, t) of fine sediment to the Tualatin River—about twice the average annual export of 1,880 t of sediment at a location 2.4 km from the creek's mouth calculated from suspended sediment load regressions from continuous turbidity data and suspended sediment samples. Carbon content from field samples of bank material, combined with fine sediment export rates, indicates that about 29–67 t of carbon, or about 49–116 t of OM, from bank sediment may be exported to the Tualatin River from Fanno Creek annually, an estimate that is a lower bound because it does not account for the mass wasting of organic-rich O and A soil horizons that enter the stream.

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1. Introduction

Low dissolved oxygen (DO) concentration is a water-quality impairment (Oregon Department of Environmental Quality, 2013; U.S. Environmental Protection Agency, 2012). One of the most important causes of low DO concentrations in streams is the decomposition of organic matter in bed sediment, which consumes oxygen from the surface water. Adverse effects on fish and benthic invertebrates potentially result from low DO concentrations (Domenici et al., 2013; Karna, 2003; Kramer, 1987). Reductions in the amount of organic matter (OM) deposited in stream sediment may decrease the rate of oxygen consumption during decomposition. Identifying and quantifying the sources and transport of OM in these systems can assist in developing policies for improving oxygen conditions. Organic carbon is a major component of OM and its characteristics can be used to help determine the source of that OM, such as terrestrial versus aquatic sources (McKnight et al., 2001). OM may adhere to or be a component of fine, cohesive sediment, and that association provides a link between water quality and fine sediment transport (Huang et al., 2006). Thus, tracking fine-sediment erosion, deposition, and transport along a channel and floodplain is one approach to characterizing temporal and spatial OM sources and movement.

Quantifying the sources and sinks of OM and organic-rich fine sediment can help guide management decisions targeting low DO. Local channel geometry may be more important to the overall transport of particulate organic matter than larger basin characteristics (Sedell et al., 1978). Sediment sources are often associated with erosional geomorphic features such as banks, hillslopes, and landslides, while sediment sinks relate to depositional features like floodplains, channel bars, or pools. An inventory of these features and their spatial distribution along a stream corridor can provide valuable information regarding the locations where fine sediment and carbon are being produced, transported, and stored. The mechanism by which those features are created or stored (Steiger et al., 2003; Wohl et al., 2012) also relates to temporal sediment mobility and interaction with the stream. Quantification of erosion and deposition of features at specific locations can indicate how sediment cycling occurs within other similar environments in the basin. Additionally, linking sediment to location and to causation is a benefit to using a

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sediment tracking approach to inform management and restoration decisions (Gellis and Walling, 2011) as well as providing information on other possible water quality concerns associated with fine sediment (e.g., turbidity; Wood and Armitage, 2007). In addition, understanding the hydrologic connectivity regime of a stream system could provide insight the transport of other pollutants or non-native species (Jackson and Pringle, 2010).

1.1. Background and purpose

Periodic low DO concentration is an impairment for certain tributaries of the Tualatin River in northwest Oregon, including Fanno Creek (Fig. 1; Bonn and Rounds, 2010; Rounds and Doyle, 1997; Rounds et al., 1999). A recent study by Bonn and Rounds (2010) in the watershed and elsewhere in the larger Tualatin River basin determined that OM in stream-bed sediment is derived primarily from terrestrial sources, based on isotopic fractionation of carbon (C) and nitrogen (N), and C to N ratios. Soil and terrestrial plant material were determined to be the most likely sources of OM to stream sediments in the Tualatin River, and isotopic results of bed sediment in Fanno Creek resembled the signature of sediment in the Tualatin River. The key terrestrial sources of OM in Fanno Creek and other Tualatin River tributaries have not been fully identified but could include litterfall biomass, eroded bank sediment, overland soil transport, or stormwater (Bonn and Rounds, 2010).

Channel erosion can be a major source of sediment in an urban basin (Nelson and Booth, 2002; Trimble, 1997). Simon et al. (2011) quantified erosion resistance and erosion rates of cohesive bed and bank material in the Tualatin River basin, finding erosion as great as 3.82 m^2 per meter of bank over the modeled period between 2000 and 2009 in parts of the Fanno Creek watershed. Using a geomorphic assessment protocol, Simon et al. (2011) evaluated 47 sites throughout the Fanno Creek watershed, finding 31 sites to be "disturbed". Their application of the Bank Stability and Toe Erosion Model at nine sites along Fanno Creek indicated no erosion at five sites but substantial bed and bank-toe erosion for four other sites for flow conditions during the years 2000–09.

Based on these previous studies (Bonn and Rounds, 2010; Rounds and Doyle, 1997; Rounds et al., 1999; Simon et al., 2011) and the heavily developed land use (U.S. Geological Survey, 2011), we hypothesize large quantities of channel bank erosion could account for the dominant contribution of OM in Fanno Creek. The purpose of this study was to identify the key sources of terrestrial organic carbon within the Fanno Creek watershed and quantify the amounts of sediment and associated OM being eroded, deposited, and transported. Understanding the relative contributions of organic matter from different terrestrial sources can inform management actions. To determine the amount of sediment and OM being eroded, deposited, and transported, a geomorphic approach was adopted that identified specific sources and sinks of fine sediment and applied measurements of erosion, deposition, and total organic carbon (TOC) content. OM and fine-sediment export from Fanno Creek to the Tualatin River was estimated and then compared to the export of suspended sediment calculated from continuously monitored turbidity. These data and techniques were used to provide insight into the primary sources of OM in Fanno Creek and estimate the amount of that material exported to the Tualatin River.

1.2. Concurrent research

This article summarizes the second component of a three-part investigation to quantify sources of organic matter (OM) to Fanno Creek in northwest Oregon, where it can then decompose and deplete dissolved oxygen levels. The first component of the study (Sobieszczyk et al., 2014) investigated and quantified annual loads of riparian sources of organic matter, such as foliage and leaf litter biomass. This paper focuses on sources, sinks, and transport of organic matter associated with fine sediment. The third part of the study used measurements of water-quality characteristics to determine instream loads and export rates of organic matter and quantify seasonal variations that relate to OM sources (Goldman et al., 2014).

1.3. Study area

Fanno Creek is a 27-km (km) long tributary to the Tualatin River (Fig. 1) draining 82.4 square kilometers (km^2) near Portland, Oregon. Fanno Creek originates in the Hillsboro Formation, terrestrial sedimentary rock, but shortly thereafter flows into fine-grained Missoula Flood and other Pleistocene lacustrine deposits (Ma et al., 2009; Wilson, 2000). Soils are silty with slow infiltration rates (Natural Resources Conservation Service, 2012).

The Fanno Creek watershed is dominated by urban land use (89% developed, 8% forested, and 3% other; U.S. Geological Survey, 2011). The main-stem channel flows through moderately forested riparian corridors, open wetland zones, and dense residential or industrial areas. The banks of Fanno Creek have been stabilized at numerous locations, especially where the channel is adjacent to business and residential zones. Dominant bed material varies between silt–clay muds mixed with organic detritus and more resistant hardpan clay (dense, low permeability soil). Natural accumulations of sand and gravel are present only in the uppermost and lowermost segments, but local accumulations of introduced gravel to boulder-sized rock, either intentionally placed in the channel or mobilized from bank armoring, are found throughout Fanno Creek.

The USGS operates two year-round streamflow-gaging stations in the watershed (Fig. 1; U.S. Geological Survey, 2013a): Fanno Creek at 56th Avenue in the upper watershed (station 14206900) and Fanno Creek at Durham Road in the lower watershed (station 14206950). A high density of impervious areas within the urban setting, combined with poorly drained soils along much of Fanno Creek, creates a hydrologically flashy environment where discharge and stage rise and fall quickly with precipitation (Chang, 2007). At the lower station (14206950), typical summertime low flows as estimated by the 7Q10 statistic (annual 7-day minimum flow with a 10-year recurrence interval; Risley et al., 2008) are 0.056 cubic meters per second (m^3/s), whereas the two-year recurrence-interval flow is approximately 18.7 m^3/s (U.S. Geological Survey, 2013b).

The Fanno Creek study area is approximately confined to 13 reaches of the geomorphic floodplain (Fig. 1), as previously mapped by Sobieszczyk (2011), but this research focused on the active channel and riparian corridor where sediment exchange is most prevalent; that is, where flooding regularly inundates the floodplain. The geomorphic floodplain does not relate to a specific flood magnitude or frequency, or a specific morphologic feature such as "bankfull" (Leopold et al., 1964; Osterkamp and Hupp, 1984), but rather is the area of landforms and processes that have been created by the fluvial system since the Holocene. Heavy urbanization in the area and changes in land use have disconnected portions of the geomorphic floodplain from the channel. Reaches have channel slopes ranging from 0.013 meter/meter (m/m) in the upper watershed to 0.001 m/m in the middle and lower watershed reaches (Table 1; Fig. 2).

2. Methods

2.1. Identifying sediment sources and sinks

Erosional and depositional areas within the Fanno Creek geomorphic floodplain were mapped by two methods: (1) field mapping in June through August of 2012 during the low-flow period

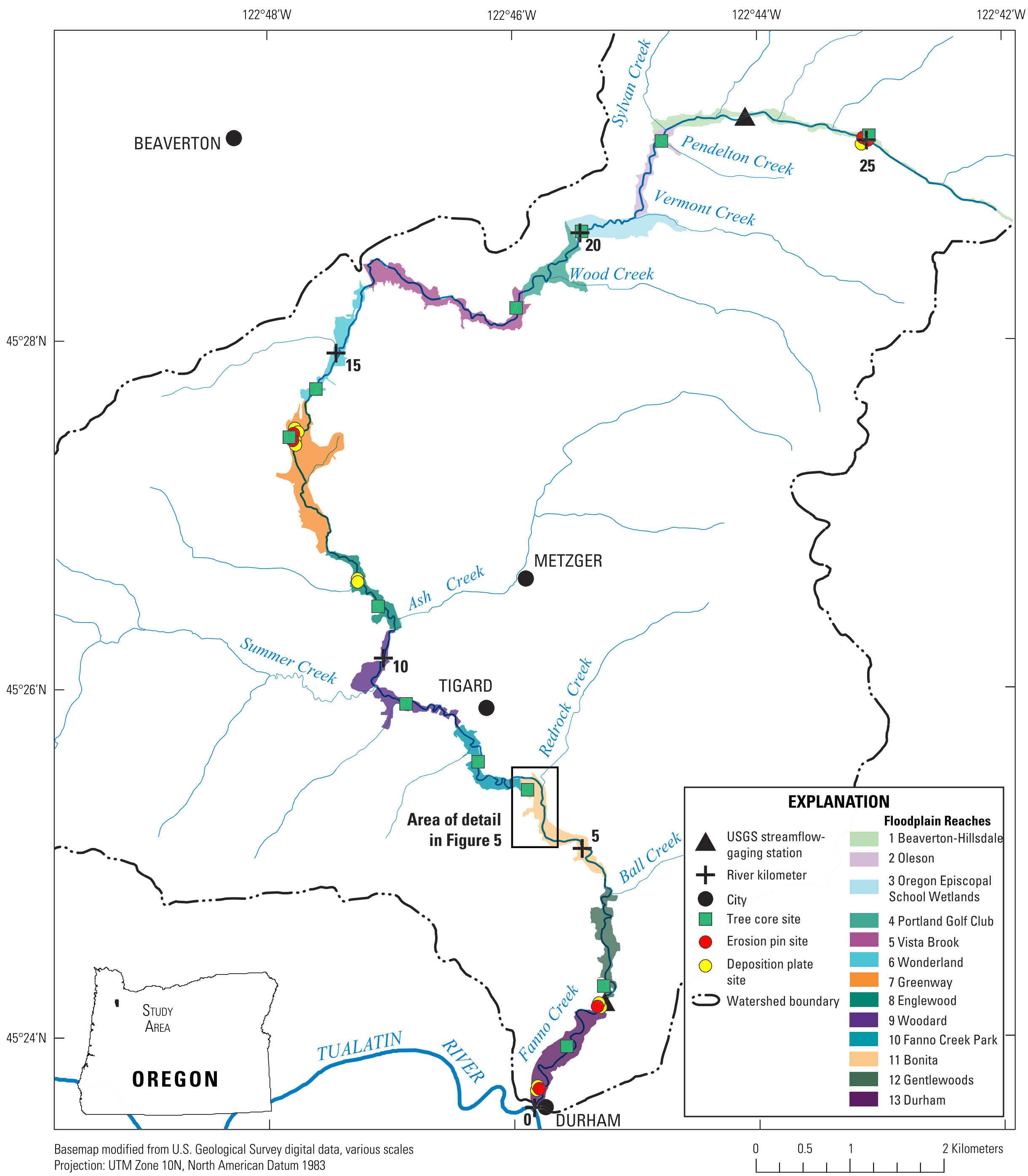

Fig. 1. Study area for Fanno Creek in northwest Oregon, including reaches and key locations.

and, (2) digital mapping from aerial photography and light detection and ranging (LiDAR) topography in the fall and winter of 2012–13. The full length of the stream was not field-mapped due to private property access restrictions, heavy riparian cover, and time constraints. As part of the mapping, locations within the floodplain and active channel were functionally identified as sediment sinks (such as in-channel bars or floodplain depressions) or sources (such as cut banks or mass failures). Mapping of features was aided by LiDAR topography acquired in 2004 (2-m resolution; Puget Sound LiDAR Consortium, 2004) and 2007 (1-m resolution; Oregon Department of Geology and Mineral Industries, 2009). LiDAR topography, LiDAR derivatives including height above water surface and slope maps, and 2010 aerial photography (15-cm resolution; Metro Data Resource Center, 2011) were used as base layers for delineating feature boundaries where possible and were the sole method of delineation where not visited in the field.

Field-mapped features (geomorphic surfaces similar to those described in Osterkamp and Hupp, 1984; Table 2), supplemented with remote mapping at a scale of 1:1,000 or finer, were converted to digital features in ArcGIS 10.0. A polygon feature class shapefile was created (available at http://water.usgs.gov/lookup/getspatial?fannoCk_erosion_deposition_2012.xml) and includes details about the mapped features (Table 2). Each feature was assigned an *Erosion* and *Deposition* type, which generalized the processes characterizing that feature. Most commonly, erosion and deposition types were assigned a *Fluvial* or *Mass wasting* designation, as

Table 1
Summary characteristics for study reaches on Fanno Creek, northwest Oregon. [Abbreviations: RKM, river kilometer; km, kilometer; m/m, meter per meter; km^2, square kilometer.]

Reach		RKM	Length, km	Slope, m/m	Drainage area, km^2	Soil composition[a]	Surficial geology[b]
1	Beaverton–Hillsdale	22.4–26.9	4.5	0.013	8.5	Fine-silty	Hillsboro Formation, Missoula Flood deposits
2	Oleson	20.8–22.4	1.6	0.005	13.3	Fine-silty	Missoula Flood deposits
3	OES Wetlands	19.9–20.8	0.9	0.003	17.3	Fine-silty	Missoula Flood deposits
4	Portland Golf Club	18.8–19.9	1.1	0.004	21.3	Fine-silty	Missoula Flood deposits
5	Vista Brook	15.95–18.8	2.9	0.002	24.4	Fine-silty	Missoula Flood deposits
6	Wonderland	14.15–15.95	1.8	0.002	26.7	Fine, fine-silty	Missoula Flood deposits
7	Greenway	11.85–14.15	2.3	0.001	30.6	Fine, fine-silty	Missoula Flood deposits
8	Englewood	10.35–11.85	1.5	0.002	44.5	Fine, fine-silty, fine-loamy	Missoula Flood deposits
9	Woodard	8.0–10.35	2.4	0.001	64.2	Fine, fine-silty, fine-loamy	Missoula Flood deposits
10	Fanno Creek Park	6.6–8.0	1.4	0.001	66.0	Fine, fine-silty, fine-loamy	Missoula Flood deposits
11	Bonita	4.45–6.6	2.2	0.001	72.8	Fine, fine-silty, fine-loamy	Missoula Flood deposits
12	Gentlewoods	2.40–4.45	2.1	0.001	80.5	Fine, fine-silty, fine-loamy	Missoula Flood deposits
13	Durham	0–2.40	2.4	0.002	82.4	Fine-silty, loamy skeletal	Missoula Flood deposits, Tualatin River alluvium

[a] *Source*: NRCS (2012); within floodplain.
[b] *Source*: Ma et al. (2009); within floodplain.

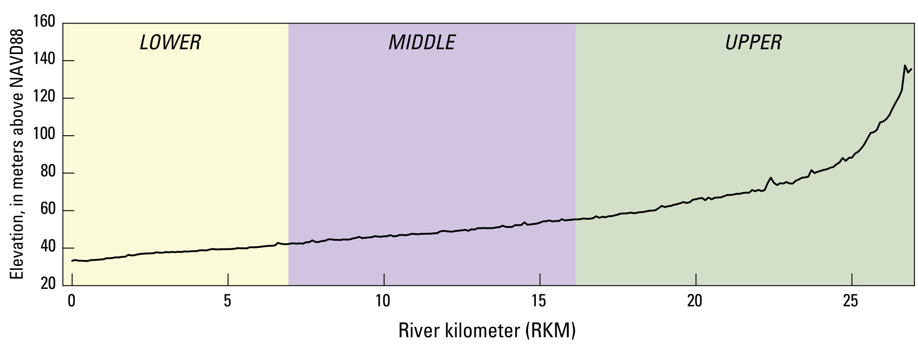

Fig. 2. Longitudinal profile of Fanno Creek, northwest Oregon from LiDAR topography.

these two processes were apparent and distinct throughout the watershed, yet not mutually exclusive based on observations that much of the mass wasting is a product of severe or long-term fluvial erosion. *Other* types of erosion and deposition mechanisms consist of hillslope, stormwater, or other urban or biotic disturbances. Disturbances by aquatic rodents, such as beaver slides, were often observed and sometimes noted but were not systematically mapped as these features were generally below a mappable resolution. Reinforced areas and culverts were included as feature types but are not an all-inclusive inventory and were limited to field visited areas, where not obscured by vegetation or eroding bank, or to those areas visible from remote sources. Relevant field notes are included in the GIS dataset, and, for field-visited sites, include information indicating the amount of bank undercutting, grain-size of sediment deposition, or height of flotsam above the floodplain surface.

2.2. Quantifying sediment sources, sinks, and transport

2.2.1. Dendrogeomorphic analysis

Dendrochronology can be used to estimate long-term rates of change or timing of events, such as bank erosion or accretion within or along a stream channel (Gartner, 2007; Gottesfeld and Gottesfeld, 1990; Heimann and Roell, 2000; Hupp and Bornette 2003; Malik and Matyja, 2008; Speer, 2010; Stoffel et al., 2012). Long-term average erosion rates were assessed with dendrogeomorphic techniques at 12 sites along Fanno Creek during the summer of 2012 (Fig. 1). Trees along the streambank were chosen on the basis of having diameters greater than 10 cm, having a degree of erosion that was representative of the reach, and not being located in an environmentally protected or sensitive area. Trees were cored with an increment borer at heights less than 50 cm above the ground surface similar to the techniques of Heimann and Roell (2000). The horizontal distance between exposed roots and undercut bank of the cored trees was measured at low flow. Where the degree of undercutting varied vertically along the bank face, multiple measurements were averaged. Tree cores were scanned at 600 dots per inch to magnify the appearance of growth rings on a computer monitor and more accurately determine tree age. The average undercutting distance was divided by tree age to estimate long-term erosion rates.

2.2.2. Erosion pins

Several studies (e.g. Bull, 1997; Hooke, 1980; Hupp et al., 2009, 2013; Kronvang et al., 2012; Laubel et al., 2000; Staley et al., 2006) have employed the use of erosion pins to measure the erosion or accretion of stream banks. For this study, short-term, event-based bank erosion was monitored at six sites in the Fanno Creek watershed (Fig. 1) with erosion pin arrays. Arrays were placed on the left and right banks at a straight site and a meander site in the upper, middle, and lower watershed for a total of 12 pin arrays. Sites were chosen primarily for exposed banks that could house an array, meanders and straights representative of the watershed position, and site accessibility. Thirty-centimeter-long erosion pins were driven horizontally into exposed channel banks leaving about 5.1 cm of the pin exposed. Pin heads were pre-painted for easier detection during subsequent field visits. Depending on the bank dimensions at each site, pin arrays ranged from 12 to 20 pins

Table 2
List of features and possible erosion and deposition types mapped for Fanno Creek, northwest Oregon during 2012–13. [GIS dataset of geomorphic mapping available at http://water.usgs.gov/lookup/getspatial?fannoCk_erosion_deposition_2012.xml; Abbreviations: NA, not applicable.]

Attribute	Attribute options	Description
Feature	Wetted channel	All wetted channel areas within the active channel
	Floodplain	Floodplain, including aquatic features on the floodplain
	Culvert	Culverts
	Banks	Banks, sometimes including valley wall outside of the floodplain if likely a source of sediment, most banks include some adjacent floodplain because of mapping scales
	Bar	Accumulated sediment and organic material in bar form
	Low bench	Low benches or downdropped blocks that form small shelves within the active channel; similar to active-channel shelves described by Osterkamp and Hupp (1984)
	Dam	Dams include beaver dams, log-jam dams, or any other structure and woody debris that blocks most of the active channel
	Reinforced	Reinforced areas include, riprap, revetments, walls, or other structures designed to stabilize channel; banks with this designation are often only reinforced along the lower portion
	Secondary water features	Includes side channels, tributaries, and intermittently or permanently flooded features on the floodplain such as oxbow ponds
Erosion	Mass wasting	Areas with the dominant form of erosion being mass wasting
	Fluvial	Areas with the dominant form of erosion being fluvial
	Other	Areas with the dominant form of erosion being caused by outside sources, such as stormwater erosion
	NA	Areas that do not not erode or are not a major source, typically the floodplain
	None/minimal	No erosion or reinforced areas that should not be eroding
Deposition	Mass wasting	Areas with the dominant form of deposition being from mass wasting, such as downdropped blocks
	Fluvial	Areas with the dominant form of deposition being from fluvial processes, such as the presence of bars
	Other	Areas where the dominant form of deposition is not connected to the active channel
	NA	Areas that do not aggrade or are not a major sink
	None/minimal	No deposition, or limited deposition such as on higher elevation floodplains
Notes	–	Textual description of the feature or of something that stood out in that reach/area

covering surface areas of 0.75–4.45 m^2. Arrays included arrangements of 3×4, 4×3, 5×3, and 5×4 pins across by pins high.

Following high-flows or periods of prolonged low flows between December 2011 and January 2013, pin exposure was repeatedly measured, allowing assessment of local erosion or deposition. Pins were replaced or reset to 5.1 cm when more than 12.5 cm of pin was exposed, the pin had fallen out, or the pin had been buried. If the pin had been buried, 0 cm was recorded for exposure. If the pin had been dislodged or fallen out, 30 cm of erosion was recorded for exposure. Site erosion rates were determined by dividing the average pin erosion distance for the array by the time period between measurements. Average annual rates were normalized by the number of days between each measurement period.

2.2.3. Deposition plates

Short-term, event-based deposition between December 2011 and January 2013 was monitored at 11 sites (Fig. 1) by plexiglass plates, similar to those used by Kleiss (1996) and Heimann and Roell (2000) for measuring floodplain and wetland sedimentation rates. The plexiglass plates, measuring 30 cm by 30 cm (for a total area of 900 cm^2), were scuffed on the upward side and anchored to low benches (similar to active-channel shelves described by Osterkamp and Hupp, 1984) within the active channel, adjacent floodplain, or near perennially flooded backwater. Following high flows, sediment from the plates was collected and weighed. Deposition rates were determined by dividing the mass of deposited material per plate area by the time period between collections. Average annual rates were normalized by the number of days between each measurement period. A bulk density of 0.62 grams per cubic centimeter (g/cm^3) was estimated from one of the middle watershed plates and used as a conversion factor for all plates and all measurement periods. Some plates were broken during high flows or lost to rapid vegetation growth; these plates were not replaced.

2.2.4. Suspended sediment loads

Eleven water samples were collected using standard depth-integrated techniques (U.S. Geological Survey, 2006) at the Fanno Creek at Durham Road site (station 14206950) between December 2011 and January 2013. Samples were analyzed for total suspended solids (TSS; EPA Method 160.2; U.S. Environmental Protection Agency, 1999) by the Clean Water Services water-quality laboratory (Hillsboro, Oregon) and suspended sediment concentration (SSC; Guy, 1969) by the USGS. These SSC results were supplemented with 40 additional TSS results from Clean Water Services and 56 SSC results from USGS collected at the Durham Road site between March 2001 and September 2007 (Anderson and Rounds, 2010), after first converting the additional TSS results to SSC using a SSC–TSS regression based on 10 samples from this study. TSS can be an underestimate of SSC due to laboratory subsampling procedures (Horowitz et al., 1994; Gray et al., 2000). Using 10 samples collected during 2011–13, the relation between TSS and SSC was determined to be:

$$SSC = 1.247 * (TSS)^{0.9822} \quad (1)$$

This equation yielded a coefficient of determination (R^2) of 0.99 and includes a bias correction factor of 1.01 (used to correct the SSC estimates when converted from log space to linear space). After all TSS data were converted to SSC, a regression model was developed between SSC and turbidity data from a continuous monitor at the Durham Road site. This correlation between the 107 SSC samples and turbidity enabled use of continuous instream turbidity measurements to calculate hourly SSC values for Fanno Creek. A regression model was developed for SSC and turbidity, taking advantage of a spreadsheet tool from Rasmussen et al. (2009, available at http://water.usgs.gov/osw/suspended_sediment/time_series.html),

$$SSC = 0.9629 * Turb^{0.9939} \quad (2)$$

where SSC is in milligrams per liter (mg/L) and Turb is turbidity in formazin nephelometric units (FNU). This equation yielded an R^2 of 0.86 and a bias correction factor of 1.08.

Suspended sediment loads were determined from the hourly SSC estimates with the following equation:

$$SSL = Q * SSC * 0.0036 \quad (3)$$

where SSL is suspended sediment load in metric tons (tonnes, t) per hour (h), Q is discharge in m^3/s, SSC is in mg/L, and the constant 0.0036 converts the result into t/h. Suspended sediment loads were computed over the same periods as the erosion pin and deposition measurements. For periods in which no turbidity data were available (2.6% of the values for the sampling period), suspended sediment load values were estimated from the lowest adjacent turbidity value. Additionally, the seven hourly turbidity measurements exceeding 210 FNU were adjusted to 210 FNU, because this value was the highest sampled turbidity value for which SSC data were available and any higher model predictions of SSC could not be verified. Consequently, the resulting suspended sediment loads likely underestimate actual stream loads of suspended sediment.

Potential sources of error in the computation of suspended sediment concentrations and loads from turbidity monitoring, suspended sediment sampling and associated lab analyses, the TSS-SSC model, and correlation models were assessed. The potential magnitude of those errors was estimated and combined using the root mean square error propagation method outlined by Topping (1972) and Harmel et al. (2006):

$$E_p = \sqrt{E_1^2 + E_2^2 + \cdots + E_n^2} = \sqrt{\sum_i E_i^2} \quad (4)$$

where E_p is the probable error of a calculated quantity, n is the number of sources of error, and E_1 through E_n are the errors from each source. Standard errors were estimated and then converted to percentage errors for convenience. When standard errors were not available, error intervals were estimated. Specific error sources included in this analysis were: sensor electronic noise (1%), variability in the stream during the measurement or sample-collection period (1%), cross-sectional variations (1%), errors in the drift corrections applied to sensor data (5%), analytical error in lab samples (3%), model regression error for the TSS-SSC (11.8%) and the turbidity-SSC relations (37.9%), and uncertainty in the hourly discharge measurements (5%).

2.3. Sediment characteristics

2.3.1. Particle size

Material collected from the deposition plates was analyzed for particle size. Sediment was dried in an oven at 55 °C and weighed. Samples were dry sieved with an RX-86 SieveShaker and each size fraction was weighed. Grain sizes of each deposition sample were divided into three categories: sand (>2 mm), silt (2 mm–63 microns [μm]), and clay (<63 μm). To better assess the relation between particle size and TOC, samples of the same grain size were aggregated for sites in the upper, middle, and lower watershed for the following flow conditions: (1) first seasonal flush of the fall rainy season following the summer low-flow period (10/03/12 to 11/08/12), herein referred to as fall flush, (2) high-flow period including the largest peak-flow (17.8 m^3/s on 12/20/12; mean daily discharge of 14.0 m^3/s) of the sampling period (11/08/12 through 01/04/13), herein referred to as the period spanning the highest-flow event, and (3) annual composite of all samples collected at each site throughout the sampling period (approximately 12/22/11 to 01/04/13). The upper watershed and middle watershed ponded sites did not accumulate enough material for periods spanning the fall flush or highest-flow events; consequently, only annual composites were analyzed for these sites.

2.3.2. Total organic carbon content

In addition to particle size, samples from deposition plates were analyzed for TOC content. Eight samples for highest-flow, fall flush, and annual composites were evaluated. Six additional bank-material samples collected at the erosion pin sites in October 2012 were also analyzed for TOC. All samples were stored at −20 °C between collection, drying, and analyses. Samples were sent to the U.S. Geological Survey National Water Quality Laboratory (Denver, Colorado) for analysis, following the loss of ignition protocol of Wershaw et al. (1987) for TOC.

2.4. Organic matter export

The amount of TOC moving through Fanno Creek and exported to the Tualatin River was estimated from geomorphic mapping, field measurements of erosion and deposition, and sediment sample characteristics. The mapped area of potential eroding banks as a result of fluvial or mass-wasting processes was multiplied by average long- and short-term erosion rates for each reach to calculate the total volume of erosion. Likewise, the total depositional volume per reach was a product of mapped deposition areas and average depositional rates from pin and plate measurements, similar to the approach taken by Hupp et al. (2013) to measure floodplain sedimentation along Difficult Run in Virginia. The distal floodplain is not likely a major depositional zone except for extraordinary conditions, so the total depositional area from fluvial or mass-wasting processes was considered to be within 30 m of the channel centerline and limited to areas less than about 1.5 m above the wetted channel on the basis of the general patterns of inundation during the study period. Erosion and deposition rates for the middle watershed sites were applied to the Oregon Episcopal School (OES) Wetlands and Portland Golf Club reaches (which are within the upper watershed), based on field observations of sediment patterns that were more similar to other middle watershed sites. The erosion and deposition volumes were converted to mass by assuming a bulk density of 1.3–1.7 g/cm^3 for erosion (low and high bulk densities for soils similar to those in the Fanno Creek floodplain providing a range of eroded volumes; Aşkin and Özdemir, 2003; Donahue et al., 1977; Natural Resources Conservation Service, 2008; Rivenshield and Bassuk, 2007) and 0.62 g/cm^3 for deposition. The amount of deposition was then multiplied by percent particle size fraction smaller than 2 mm from the annual composite because all larger deposited particles were from litterfall biomass or other organic debris. No particle size analysis was completed for the bank material samples, although the dominant material was sand or finer. The resulting estimate of net erosion or deposition was multiplied by fractional carbon content to determine the amount of carbon being eroded and transported as a result of bank erosion. Soil organic matter content is typically 1.724 times the percent of carbon present (Birkeland, 1999; Natural Resources Conservation Service, 2009), and the annual average carbon export from bank material was converted to OM accordingly.

3. Results

Erosion and deposition were apparent to varying degrees throughout all reaches of the Fanno Creek watershed. The largest mapped area of erosion from bank material was in the Beaverton–Hillsdale reach, followed by the Durham Reach. When average annual erosion rates are applied to each reach, the farthest downstream reaches show maximum erosion. Deposition dominated the Greenway reach in terms of mapped area, followed by other middle reaches. After applying average annual rates of deposition and a grain-size scaling factor, these middle watershed reaches still account for the most deposition. The fine sediment flux from each reach shows Durham having the greatest amount of erosion and Greenway the most deposition. Scaling these numbers by the percent TOC and using a conversion factor of OM, the data indicate that the greatest sources of organic matter are in the Beaverton–Hillsdale and Durham reaches, while the greatest sinks for OM are in the Greenway and Englewood reaches.

3.1. Identifying sediment sources and sinks

The distribution of features mapped as erosional along Fanno Creek varies by reach (Figs. 3 and 4; dataset available at http://water.usgs.gov/lookup/getspatial?fannoCk_erosion_deposition_2012.xml). Valley walls and terraces contributing sediment to the main Fanno Creek channel are most prevalent in the uppermost reach (Beaverton–Hillsdale; Fig. 4) where only a very narrow or no floodplain exists. Areas with high potential for erosion are most prevalent in the upper watershed (Beaverton–Hillsdale = 17%, Oleson = 15% of the reach area mapped within the geomorphic floodplain) although other middle watershed (Woodard = 13%) and lower watershed (Durham = 10%, Gentlewoods = 10%, Bonita = 10%) reaches had relatively large areas subject to erosion (Fig. 4). Most locations of bank erosion were mapped as the byproduct of fluvial processes – slow, steady bank erosion with low volumes of sediment input to the channel. Mapped erosion attributed to mass wasting, such as bank failures or prolonged or intense fluvial processes (quick rise in stage and discharge driven by heavy precipitation and runoff), was most prevalent in the Wonderland, Woodard, and Gentlewoods reaches (Fig. 4). These processes likely contribute more sediment to the Fanno Creek channel than simple bank erosion. The total mapped area subject to fluvial and mass wasting processes was about 159,000 m^2. Other erosion sources (Fig. 4, Table 2) were observed from hillslopes, stormwater drainages, and at beaver slides and nutria burrows, but individually, these sources likely contribute negligible amounts of sediment with less than 2.5% of total reach area mapped as other types in all reaches except Beaverton–Hillsdale (16.5% other types by reach area). Reinforced bank areas were identified in every part of the watershed during mapping but were most prevalent, by count, in the Vista Brook and Woodard reaches in residential or industrial areas. The Beaverton–Hillsdale, Portland Golf Club, and Vista Brook reaches contain the greatest amount by area of mapped bank reinforcement.

Depositional features and the amount of sediment storage vary substantially along the length of the Fanno Creek channel (Figs. 3 and 4). Depositional areas compose 25% to more than 92% of total reach area mapped within the geomorphic floodplain. The largest depositional areas are in wide, low-gradient wetland reaches such as Greenway and Englewood in the middle watershed. By area, the Beaverton–Hillsdale reach is about 47% floodplain with a floodplain and channel area that is relatively small compared to other reaches, whereas all other reaches have floodplains that comprise 71 to 84% of the reach area (Fig. 4). Bars or zones of sediment and OM accumulation were most abundant in the most downstream reach (Durham, $n = 41$); Fanno Creek Park (Fig. 5) and Greenway each had 17 mapped instances. Beaverton–Hillsdale had 21 mapped instances of bars, although these were commonly composed of sand and fine gravel. Most of the fluvially deposited bars appeared to have a large organic component and to be more mobile than bars or low benches deposited by mass wasting to the stream. The occurrence of mapped secondary water features, most commonly floodplain ponds or wetlands that likely provide longer-term storage for sediment, is greatest for the OES Wetlands, Vista Brook, Englewood, and Bonita reaches, although at least one instance of a secondary water feature was present in each reach. Dams or wood jams partially blocking the channel, and commonly retaining sediment and OM, were identified in most reaches with the greatest abundance in the Greenway, Woodard, and Durham reaches (middle and lower watershed).

3.2. Quantifying sediment sources, sinks, and transport

3.2.1. Dendrogeomorphic analysis

Twelve trees along the streambank were cored throughout the Fanno Creek watershed (Table 3). Species included Oregon ash (*Fraxinus latifolia*), alder (*Alnus* sp.), maple (*Acer* sp.), black hawthorn (*Cretaegus douglasi*), and Douglas-fir (*Pseudotsuga menziesii*). Tree ages ranged from 19 to 61 years and the degree

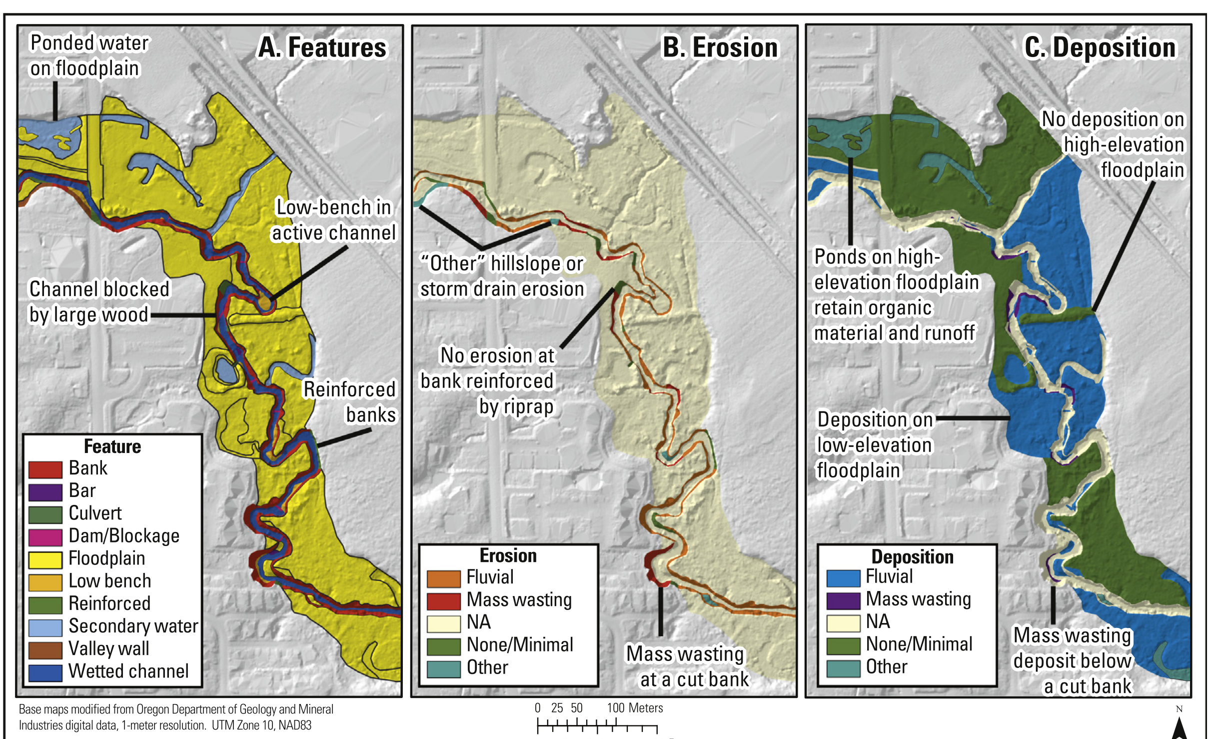

Fig. 3. Example of features (A), erosional classification (B), and depositional classification (C) from geomorphic mapping between RKM 6.7 and 5.5 in the Bonita and Fanno Creek Park reaches along Fanno Creek, northwest Oregon.

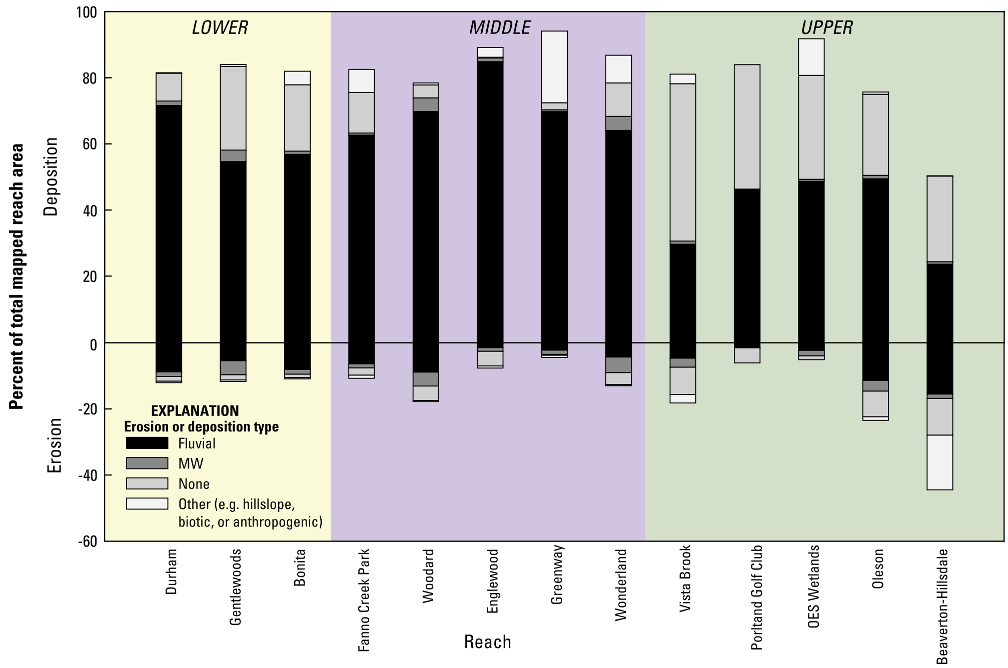

Fig. 4. Mapped deposition (positive values) and erosion (negative values) by reach as a fraction of total reach area along Fanno Creek, northwest Oregon. [Abbreviation: MW, mass wasting.]

of undercutting was as high as 116 cm. Estimated average long-term erosion rates ranged from 0.8 to 4.0 cm/year (Fig. 5A). No clear trend was evident between tree age or watershed location or with degree of undercutting for this small dataset.

3.2.2. Erosion pins

3.2.2.1. Upper watershed. Over the course of this study, most of the erosion pin arrays in the upper watershed showed net deposition. At these sites, average cumulative deposition from soil creep and fluvial deposition was 0.29 cm in the straight segment and 2.85 cm in the meander segment (Table 4). The straight site showed less change over most measurement periods than the meander site. The left bank at the straight site was hardpan clay and was the only upper watershed site of cumulative erosion, while the right bank pin array was set in loose, low density soil and sandy bed material that had fluvial deposition and some observed soil creep for net deposition over the sampling period. The inside meander array consistently showed fluvial accumulation of sand and gravel, as much as 4.5 cm during one measurement period, while the outside meander bend, in hardpan clay, showed mostly minor erosion except for an episode of bank failure and more substantial erosion. Bank erosion rates varied from 0 to 46.13 cm/year at the upper watershed sites over the sampling period. Here, more channel change was apparent during periods of many moderate flows as opposed to occurring during one large flow. Substantial erosion occurred during the fall flush (average rate of 1.10 cm/year for the four arrays, Period 8), whereas a net deposition (average rate of 2.30 cm/year for the four arrays, Period 9) was measured following the highest-flow period. Average annual rates of bank change for the sampling period at the upper watershed sites ranged from 11.00 cm/year of deposition to 13.15 cm/year of erosion (Fig. 5B).

3.2.2.2. Middle watershed. As in the upper watershed, a marked difference was observed between erosion and deposition rates in straight versus meander reaches; the straight reach in the middle watershed generally showed deposition whereas the meander reach showed erosion. Both straight bank arrays were in unconsolidated, soil bank material and showed mostly small but consistent burial (burial rates ranged up to 11.46 cm/year; Table 4). Bank accretion was from sediment and vegetation moving downslope rather than fluvial deposition of channel material. Banks at the meander site were steeper and less stable than those at the straight site. Loss of more than 6.7 cm (erosion rate of 84.46 cm/year) was measured following one flow event at the inside meander as a result of slumping bank material. Other substantial changes occurred during higher flow events and periods of prolonged soil saturation. Nutria burrow holes were observed in the bank near the inside meander site. A blockage downstream of the straight sites potentially affected water stage, probably decreasing erosion at that site after the October 2012 measurement. The straight site was in a reach where the channel had been restored between 2007 and 2010. Average annual sampling period rates ranged from 8.61 cm/year of deposition to 13.82 cm/year of erosion (Table 4, Fig. 5B).

3.2.2.3. Lower watershed. Erosion and deposition at erosion pin sites in the lower watershed depended on local channel materials and morphology, but overall rates were within the range of those observed at upstream sites. Maximum erosion rates (Table 4) were 39.24 cm/year at the straight site and 23.87 cm/year at the meander site. Bank material at the straight site was dominantly hardpan clay, but the lowest rows of the array on the left bank were in fluvially deposited sediment over the hardpan clay. These lower pins showed net deposition while higher pins in the array and pins in the opposite bank showed mostly minor erosion over the sampling period. The outside meander array was also dominantly composed of hardpan clay while the inside bend was largely unconsolidated soil and fine alluvial sediment. Most of the erosion at the outside meander array resulted from small failures of the hardpan clay. Erosion on the inside meander reached 6.51 cm during one period while deposition reached 2.77 cm during another period and

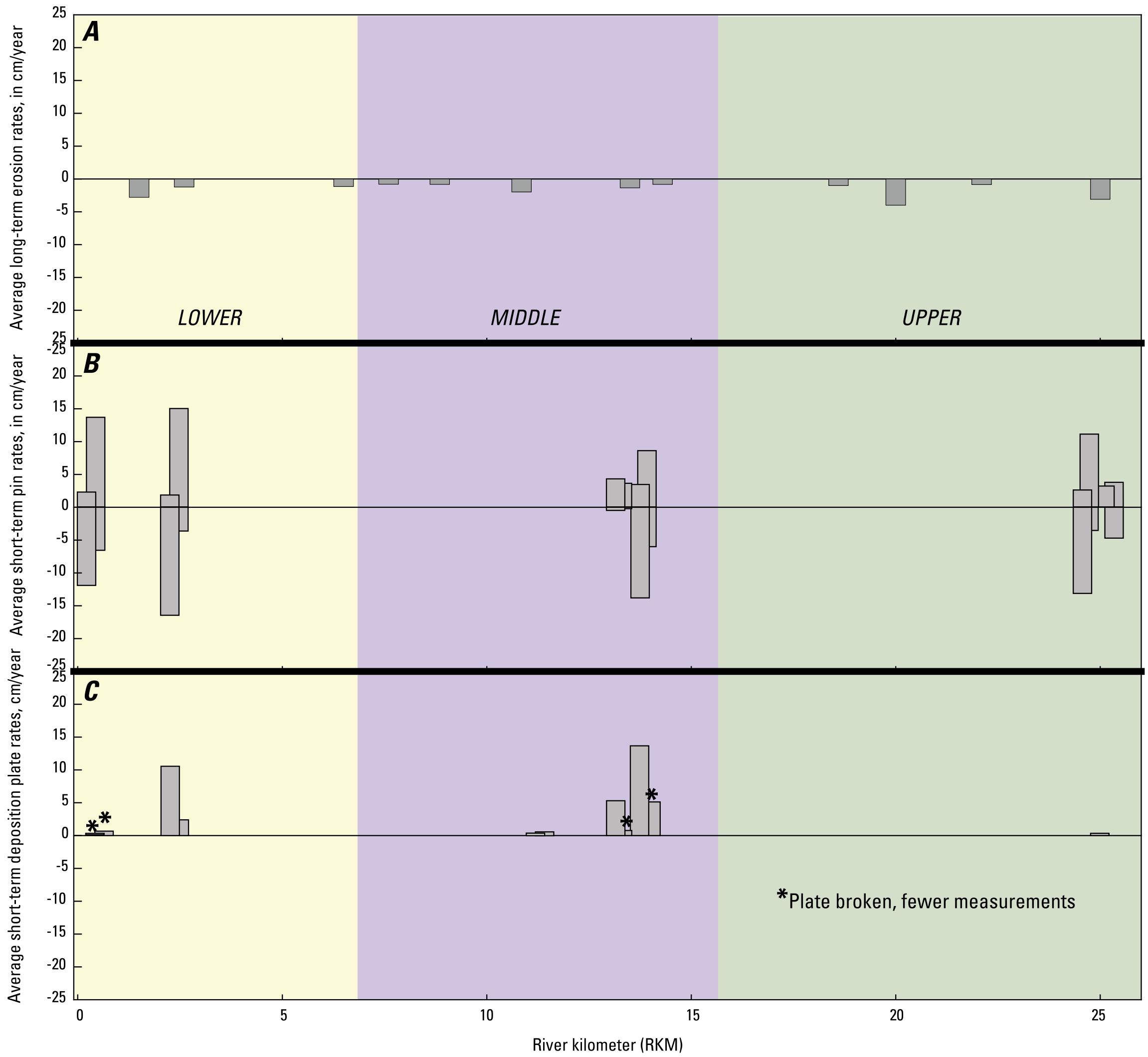

Fig. 5. Annual average erosion (negative) and deposition (positive) rates by river kilometer measured from dendrogeomorphic analysis (A), erosion pins (B), and deposition plates (C).

Table 3
Summary of tree core data collected to estimate erosion rates at a few point locations along Fanno Creek, northwest Oregon.

Reach		River kilometer	Tree	Age	Erosion rate, centimeters per year[a]
1	Beaverton–Hillsdale	25.0	Maple	38	3.1
2	Oleson	22.1	Douglas-fir	36	0.9
3	OES Wetlands	20.0	Oregon ash	22	4.0
4	Portland Golf Club	–	–	–	–
5	Vista Brook	18.6	Alder	19	1.0
6	Wonderland	14.3	Maple	29	0.8
7	Greenway	13.5	Oregon ash	31	1.4
8	Englewood	10.9	Black hawthorn	30	2.0
9	Woodard	8.9	Oregon ash	61	0.8
10	Fanno Creek Park	7.6	Oregon ash	38	0.8
11	Bonita	6.5	Alder	27	1.2
12	Gentlewoods	2.6	Alder	21	1.2
13	Durham	1.5	Oregon ash	19	2.8

[a] Average horizontal undercutting divided by tree age.

resulted from mass wasting repeatedly burying and exposing pins. The meander site was episodically inundated by backwater from the Tualatin River, so not all time periods were measured at this pin site. In the lower watershed, average annual rates ranged from 14.99 cm/year of deposition to 16.45 cm/year of erosion (Fig. 5B).

3.2.3. Deposition plates

The deposition plate in the upper watershed was positioned on the floodplain inside a low meander bend. Measured deposition for 5 measurements ranged from 0.4 to 130.9 grams (g) over a plate area of 900 cm^2. Most of the collected material was litterfall. The small amount of clastic sediment accumulation appeared to be a

Table 4
Erosion pin array locations and measurement summary along Fanno Creek, northwest Oregon. [Abbreviations: RKM, river kilometer; cm, centimeter; –, no measurement. Time for periods where no measurement was made is accounted for in the following period rate.]

Watershed location and Reach	Site	RKM	Bank	Installation date	Period 1: Installation – 2/2/12		Period 2: 2/2/12–3/8/12		Period 3: 3/8/12–4/24/12		Period 4: 4/24/12–5/15/12		Period 5: 5/15/12–6/11/12		Period 6: 6/11/12–7/11/12		Period 7: 7/11/12–10/3–4/12		Period 8: 10/3–4/12–11/8/12[a]		Period 9: 11/8/12–1/4/13[b]		Average erosion rate, cm/year[c]	Average deposition rate, cm/year[d]
					cm	cm/year	cm	cm/year	cm	cm/year	cm	cm/year	cm	cm/year	cm	cm/year	cm	cm/year	cm	cm/year	cm	cm/year		
Upper, Beaverton–Hillsdale	Straight	25.0	Left	01-04-2012	−0.85	−10.66	0.00	0.00	–	–	−0.58	−3.12	–	–	1.08	6.95	0.49	2.10	−0.58	−6.07	−0.42	−2.71	−4.71	3.27
			Right	01-04-2012	−0.36	−4.53	0.50	5.34	–	–	−0.21	−1.14	–	–	0.71	4.54	1.02	4.36	−0.69	−7.17	0.19	1.22	−3.51	3.78
	Meander	25.0	Left (inside)	01-04-2012	0.99	12.52	2.30	24.65	–	–	0.39	2.10	–	–	2.77	17.76	0.72	3.09	0.28	2.87	4.54	29.07	0.00	11.00
			Right (outside)	01-04-2012	−2.12	−26.64	−4.30	−46.13	–	–	−0.36	−1.93	–	–	0.08	0.54	−0.16	−0.68	0.57	5.96	−2.87	−18.37	−13.15	2.64
Middle, Greenway	Meander	13.6	Left (outside)	01-04-2012	−0.42	−5.33	−1.58	−16.93	–	–	−0.37	−1.99	–	–	1.34	8.61	−0.48	−2.07	–	–	−2.22	−8.72	−6.01	8.61
			Right (inside)	01-04-2012	−6.71	−84.46	−0.53	−5.68	–	–	−0.58	−3.12	–	–	0.54	3.46	−0.18	−0.78	–	–	−3.66	−14.37	−13.82	3.46
	Straight	13.5	Left	01-04-2012	0.17	2.13	−0.02	−0.23	–	–	1.63	8.75	–	–	1.05	6.70	0.47	2.01	–	–	0.77	3.07	−0.23	4.32
			Right	01-04-2012	0.91	11.46	0.95	10.23	–	–	0.78	4.20	–	–	0.31	1.97	−0.12	−0.50	–	–	0.75	2.98	−0.50	3.64
Lower, Durham	Straight	2.4	Left	12-22-2011	2.38	20.69	−0.17	−1.82	0.56	4.36	−0.22	−3.86	2.30	31.05	−0.31	−4.15	−0.94	−4.09	5.44	55.15	0.29	1.83	−3.62	14.99
			Right	12-22-2011	−1.24	−10.76	−0.62	−6.70	0.24	1.89	−0.13	−2.21	−0.04	−0.57	0.14	1.86	0.24	1.06	0.30	3.00	−6.13	−39.24	−16.45	1.73
	Meander	0.4	Left (inside)	12-22-2011	–	–	–	–	−6.51	−19.31	0.49	8.43	−1.08	−14.55	0.00	0.00	−0.05	−0.21	2.77	28.09	–	–	−11.91	13.66
			Right (outside)	12-22-2011	–	–	–	–	−1.25	−3.71	−1.37	−23.87	0.25	3.39	0.10	1.31	−0.31	−1.35	−1.81	−18.40	–	–	−6.57	2.30

[a] Period spans fall-flush event.
[b] Period spans highest-flow event.
[c] Average erosion rates from negative period values, normalized by number of days.
[d] Average deposition rates from positive period values, normalized by number of days.

Table 5
Deposition plate locations and measurement summary along Fanno Creek, northwest Oregon. [Abbreviations: RKM, river kilometer; m, meter, g, grams; cm, centimeter. Rates based on plate dimensions of 30 cm by 30 cm and a bulk density of 0.62 g/cm^3. Time for periods where no measurement was made is accounted for in the following period rate.]

Watershed location, Reach	RKM	Height above water surface, m[a]	Plate location description	Installation date	Period 1: Installation – 2/9/12		Period 2: 2/9/12–4/24/12		Period 3: 4/24/12–5/15/12		Period 4: 5/15/12–6/11/12		Period 5: 6/11/12–7/11/12		Period 6: 7/11/12–11/8/12[b]		Period 7: 11/8/12–1/4/13[c]		Annual average deposition rate[d]
					g	cm/year	g	cm/year	g	cm/year	g	cm/year	g	cm/year	g	cm/year	g	cm/year	cm/year
Upper, Beaverton–Hillsdale	25.0	1.22	Low terrace near left bank, inside of meander, outside of active channel	01-04-2012	0.4	0.01	–	–	3.2	0.02	–	–	1.4	0.02	23.8	0.13	130.9	1.50	0.29
Middle, Greenway	13.6	0.44	Low floodplain near left bank, on the inside of a meander, upstream of meander pin site	01-04-2012	278.8	5.07	–	–	746.5	5.14	–	–	–	–	–	–	–	–	5.12
		0.13	Low floodplain near right bank, on the outside of a meander and near small tributary, upstream of meander pin site	01-04-2012	704.0	12.79	–	–	1,307.4	9.00	–	–	295.8	3.39	805.2	4.39	4,433.3	50.88	13.52
	13.5	0.50	Low floodplain near left bank, downstream of straight pin site	01-04-2012	42.3	0.77	–	–	–	–	–	–	–	–	–	–	–	–	0.77
		0.79	Low floodplain near left bank, downstream of straight pin site	01-04-2012	221.9	4.03	–	–	335.1	2.31	–	–	160.4	1.84	497.3	2.71	1,658.5	19.03	5.15
Middle, Englewood	11.3	0.22	Near ponded water west of Fanno Creek, upstream plate	01-10-2012	97.0	2.11	–	–	23.4	0.16	–	–	1.2	0.01	16.5	0.09	61.5	0.71	0.36
		0.07	Near ponded water west of Fanno Creek, downstream plate	01-10-2012	45.7	1.00	–	–	31.3	0.22	–	–	5.8	0.07	5.6	0.03	26.2	0.30	0.21
Lower, Durham	2.4	1.67	On low bench just downstream of bridge on right bank, upstream of straight pin site	12-22-2011	260.0	3.47	284.0	2.51	3.8	0.12	–	–	1.3	0.01	45.8	0.25	698.2	8.01	2.24
		0.93	On floodplain near left bank, just upstream of straight pin site	12-22-2011	314.9	4.20	504.2	4.46	1.2	0.04	–	–	6.3	0.07	23.7	0.13	5,103.4	58.57	10.30
	0.4	0.10	Low bench in active channel near right bank, on the outside of meander, just upstream of the meander pin site	12-22-2011	–	–	20.0	0.11	19.0	0.59	59.2	1.43	86.4	1.88	5.3	0.03	–	–	0.39
		0.28	Low bench in active channel near right bank, on the outside of meander, just downstream of the meander pin site	12-22-2011	–	–	21.8	0.12	–	–	–	–	–	–	–	–	–	–	0.12

[a] Height above low-flow water surface. Elevation difference between plate and water surface measured from 2012 LiDAR.
[b] Period spans fall-flush event.
[c] Period spans highest-flow event.
[d] Normalized by number of days.

product of rain splash. The plate was apparently never inundated; consequently there is no correlation between sediment deposition and timing or intensity of flow at this site. A cumulative 159.7 g of material was collected over the sampling period between January 2012 and January 2013, resulting in an annual average rate of deposition of 0.29 cm/year (Fig. 5C; Table 5).

Two plates in the middle watershed at the ponded site also accumulated very small amounts of sediment, ranging from 1.2 to 97.0 g per sampling period ($n = 10$, Englewood site, Table 5). Plate material commonly contained duckweed, fecal matter, or other wetland materials. A total of 314.2 g of deposited material was collected over the sampling period at the ponded site. Deposition rates for the sampling period averaged 0.21 cm/year and 0.36 cm/year (Fig. 5C; Table 5).

The other middle watershed plates were located in the floodplain adjacent to straight and meander sections and collectively trapped substantially greater amounts of sediment and large OM than other watershed locations. While the number of these plates varied from 4 to 2 over the sampling period, a total of 11,486.5 g, ranging from 42.3 to 4,433.3 g per sampling period ($n = 13$, Greenway site) of deposited material was collected. Approximately 70% of sediment deposited at the two meander plates was deposited on the outside of the meander (periods 1 and 3) and 62–86% of sediment deposition occurred at the meander site versus the straight site. Following the fall flush and highest-flow periods, 1,302.5 g and 6,091.8 g of respective sediment was deposited on the middle watershed non-ponded plates. Rates of deposition for the sampling period for plates near the meander averaged 5.12 and 13.52 cm/year, while rates from plates near the straight segment averaged 0.77 and 5.15 cm/year (Fig. 5C; Table 5).

Plates in the floodplain as well as on low benches in the active channel trapped variable amounts of sediment in the lower watershed. Over the sampling period, a total of 7,458.5 g (ranging from 1.2 to 5,103.4 g per sampling period; $n = 18$) of sediment was collected. During higher-flow collection periods, more than 90% of collected sediment was from plates located on the floodplain adjacent to the straight site. During lower-flow collection periods, about 80–92% of deposition was located on the low benches. Rates of deposition for the sampling period at the straight site were 2.24 and 10.30 cm/year, while rates from plates on low benches at the meander site were 0.12 and 0.39 cm/year (Fig. 5C; Table 5).

3.2.4. Suspended sediment loads

Annual suspended sediment loads exported from Fanno Creek to the Tualatin River, and the associated uncertainties, were estimated for the time period of January 2003 through August 2013 (Table 6) using continuous measurements of turbidity and discharge along with a regression model of suspended-sediment concentration as a function of turbidity. The greatest source of uncertainty in the hourly and daily load estimates was from the regression model used to estimate suspended sediment concentrations from continuous turbidity data; however, the uncertainty associated with annual loads decreases with an increasing sample size. The calculation period encompasses the erosion and deposition sampling period of 12/22/11 through 1/4/13 when approximately 2,610 t (±5.6%) of suspended sediment was exported from Fanno Creek to the Tualatin River (Fig. 6B). Loads were higher in water year (WY) 2006 (2,990 t ± 5.9%) and similar in WY 2011 (2,520 t ± 6.0%). The smallest load calculated was for WY 2005 (1,110 t ± 7.1%). Over the sampling period, suspended sediment loads varied with discharge and turbidity values (Fig. 6). Loads were greatest for the high-flow period between 11/8/12 and 1/4/13 (890 t ± 10.1%) accounting for 34% of the total suspended sediment load estimated for the sampling period.

Table 6
Annual suspended sediment loads calculated from continuous discharge and turbidity measurements at the USGS streamflow-gaging station Fanno Creek at Durham Road, Oregon (station 14206950).

Water year	Suspended sediment load, tonnes	Error, in percent
2003[a]	1,450	7.96
2004	1,580	5.73
2005	1,110	7.05
2006	2,990	5.93
2007	1,860	5.73
2008	1,650	7.35
2009	1,570	10.23
2010	1,960	5.58
2011	2,520	6.04
2012	1,830	6.86
2013	1,740	6.60

[a] 1/11/03 through 9/30/2003.

3.3. Sediment characteristics

3.3.1. Particle size

The grain sizes of the materials accumulated on the deposition plates varied with local depositional context and watershed position. No attempt was made to distinguish OM from inorganic sediment when sieving deposition samples; however, no gravel was present and all material greater than 2 mm was OM. For an annual composite, 92.8% of deposition-plate materials in the upper watershed were greater than 2 mm in size (Table 7). Material deposited at the middle watershed ponded site (Englewood) was finer, with only of 12.9% greater than 2 mm and 58.0% finer than 63 μm. Annual composites of middle watershed floodplain deposition samples (Greenway) contained 5.2% material greater than 2 mm and were mostly composed of sand-sized material (74.9%) and some finer material (19.9%). Grain-size distributions for the middle watershed fall-flush and highest-flow periods were similar to the annual trend (Table 7). The lower watershed annual composite was composed of particles about 2.7% greater than 2 mm, 88.4% between 2 mm and 63 μm, and 9.0% finer material. The size distribution for the period spanning the highest-flow event was very similar to the annual distribution, but the grain-size distribution from the fall flush event had greater amounts of coarse and fine material, with 40.7% of the mass greater than 2 mm and 18.3% finer than 63 μm.

3.3.2. Total organic carbon content

Bank samples had substantially lower TOC content than deposition samples from the floodplain and low benches within the active channel (Table 7). Also, flotsam accumulation on plates in the upper watershed and near the ponded site had high amounts of organic matter (41.6% and 11.3% for the annual composites, respectively) as compared with sediment depositing on plates in the middle and lower watershed (4.2% and 2.5% for the annual composite, respectively). Additionally, carbon content was greater for fall flush and high-flow events in the middle and lower watershed compared to the annual composites at those sites (Table 7).

3.4. Organic matter export

Mapping and field measurements were combined to identify reaches that might be sources and sinks for organic matter in the Fanno Creek watershed (Table 8, Fig. 7). The total mass of eroding bank material in Fanno Creek from fluvial and mass wasting processes was estimated to be about 8,800–11,500 t while the scaled deposition was about 8,200 t (Table 8). The resulting net sediment export from Fanno Creek (550–3,250 t) brackets the average annual SSL and the SSL measured over the sampling period (1,880 t and 2,610 t, respectively). These SSL estimates were determined for the Fanno Creek at Durham Road site, which is near the upstream end of the Durham reach; excluding this reach from the erosion–deposi-

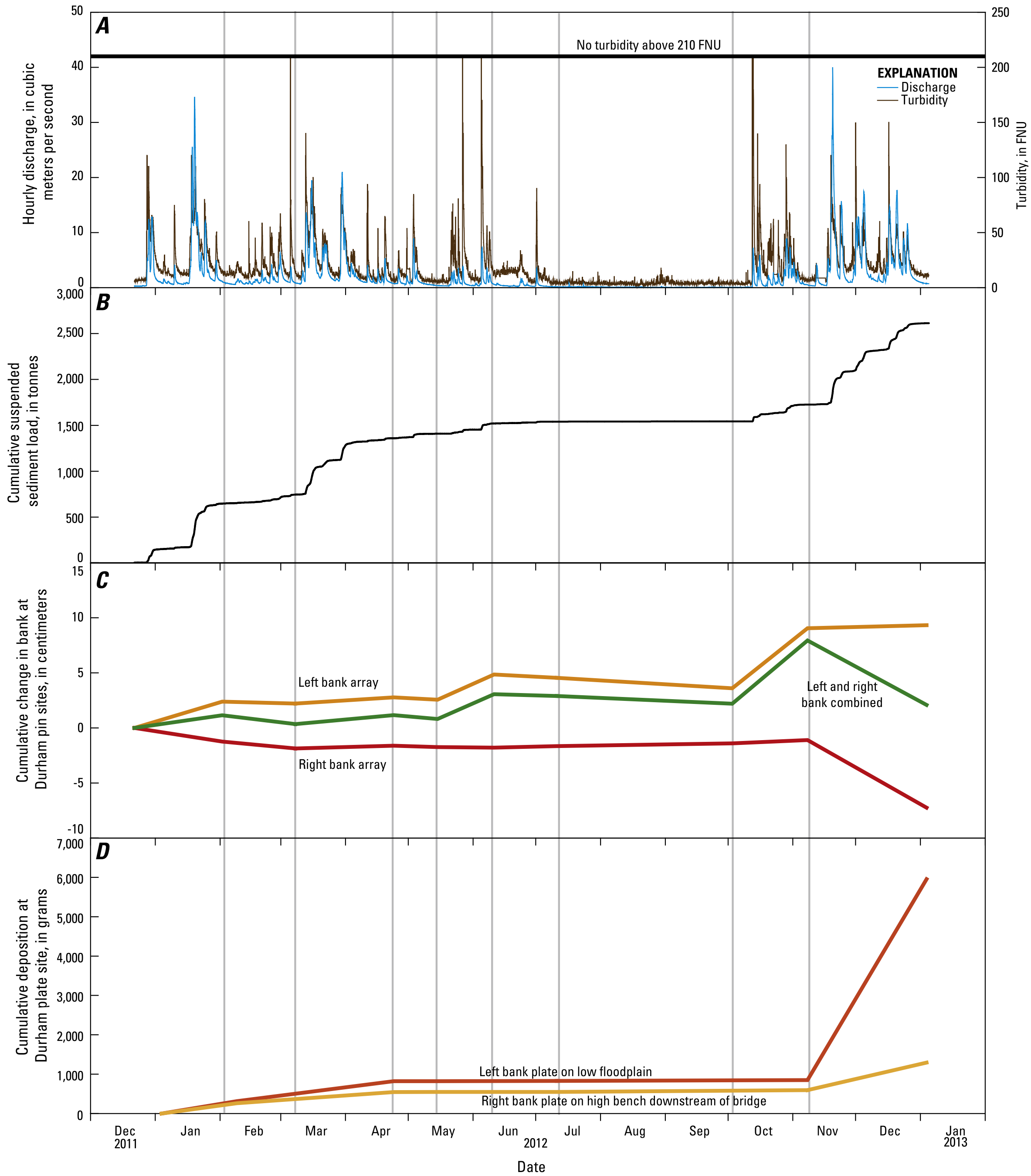

Fig. 6. Discharge and turbidity at the Fanno Creek at Durham Road site (A), cumulative calculated suspended sediment loads at that site (B), cumulative lower watershed pin measurement changes (C), and cumulative lower watershed plate deposition measurements (D) between December 2011 and January 2013 for Fanno Creek, northwest Oregon. The light gray vertical lines separate the sampling periods for the erosion pin and deposition plate measurements.

tion balance accounts for about 1,480 t of suspended sediment transported past that location. Assuming that the portion of suspended sediment derived from bank material has the same carbon content as bank material, the average annual amount of organic carbon and organic matter from bank material exported to the Tualatin River would be 29–67 t and 49–116 t, respectively (Table 8, Fig. 7).

4. Discussion

4.1. Fine sediment sources and sinks

The purpose of this study was to identify the key sources of organic carbon within the Fanno Creek watershed and quantify the amounts of sediment and associated OM being eroded, deposited, and transported. We hypothesized that large quantities of channel bank erosion could account for the presence and transport of OM in Fanno Creek. Results from our research show that bank sediment is a substantial contributor of sediment and OM to the stream. However, when compared with OM sourced from riparian biomass presented in companion paper 1 (Sobieszczyk et al., 2014), bank sediment is not likely the dominant source of OM.

4.1.1. Sinks

The geomorphic mapping approach used to identify fine sediment sources and sinks showed that dominant zones of deposition occur in the middle reaches of the watershed. While the total

Table 7
Grain size and total organic carbon amounts for composite deposition plate samples and total organic carbon for bank samples collected at erosion pin sites for Fanno Creek, northwest Oregon [All material measured as in the greater than 2 mm size fraction was organic matter. Abbreviations: TOC, total organic carbon; mm, millimeters; μm, microns; –, no data].

Basin location and reach	Sample		Grain size			TOC	Comments
	Type	Composite or location	>2 mm	2 mm to 63 μm	<63 μm	Percent	
Upper, Beaverton–Hillsdale	Deposition plate	Annual	92.8	5.4	1.8	41.6	Deposition was composed entirely of terrestrial fall and plate was apparently not inundated
	Bank	Straight	–	–	–	3.3	–
	Bank	Meander	–	–	–	0.7	–
Middle, Greenway	Deposition plate	Annual	5.2	74.9	19.9	4.2	–
	Deposition plate	Fall flush	2.8	71.1	26.1	5.8	–
	Deposition plate	High flow	4.6	83.8	11.6	7.0	–
	Bank	Meander	–	–	–	1.6	–
	Bank	Straight	–	–	–	0.6	–
Middle, Englewood	Deposition plate	Annual	12.9	29.1	58.0	11.3	–
Lower, Durham	Deposition plate	Annual	2.7	88.4	9.0	2.5	Deposition plates furthest downstream were
	Deposition plate	Fall flush	40.7	41.0	18.3	36.6	inundated during periods of high flow in the Tualatin River
	Deposition plate	High flow	2.5	92.6	4.9	5.5	
	Bank	Straight	–	–	–	1.2	–
	Bank	Meander	–	–	–	1.7	–

sediment sink area is much larger than the mapped sediment source areas, the distal floodplain likely accumulates sediment only during rare and large floods. Johnston et al. (2001) noted that sedimentation rates typically decrease with distance from a stream bed and largely depend on the types of geomorphic features in and between areas. Hupp et al. (2009) show that floodplain deposition is sensitive to the connectivity of sediment laden water and the duration of overbank flow. In altered streams, levees near banks often receive less sediment than other geomorphic surfaces (Hupp et al., 2009). Sinks within the active channel, including bars, low benches, or deposits near dams and blockages, probably sequester a large proportion of sediment and OM relative to more distal floodplain areas. Although some fine sediment deposition is possible in the distal floodplain and net sediment inputs from tributaries were not estimated, the near-channel floodplain and in-channel sinks and sources probably account for most of the sediment seasonal to annual flux. The largest areas of potential sinks exist in the Greenway and Englewood reaches where the floodplain is low and wide and where wetlands tend to decrease the flow velocity due to greater surface roughness from features (i.e., topography, woody debris, tree stems, and slope; Brinson et al., 1995) and vegetation (Darby, 1999). Measurements of sediment on deposition plates show that more net accumulation occurs in meander zones on the floodplain, although large amounts of deposition are possible in straight segments where the local gradient is low.

Low benches in the channel resulting from bank failure (Hupp and Simon, 1991; Osterkamp and Hupp, 1984; Simon, 1989; Simon and Hupp, 1986) likely persist due to the cohesive nature of the sediment blocks. These deposits may become zones of future sediment accumulation especially as vegetation establishes and matures, stabilizing the block and creating a zone of roughness (Schenk and Hupp, 2010). However, deposited material on low benches can be remobilized during high flows. Although this process is poorly understood, the residence time of these deposits in Fanno Creek is probably on the order of one year if no vegetation establishment occurs. Very little floodplain sediment accumulation was measured in the upper watershed where channel gradient is steep and the floodplain is relatively high above the active channel.

4.1.2. Sources

Geomorphic mapping revealed that the dominant source of erosion in Fanno Creek is the fluvial and mass wasting of stream banks in all reaches, as opposed to other mechanisms including stormwater, biotic, or hillslope erosion. This result accords with several other studies (e.g., Simon and Darby, 2002; Simon and Hupp; 1986; Simon and Rinaldi, 2006). More than 70% of the banks along Fanno Creek are experiencing or are subject to erosion, as indicated by bare surfaces with exposed bank material, no bank protection, and no or little vegetation. The total mapped area of banks in planview subject to fluvial or mass wasting erosional processes is about 159,000 m^2, which underestimates the actual bank surface area. Fluvial erosion on exposed banks and on cut banks likely continues for many years, providing a small but continual source of fine sediment to the stream. However, seasonal mass wasting likely accounts for a substantial amount of sediment mass input to the channel. While not mapped as an erosional zone, riparian floodplain and wetland ponds may be a source of remobilized sediment during high flows, especially fine material.

Measurements at pin sites showed that erosion and deposition are more dynamic at meanders than at straight sites. Measured rates of erosion were as high as 85 cm/year, but such high rates were typically the product of mass failure, whereas average erosion rates for the sampling period from pin measurements were about 6.7 cm/year (Fig. 5B). Hardpan clay banks were determined to be more stable than unconsolidated soil and sediment banks. Gradual burial of pins through slow mass wasting of banks, possibly soil creep, was often recorded as deposition at the erosion pin sites but is ultimately another mechanism of erosion and sediment input to the channel. Long-term average erosion rates based on dendrochronology (0.8–4.0 cm/year) were generally similar to but somewhat smaller than the average annual erosion rates derived from erosion pin measurements. Given that the few dendrogeomorphic measurements were at locations where mature vegetation was securing the bank, and the erosion pin measurements were commonly at locations of evident mass wasting, the two sets of erosion rates likely bracket the range of erosion rates for the watershed as a whole, perhaps indicating an overall average rate of bank erosion of about 4.2 cm/year for Fanno Creek.

4.1.3. Transport

Bank erosion, whether from continual fluvial removal of bank material or more conspicuous mass-wasting processes, is likely to be the dominant source of suspended sediment in Fanno Creek. Given average rates of erosion and sedimentation for each reach and the areas of eroding banks and sedimentation areas mapped in 2012, the amount of sediment estimated to be transported in

Table 8
Erosion, deposition, total organic carbon, and organic material exchange along Fanno Creek, northwest Oregon. Totals excluding the Durham reach are included for comparison with suspended sediment loads calculated at the Fanno Creek at Durham Road site (station 14206950) at the upstream end of the Durham reach. [Abbreviations: <, less than; TOC, total organic carbon; m^3, cubic meters; cm, centimeters; t, tonnes; %, percent.]

	Reach	Erosion area, m^2	Deposition area, m^2	Erosion rate, cm/yr	Deposition rate, cm/yr	Annual erosion, high, t	Annual erosion, low, t	Annual deposition, t	Depositional grain size < 2 mm, %	Annual deposition < 2 mm, t	Net bank erosion, high, t	Net bank erosion, low, t	Bank TOC, %	Carbon, high, t	Carbon, low, t	Organic Matter, high, t	Organic Matter, low, t
1	Beaverton–Hillsdale	20,741	19,970	−3.9	1.8	−1,379	−1,055	220	7	16	−1,364	−1,039	2.02	−27.6	−21.0	−48	−36
2	Oleson	10,586	27,356	−2.8	1.8	−501	−383	302	7	22	−479	−361	2.02	−9.7	−7.3	−17	−13
3	OES Wetlands	6,646	25,112	−4.7	4.8	−527	−403	742	95	704	177	301	1.11	2.0	3.3	3	6
4	Portland Golf Club	1,710	12,758	−5.3	4.8	−155	−118	377	95	358	203	240	1.11	2.3	2.7	4	5
5	Vista Brook	14,662	14,954	−3.2	4.8	−790	−604	442	95	419	−371	−185	1.11	−4.1	−2.0	−7	−4
6	Wonderland	10,770	26,432	−3.1	4.8	−564	−431	781	95	741	177	310	1.11	2.0	3.4	3	6
7	Greenway	12,994	71,027	−3.3	4.8	−738	−564	2,100	95	1,992	1,254	1,427	1.11	13.9	15.8	24	27
8	Englewood	3,492	47,781	−3.7	4.8	−217	−166	1,413	95	1,340	1,123	1,174	1.11	12.4	13.0	21	22
9	Woodard	18,286	40,471	−3.1	4.8	−956	−731	1,196	95	1,135	179	404	1.11	2.0	4.5	3	8
10	Fanno Creek Park	7,704	10,532	−5.2	5.7	−684	−523	373	97	363	−321	−160	1.45	−4.7	−2.3	−8	−4
11	Bonita	16,059	7,518	−5.4	5.7	−1,472	−1,126	266	97	259	−1,213	−867	1.45	−17.6	−12.6	−30	−22
12	Gentlewoods	15,201	16,186	−5.4	5.7	−1,407	−1,076	574	97	558	−848	−517	1.45	−12.3	−7.5	−21	−13
13	Durham	19,900	9,769	−6.2	5.7	−2,105	−1,610	346	97	337	−1,768	−1,273	1.45	−25.6	−18.5	−44	−32
	Export to Tualatin River	158,751	3,29,865			−11,495	−8,790	9,133		8,244	−3,251	−547		−67	−29	−116	−49
	Excluding Durham Reach	138,851	320,096			−9,390	−7,181	8,787		7,907	−1,483	726		−41	−10	−72	−17

Fanno Creek is consistent with an independent calculation of suspended sediment loads at the Durham Road streamflow-gaging station (14206950; Tables 6 and 8). Periods of high suspended sediment loads coincide with high rates of erosion (Fig. 6C) and deposition (Fig. 6D) measured by the erosion pins and deposition plates, patterns consistent with those observed on Difficult Run in Virginia (Hupp et al., 2013; Schenk et al., 2013). Other sources of sediment, such as from stormwater drainages or biotic activity, may be important to local sediment dynamics but probably do not account for a substantial portion of the instream sediment load.

4.2. Influences on sediment dynamics

The local bank material, channel geometry, floodplain elevation, and establishment of riparian vegetation all influence sediment dynamics along Fanno Creek. Specifically, banks composed of hardpan clay appear to be more resistant to erosion, contrasting with the more dynamic banks composed of unconsolidated soils or loose alluvial material. Meander zones are more dynamic with both erosion and deposition. Based on erosion pin measurements, erosion is mostly on the outside of bends in conjunction with occasional mass wasting. Straight sites appear to be more stable, although cycling of fine sediment and OM between floodplain deposition and bank erosion was observed. In the middle watershed, the channel still may be adjusting to its new form and a lack of established vegetation post-restoration. Backwater from the Tualatin River likely reduced hydraulically induced erosion at the lower watershed meander site but probably prolonged bank saturation, thus promoting bank instability. Observations during field mapping indicate that small sediment blocks, typically with dimensions less than 30 cm, slide down the banks in the mid to late summer when flows are low, and that larger bank failures occur during the wet season when saturated banks are subject to higher seasonal flows. At the reach scale, more attenuation of flows and settling of fine sediment are evident in the wider, lower floodplain and backwater areas in and near wetlands. Forested reaches overall provide more bank stability. Large, rooted vegetation was observed preventing the slumping of bank material in more open areas.

Fluvially deposited sediment, typically abundant with particulate organic matter, appears to be more mobile than sediment emplaced in the channel via mass wasting processes. Low benches within the active channel also represent zones of accumulation but appear to be more stable over time than bars. Blocks of fine sediment that have been deposited in the channel appear to persist for several years, as indicated by relatively mature vegetation growing on many of them. Depending on relative height within the channel and seasonal flow conditions, low benches appear to serve as zones of deposition as well as sediment remobilization. Deposition plates located on low benches within the active channel near the erosion pin meander site accumulated sediment during low and moderate flows, but those deposits were remobilized during subsequent high flows. Similarly, a study by Skalak and Pizzuto (2010) on the South River, Virginia found that fine grained deposits along channel margins from suspended sediment transport and deposition contained large amounts of organic matter, and the residence times of those features was about 1.75 years.

Low floodplain areas and wetlands trap substantial amounts of sediment. Although sediment deposited in low floodplain areas could re-enter the channel during subsequent high flows, it is likely that only a fraction of that sediment is remobilized without extreme flow conditions. The amount of deposition for all plates in the middle watershed, including the ponded site, appears to be positively related to discharge. As observed from the deposition plates, herbaceous vegetation can rapidly establish during the low-flow season, potentially facilitating the persistence of some low-lying depositional areas.

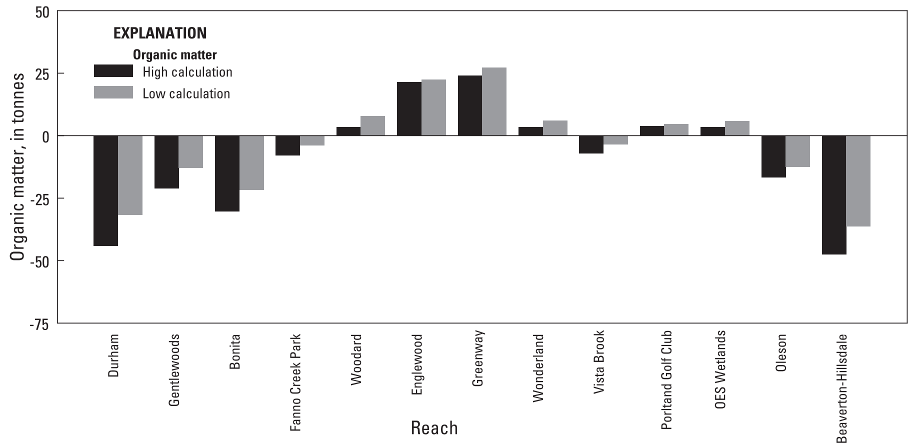

Fig. 7. High and low range of estimated organic matter fluxes by reach along Fanno Creek, northwest Oregon.

The presence of beaver dams, log jams, or other instream blockages that might retain fine sediment and OM tends to reduce the amount of organic carbon exiting a system (Bilby and Likens, 1980). Such dams occur throughout the Fanno Creek watershed (see dataset at http://water.usgs.gov/lookup/getspatial?fannoCk_erosion_deposition_2012.xml) and are most common where moderate bank erosion has undercut and toppled trees from the bank or where beavers have created structures. These instream structures likely create areas of transient sediment and carbon storage; in contrast, sequestration of sediment in distal floodplain sites could extend for thousands of years (Wohl et al., 2012). Geomorphic mapping provides an inventory of features within the floodplain and active channel that can be used to help plan, monitor, and evaluate future restoration or rehabilitation projects. Management strategies can be developed to target bank stabilization and riparian vegetation projects in open reaches where mass failure of banks is most apparent. Mapping facilitates understanding of the hydrologic connectivity and not only has implications for sediment management, but potentially for other contaminants and their interactions within ecosystems For example, in urban landscapes, restoring lost hydrologic connectivity could promote the transport of pollutants, including fine sediment and OM, or non-native species (Jackson and Pringle, 2010).

4.3. Sediment and organic matter

Taken together, the mapping and field measurements show that the reaches within the uppermost and lowermost watershed likely produced the most OM from eroding bank material, whereas OM associated with bank material was predominantly deposited in middle watershed reaches (Table 8, Fig. 7). Measured TOC values from deposition plate composites (2.5–41.6%, median 6.4%) and bank material samples (0.6–3.3%, median 1.4%) indicate that organic matter is more prevalent in recent deposits on floodplain surfaces than in material eroded from channel banks. It is likely that the banks, especially those cut banks composed of hardpan clay, are an important source of fine sediment but not the dominant source of carbon to the stream, at least over the course of a year. The amount of carbon in the banks in the middle watershed is only 15–37% of the carbon content measured in the annual composite of materials collected on the deposition plates (Table 7). In the lower watershed, the bank carbon content was higher, at 49–65% of the carbon content of the annual deposition-plate composite. In the upper watershed, almost all the material collected from the plate was composed of litterfall with virtually no sediment. It appears that a substantial amount of organic carbon may be transported in the upper watershed but that carbon is largely the product of leaf litter. Bank material is likely a more substantial contributor of carbon to the system in the lower watershed based on the higher ratios of bank carbon to deposition-plate carbon. Tributary contributions would likely increase the amount of OM export calculated from Fanno Creek. The average annual export of OM from bank material along Fanno Creek to the Tualatin River may be in the range of 49–116 t. Such estimates indicate bank material is an important, but not dominant source of OM in Fanno Creek, as the average annual input of biomass from riparian litterfall has been estimated to be 136 t directly to the stream channel and 991 t to the geomorphic floodplain (Sobieszczyk et al., 2014). A richer source of carbon (soil, leaf litter) still is required to explain the TOC content of the material being transported instream, and more suitable measures of carbon to the system, such as litter traps aimed at monitoring primary productivity, could refine the carbon budget for Fanno Creek (Goldman et al., 2014).

Seasonal variation also appears to be important in determining the amount of OM present in the stream. The ratio of carbon content in bank material to the carbon content in the deposition-plate materials decreases when bank material is compared to deposited material for the fall flush and highest-flow periods in the lower and middle watershed (Table 7). These flow events had higher carbon contents than the composites from the entire sampling period. Materials deposited in the lower watershed during the fall-flush event had the highest carbon content during the study, at more than 6 times what was deposited during the highest-flow period, demonstrating that large amounts of carbon were transported during the first-flush event, despite the fact that higher suspended sediment loads occurred later, during higher-flow events (Fig. 6B). At low flow, more of the carbon available for transport is likely from decomposing biomass (Goldman et al., 2014) and soil associated with slumping bank material. Analyses by Goldman et al. (2014) target the actual amounts and characteristics of instream organic carbon to further examine the seasonal sources and transport of organic matter in the Fanno Creek watershed.

5. Conclusions

The mapping results, along with measurements of erosion and deposition rates and carbon contents, used in conjunction with riparian biomass data from Sobieszczyk et al. (2014), indicate that dominant sources of OM to Fanno Creek likely are not derived from the distal floodplain but rather from other sources in riparian areas, areas lacking bank-stabilizing vegetation (bank sediment; such as in the Wonderland and Greenway reaches) or in wetland areas of lower, wider floodplain where more floodplain sediment and OM is reworked at moderate flows (floodplain sediment and leaf litter; OES Wetlands and Englewood reaches). In all reaches, large wood, beaver dams, or other blockages retain fine sediment and OM, at least temporarily. Most of the banks along Fanno Creek are eroding or have a high potential for erosion, possibly as a result of an imbalance in basin hydrology and stream morphology caused by anthropogenic alteration, but results indicate that the largest source of OM associated with fine sediment from bank erosion is from the uppermost and lowermost reaches (Beaverton–Hillsdale and Durham, respectively). However, along the course of Fanno Creek, much of that OM eroded in the upper reaches is exported to the floodplain and removed from the channel, making reaches in the lower watershed (Durham, Gentlewoods, and Bonita) key areas to focus on bank sediment that is transported ultimately to the Tualatin River.

The measured TOC content of bank material and deposition-plate composites indicated that the OM transported with fine suspended sediment in Fanno Creek is 2–5 times (or more) richer in carbon than the bank material. Bank material might supply a substantial fraction of the overall OM load for most normal to low flows over the course of a year, but during high-flow events, more OM is mobilized from other sources such as soil, leaf litter, and adjacent floodplain areas. From TOC data, it appears that the greatest amount of particulate OM transport may occur during the first seasonal storm event after a prolonged low-flow summer period, while larger loads of suspended sediment are transported during larger storms later in the high-flow season. Bank sediment may comprise a greater amount of the total OM load at different times of the year. A better understanding of OM transport as a function of season and flow would help to elucidate how OM sources and transport may change, especially with anticipated variations in hydrology from climate change and continuing urbanization in the Tualatin River basin (Praskievicz and Chang, 2011).

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Investigating organic matter in Fanno Creek, Oregon, Part 3 of 3: Identifying and quantifying sources of organic matter to an urban stream

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SUMMARY

The sources, transport, and characteristics of organic matter (OM) in Fanno Creek, an urban stream in northwest Oregon, were assessed and quantified using: (1) optical instruments to calculate transported loads of dissolved, particulate, and total organic carbon, (2) fluorescence spectroscopy and stable isotope ratios ($\delta^{13}C$, $\delta^{15}N$) to elucidate sources and chemical properties of OM throughout the basin, and (3) synoptic sampling to investigate seasonal and hydrologic variations in the characteristics and quantity of OM. Results from this study indicate that of the roughly 324 (±2.9%) metric tons (tonnes, t) of organic carbon exported from the basin during March 2012 to March 2013, most of the OM in Fanno Creek was dissolved (72%) and was present year-round at concentrations exceeding 3–4 milligrams of carbon per liter, whereas particulate carbon typically was mobilized and transported only by higher-flow conditions. The isotopic and fluorescence characteristics of Fanno Creek OM indicate that the carbon originates primarily from terrestrial inputs, most likely riparian vegetative biomass that enters the stream via litterfall and overland transport and then travels through the system episodically as a result of hydrologic processes. The amount of OM exported from the Fanno Creek drainage over the course of a year in this study is consistent with previous estimates of annual riparian litterfall in or near the creek. Although the creek channel is actively eroding, most bank material has too little OM for that to be a dominant source of OM to the stream. Fluorescence data revealed that the OM contains primarily humic and fulvic-like components that become less aromatic as the OM moves downstream. The most significant seasonal variation was associated with OM transported in the first storms of the autumn season (fall flush). That material was characteristically different, with a larger fraction of microbially derived OM that probably resulted from an accumulation of easy-to-mobilize and decomposing material in the streambed during previous months of summertime low-flow conditions. The first fall flush produced the highest concentrations of OM of the entire year, and the resulting load of mobilized and decomposing OM resulted in a significant oxygen demand immediately downstream in the Tualatin River.

1. Introduction

1.1. Background and problem

Organic matter (OM) is ubiquitous in all aquatic ecosystems (Battin et al., 2009). OM is the base of the food web, providing energy to heterotrophic organisms (Jaffe et al., 2008), and is a critical component of many biological processes such as light limitation for photosynthesis (Wetzel, 1992), transport of toxic metals and other contaminants (Aiken et al., 1985), and exertion of bed-sediment oxygen demand (Thacker et al., 2005). Typical sources of OM include decaying plants and animals, exudates from algae and bacteria, and anthropogenic inputs from sewage, agriculture, and urban landscapes. Although OM has an essential role in ecosystem food webs and biogeochemical processing, excessive amounts that generate large oxygen demands can be detrimental to aquatic ecosystems. Identifying and quantifying the sources and transport of OM is important to the management of ecosystem health in some aquatic ecosystems.

Natural OM is a heterogeneous mixture of complex organic materials that has been difficult to measure and assess as a whole. Absorbance and fluorescence spectroscopy are relatively inexpensive and simple methods to assess, monitor, and study the dissolved organic matter (DOM) fraction, which represents the largest detrital organic carbon pool. Measurements of the optically active DOM can provide information about the characteristics,

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quantity, and sources of the DOM pool (Coble, 1996, 2007; Downing et al., 2009; Hudson et al., 2007; McKnight et al., 2001). Fluorescence spectroscopy targets the fraction of DOM that absorbs light energy and re-emits it at a longer wavelength (Murphy et al., 2010). By measuring the intensity of fluorescence over a range of excitation and emission wavelengths, thus creating an excitation-emission matrix (EEM), patterns in those data can be used to infer the sources and characteristics of the OM, such as the amount of humic and fulvic acids, protein-like material, and phytoplankton-derived material (Coble, 1996; McKnight et al., 2001; Stedmon et al., 2003). Advances in optical sensor technology have made it possible to use in-situ fluorometers to quantify DOM concentration and composition. Specifically, the fluorescing component of DOM (FDOM) can be measured continuously and used as a reliable proxy for concentrations of dissolved organic carbon (DOC); with the addition of other signals such as turbidity, FDOM also can be used to estimate particulate organic carbon (POC) and total organic carbon (TOC) concentrations (Bergamaschi et al., 2005, 2012; Pellerin et al., 2012; Saraceno et al., 2009; Spencer et al., 2007).

In addition to fluorescence, elemental analysis of carbon (C) and nitrogen (N) can be used to distinguish among sources of OM in fresh water systems (Finlay and Kendall, 2007; Hood et al., 2005). Algal and microbial activity results in isotopic fractionation of OM and tends to produce a lower C:N ratio and less aromatic carbon than OM from a terrestrial source (Aiken et al., 1992; McKnight et al., 1991). Tracking changes in the isotopic properties, C:N ratios, and fluorescence properties of OM in an aquatic ecosystem can provide useful information on composition, origin, and function of that material.

The Tualatin River and some of its tributaries in northwest Oregon periodically have low dissolved oxygen (DO) concentrations caused in part by the decomposition of OM both in the water column and the bed sediment (Rounds et al., 1999). The health of aquatic ecosystems can become impaired by low DO concentrations; conditions in the Tualatin River and its tributaries are being managed and regulated through a Total Maximum Daily Load program to improve DO conditions, among other issues (Oregon Department of Environmental Quality, 2001). Previous studies measured the rate of sediment oxygen demand (SOD) in both the Tualatin River and its tributaries (including Fanno Creek), found significantly higher SOD rates in the tributaries, and hypothesized that OM in tributary sediments might be more labile because it is closer to its sources (Rounds and Doyle, 1997). Higher rates of SOD in Fanno Creek also appear to occur in areas more likely to have higher rates of organic matter deposition. Another study in the Tualatin River basin used stable isotopes of C and N to determine that much of the bed sediment OM, which is the source of the SOD, was derived primarily from terrestrial sources (Bonn and Rounds, 2010). In order to improve the low DO concentrations and comply with water-quality standards, the sources of OM in these streams need to be identified and quantified, and the transport and fate of the OM needs to be better understood.

1.2. Concurrent research

The research presented in this article summarizes the third component of a three-part investigation. The overall goal was to identify and quantify the sources of organic matter to an urban stream (Fanno Creek) and its bed sediments that then decompose and deplete oxygen. The first component of the study (Sobieszczyk et al., 2014) quantified annual loads of riparian organic matter from litterfall. The second component (Keith et al., 2014) focused on sediment-related sources, sinks, and transport of organic matter through geomorphic mapping and measurement of rates of erosion and deposition. The third component (this research) assessed the sources and quantities of OM in Fanno Creek using: (1) optical instruments to calculate the transport and basin export of dissolved, particulate, and total organic carbon, (2) fluorescence spectroscopy and stable isotopes of C and N to characterize the sources and chemical properties of OM throughout the basin, and (3) synoptic sampling to investigate seasonal and hydrologic variations in characteristics and quantity of OM.

1.3. Study area

Fanno Creek is an urban tributary to the Tualatin River in northwest Oregon (Fig. 1). The creek flows 27 kilometers (km) through a riparian corridor comprised of wetlands, parks, residential neighborhoods, golf courses, businesses, and small forested areas. The creek drains approximately 82.4 km^2 of predominantly urban landscape. Eastward-tracking storms from the Pacific Ocean during the November through May rainy season produce episodic high-flow events in response to precipitation. A high density road network and other impervious areas near the creek combined with poorly drained soils create a hydrologically flashy environment where the response of stream discharge to precipitation is rapid (Chang, 2007). In contrast, the June or July through October period in western Oregon is characterized by few storms, as the jet stream tends to guide storms northward into Canada during summer. In summer, streamflow in Fanno Creek is characteristically low, on the order of about 0.1 m^3/s, and much of the water in the creek is derived from groundwater discharge.

Extensive hydrologic and water-quality datasets have been collected in the Fanno Creek watershed through routine monitoring and special studies. Combined with some water-quality problems and the need to manage a large variety of urban stressors to the ecosystem, this watershed is a good choice for a study of OM sources. Two year-round streamflow-gaging stations are operated and maintained by the U.S. Geological Survey (USGS), one in the upper watershed at 56th Avenue (station 14206900) and another located 2.25 km from the mouth at Durham Road (station 14206950). The Durham Road site includes instrumentation that has continuously monitored a suite of water-quality parameters since 2003.

2. Methods

2.1. Continuous FDOM sensor

Continuous measurements of FDOM were made using a Turner Cyclops-7 FDOM probe (excitation/emission wavelengths: 370/460 nm) attached to a Turner Sensor Adapter on a YSI model 600-OMS data sonde. The FDOM probe was deployed and co-located with a multiparameter water-quality monitor at the Fanno Creek at Durham Road streamflow-gaging site (station 14206950). The multiparameter monitor was a YSI model 6920V2 data sonde collecting water temperature, specific conductance, dissolved oxygen, pH, and turbidity. Measurements were taken with the instruments and telemetered every hour. The FDOM probe was deployed on March 13, 2012 and removed a year later to provide data over a full annual seasonal cycle of flow conditions.

The FDOM probe was operated and maintained according to standard USGS protocols used for other continuous monitors (Wagner et al., 2006). The probe was calibrated using Turner PTSA (1,3,6,8-pyrenetetrasulfonic acid tetrasodium salt) standards and cleaned at regular intervals, often weekly. Data corrections due to fouling and drift derived from field data were applied to the raw readings. In addition to standard USGS data-processing protocols to correct for fouling and drift, FDOM data require additional post-processing to account for temperature effects as well as

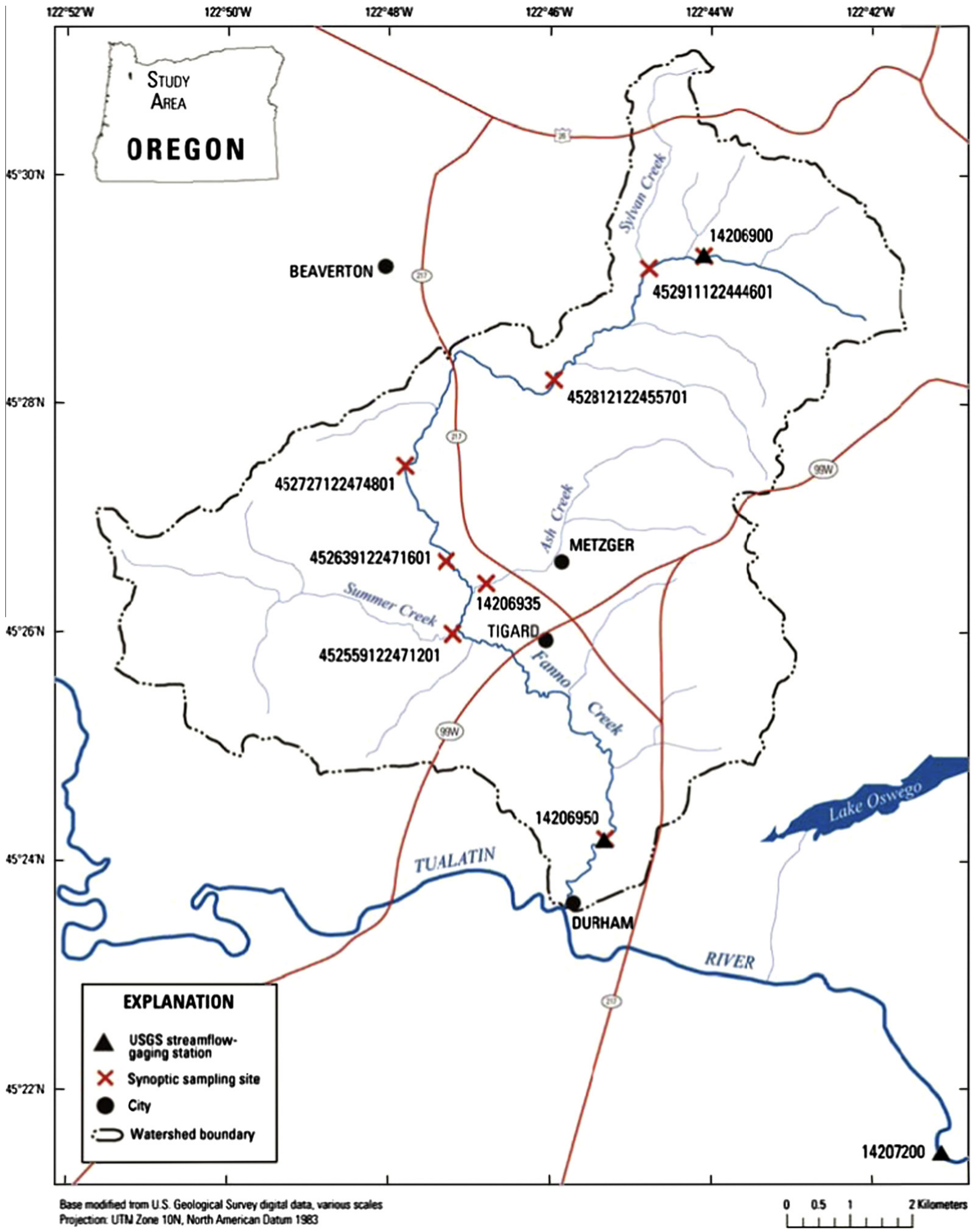

Fig. 1. Site map of Fanno Creek watershed showing locations of sampling sites and U.S. Geological Survey continuous monitoring stations.

signal-quenching effects from particles that can scatter and attenuate the excitation and emission light signals. The temperature and turbidity corrections were applied in accordance with protocols described by Downing et al. (2012). In addition, discrete water samples were collected for laboratory FDOM analysis for a variety of purposes, including verification of probe data.

2.2. Synoptic sampling

Ten synoptic samplings were completed over a range of hydrologic conditions between January 2012 and January 2013 to collect data and samples to characterize the organic materials present and being transported in Fanno Creek (Table 1). Fanno Creek was divided into 13 reaches based on land cover, geomorphic

Table 1
Synoptic sample dates and conditions in Fanno Creek, northwest Oregon. [Flow condition categories at Fanno Creek at Durham Road (station 14206950): low <3.4 m^3/s, mid 3.5–15 m^3/s, high >15 m^3/s.]

Synoptic	Date	Season	Flow
S1	1/10/2012	Winter	Low
S2	2/2/2012	Winter	Low
S3	3/15/2012	Spring	High
S4	5/8/2012	Spring	Low
S5	6/5/2012	Spring	Mid
S6	8/15/2012	Summer	Low
S7	10/12–13/2012	Fall (first-flush)	Mid
S8	11/12/2012	Fall	Mid
S9	11/19/2012	Fall	High
S10	1/25/2013	Winter	Low

Table 2
Synoptic sample sites and description in Fanno Creek, northwest Oregon.

Site	Station ID	Kilometer (km from mouth)	Description
		Fanno Creek Main-Stem Sites	
Fanno at 56th	14206900	23.3	Upper basin
Fanno at pumphouse	452812122455701	18.7	Below golf course and wetlands
Fanno at Greenway Park	452727122474801	13.6	Middle basin restoration site
Fanno at Ironwood	452639122471601	11.4	Wetlands
Fanno at Durham Road	14206950	2.4	Lower basin
		Fanno Creek Tributary Sites	
Sylvan Creek	452911122444601	22.2	Urban
Ash Creek	14206935	10.4	Industrial
Summer Creek	452559122471201	9.6	Park/Urban

characteristics, major road boundaries, and riparian vegetation (Sobieszczyk et al., 2014). Five sites along Fanno Creek and sites in three tributaries were chosen to represent the different reaches and potential sources of OM (Table 2, Fig. 1).

Discrete water samples were collected at all sites during synoptic events, with two exceptions (synoptic #7 (S7)- Fanno Creek at Ironwood, and synoptic #9 (S9)- Sylvan Creek) when sites were inaccessible due to high water. Field parameters (temperature, specific conductance, pH, dissolved oxygen, and turbidity) were collected at each site using a calibrated multiparameter instrument according to USGS protocols (Gibs et al., 2007). Discharge measurements were taken at sites without continuous streamflow-gaging stations using standard USGS methods (Rantz et al., 1982). Water samples were collected mid-stream using a depth-integrated methodology (Edwards and Glysson, 1999). Samples were transferred directly into a 1-liter combusted amber glass bottle. All samples were analyzed for dissolved organic carbon (DOC), total particulate carbon and nitrogen (TPCN), optical parameters including fluorescence and absorbance, and stable isotopes of carbon and nitrogen. At the Fanno Creek at Durham Road site, additional water samples were collected for analysis of suspended sediment.

2.3. Sample analyses

2.3.1. Dissolved organic carbon (DOC) and total particulate carbon and nitrogen (TPCN)

Samples for DOC and TPCN analyses were filtered (Whatman, 0.7 μm glass fiber filter, combusted at 450 °C for 4 h) through a borosilicate glass filtration unit. Filtrate was collected into precombusted 125 mL glass amber bottles for DOC, acidified with 1 mL of 4.5 N sulfuric acid and analyzed for DOC at the USGS National Water Quality Laboratory (NWQL: Denver, Colorado) using persulfate oxidation methods described by Brenton and Arnett (1993). Three filters were collected and processed per sample for TPCN and analyzed at the USGS NWQL using protocols described by the U.S. Environmental Protection Agency (2000).

2.3.2. Optical analysis

Sample filtrate for optical analysis was collected into precombusted 40 mL glass amber bottles and stored in the dark at 4 °C. All samples were analyzed within 5 days of collection. A fluorescence excitation-emission matrix (EEM) and absorbance scan measurements were collected using a Horiba Jobin Yvon Aqualog benchtop fluorometer. EEMs were constructed using excitation (ex) wavelengths of 240–600 nm at intervals of 3 nm and emission (em) wavelengths of 200–620 nm at intervals of 3.2 nm, with an integration time of 1 s and a CCD Gain set of medium. Ultraviolet and visible absorbance measurements were recorded for wavelengths of 240–600 nm at intervals of 3 nm.

Several standard corrections and normalizations were applied to the EEM data. The ex and em data were corrected for instrument-specific response, and the EEMs were blank-corrected against a Starna 3Q-10 Raman response. UV–visible absorption data (which ranged from 0 to 0.45 absorbance units, with only 7% of the samples exceeding the 0.3 absorbance unit threshold that sometimes indicates inner-filter-effect problems (Ohno, 2002)) were used to correct all values for inner filter effects. Lastly, the EEM was normalized to the area under the water-Raman curve at an excitation wavelength of 350 nm converting the arbitrary units to Raman units (Murphy et al., 2010; Stedmon et al., 2003). The corrected EEMs then were imported into Matlab R2009A for further analysis, including removing interference from Raleigh scattering, cutting and interpolating the region of the EEM not affected by scattering and/or particles, converting the data into vectors, selecting characteristic peak signals and ratios based on documented literature (Coble, 2007; Hudson et al., 2007; Stedmon and Bro, 2008), and plotting the data into contour and surface maps. Three key descriptors were derived from optical absorbance and fluorescence measurements: (1) specific ultraviolet absorbance at 254 nm normalized to DOC ($SUVA_{254}$, hereafter referred to as SUVA) (Weishaar et al., 2003), (2) fluorescence index (FI), which is the ratio of emission at 470 nm to the emission at 520 nm with an excitation of 370 nm (McKnight et al., 2001), and (3) humification index (HIX), which is the ratio of the emission intensity in the 300–480 nm region to the emission intensity in the 300–345 nm region with an excitation at 254 nm (Ohno, 2002).

2.3.3. Stable isotopes

Samples for analysis of stable isotopes of particulate carbon (C) and particulate nitrogen (N) were sent to the Stable Isotope Facility at the University of California, Davis. Samples were collected on glass fiber filters and submitted in triplicate. Samples were analyzed for $^{13}C/^{12}C$ and $^{15}N/^{14}N$ isotope ratios using an Elemental Vario El Cube elemental analyzer. The final ratios were expressed relative to standard reference materials ($\delta^{13}C$, $\delta^{15}N$) according to Sharp (2005). Triplicate results were assessed based on their means, standard deviation, and 95% confidence intervals. Outliers due to laboratory errors were removed from the dataset.

2.4. Statistical analyses

2.4.1. Parallel Factor Analysis

Parallel Factor Analysis (PARAFAC) was used to decompose the fluorescence signatures in the corrected EEMs into unique components that contain information about the characteristics of the DOM pool (Bro, 1997). EEM–PARAFAC is a three-way principal components analysis that resolves absorption and emission spectra into orthogonal fluorophore groups (components) and determines loadings for each component that are proportional to their concentration. Component percentages can be calculated by dividing each component loading by the sum of the component loadings to reveal qualitative differences between samples (Andersson and Bro, 2000). Procedures established by Stedmon and Bro (2008) were used to develop a PARAFAC model for the Fanno Creek study samples using the N-way toolbox, version 6.1 (Andersson and Bro, 2000; Bro, 1997) in Matlab. The model included a non-negative constraint to help alleviate issues with higher relative instrument noise in samples having low fluorescence. The PARAFAC model was validated using a combination of outlier identification, residual analysis, component validation, and replication by split-half analysis (Stedmon and Bro, 2008).

2.4.2. Principal component analysis

Pattern identification in the dataset was aided through the use of Principal Components Analysis (PCA). PCA was conducted using a covariance matrix with the The Unscrambler X software, version 10.2. (Camo Software, Inc.) and used to analyze the variance in the synoptic sample dataset. Several key variables were included in the analysis, including PARAFAC component loadings (components C1–C4), fluorescence variables (FI, HIX, SUVA), and the means of the triplicate carbon isotope results. PCA scores were computed and graphically represented by plotting the first principal component against the second.

2.4.3. Regression analysis

Linear regression of discrete measurements of DOC and continuous FDOM at the same date/time produced an equation that was used to convert the continuous FDOM data into continuous estimates of DOC concentration. The fluorescence response of FDOM is a particularly good indicator of the DOC concentration, so no further information was needed to create a good regression model. To construct the best predictive model for POC and TOC, an exploratory analysis was conducted. Several goodness-of-fit statistics (Mallow's Cp, adjusted R^2, PRESS) and the variance inflation factor (VIF) were used to determine that FDOM and turbidity inputs were the best predictors of POC in a multivariate regression model. Continuous measurements of FDOM and turbidity then were used to create continuous estimates of POC. A TOC time series was constructed by adding the time-series estimates of DOC and POC derived from the continuous FDOM and turbidity data.

2.4.4. Uncertainties in carbon loads

Water quality monitoring, sample collection, laboratory analyses, and correlation models all have inherent uncertainties. Each of the potential sources of error in the computation of carbon concentrations and loads were assessed and the potential magnitude of those errors estimated. The root mean square error propagation method outlined by Topping (1972), Harmel et al. (2006) was applied to combine the error estimates:

$$E_P = \sqrt{E_1^2 + E_2^2 + \cdots + E_n^2} = \sqrt{\sum_i E_i^2} \tag{1}$$

where E_p is the probable error of a calculated quantity, n is the number of sources of error, and E_1 through E_n are the errors from each source. Standard errors were estimated and then converted to percentage errors for convenience. When standard errors were not available, error intervals were estimated. Sources of errors included in this analysis were: sensor electronic noise, variability in the stream during the measurement or sample-collection period, cross-sectional variations, errors in the cleaning and drift corrections applied to sensor data, errors in other corrections to the sensor data, analytical error in lab validation samples, model regression error, and uncertainty in the hourly discharge measurements. Uncertainties first were estimated for DOC and TOC concentrations and instantaneous loads. After annual loads were computed, an uncertainty for the POC load was estimated by difference.

3. Results and discussion

3.1. Quantifying carbon export

The amount of OM exported from the Fanno Creek watershed was estimated over the course of a year and during specific seasons and hydrologic conditions to provide information about OM sources and transport. By quantifying the annual export of OM, the source estimates from riparian litterfall (Sobieszczyk et al., 2014) and bank erosion (Keith et al., 2014) can be compared and put into proper context. Even order-of-magnitude source and transport/export estimates are helpful in determining whether a particular source is important or inconsequential. Furthermore, the OM loads and characteristics during particular seasons and hydrologic events provide further information to identify and quantify potential sources and transport processes.

3.1.1. Continuous FDOM as a surrogate for carbon

Continuous measurements of FDOM and turbidity at the Fanno Creek at Durham Road site were used to estimate continuous organic carbon concentrations at that site. Results from discrete samples (DOC, POC) were used to develop regression models that convert the continuous FDOM and turbidity data into continuous time-series estimates of DOC and POC. For this study, the continuous FDOM data were used to estimate DOC using a simple linear regression:

$$\mathrm{DOC} = 0.0501 * \mathrm{FDOM} - 0.4036 \qquad R^2 = 0.96 \tag{2}$$

where DOC is in mg/L and the FDOM data are in units of micrograms per liter (μg/L) of PTSA. The relations between FDOM and POC proved to be more complex. A simple linear regression using only FDOM data was unable to reproduce the low POC values that occur during low-flow conditions. The FDOM signal during low flows reflected the presence of a substantial baseline concentration of DOC, so another input was needed to capture the fact that particulate concentrations were low during baseline conditions. Turbidity data typically are an excellent surrogate for suspended particulate material (Rasmussen et al., 2009); therefore, multivariate correlations using several continuous inputs (FDOM, specific conductance, pH, dissolved oxygen, and turbidity) were explored. The best regression model (Mallow's Cp, 3.0;VIF, 0.041; PRESS, 6.55) for POC used both turbidity and FDOM as inputs:

$$\mathrm{POC} = 0.0412 * \mathrm{Turbidity} + 0.0187 * \mathrm{FDOM} - 1.98 \qquad R^2 = 0.96 \tag{3}$$

where POC is in mg/L, turbidity is in formazin nephelometric units (FNU), and FDOM is in μg/L of PTSA. Using these regression models, continuous estimates of TOC were produced through a simple addition of the DOC and POC model predictions. These models for DOC, POC, and TOC predict the available measurements well (Fig. 2), capturing both the baseline values as well as responses to storm events.

Uncertainties in the concentrations of DOC and TOC were estimated based on a combination of probable errors from all known sources of field and laboratory measurements and model analyses. The overall probable errors in the instantaneous DOC and TOC concentrations were about 15% and 24%, respectively. The largest contributor to those uncertainties (14% and 19%, respectively) was the error associated with the regression models. Probable errors in the individual POC concentrations were not estimated as percentages, but typically were less than about 0.7 mg/L.

3.1.2. Carbon loads

The continuous estimates of DOC, POC, and TOC were combined with measured streamflow data to determine the total amount of OM moving through and being exported from the watershed. The continuous carbon estimates were converted to loads using the following equation:

$$\text{Load} = \text{Discharge} * \text{OC} * 0.0036 \quad (4)$$

where the load is in tonnes per hour, discharge is in m^3/s, and the DOC, POC, or TOC concentration is in mg/L. Monthly and annual carbon loads were calculated for the deployment of the FDOM probe from March 13, 2012 to March 13, 2013 (Table 3). Uncertainties associated with the instantaneous hourly DOC and TOC loads were about 16% and 24%, respectively. For the annual loads, uncertainties are expected to be lower, but autocorrelation issues make it difficult to estimate the uncertainty definitively. Assuming some measure of independence in the daily loads (perhaps valid for a flashy urban stream such as Fanno Creek) and applying the same root mean square error propagation method, uncertainties in the annual loads as derived from the daily loads are only 1.8% and 2.9% for the annual DOC and TOC loads, respectively. Using those values, the uncertainty associated with the annual POC load is about 6.1%. The total load of organic carbon exported from Fanno Creek during that period, based on the continuous data, was approximately 324 t ± 9 t.

For comparison to these instream loads, Sobieszczyk et al. (2014) estimated the annual loading of riparian litterfall directly to the Fanno Creek stream channel to be 136 t ± 24% of total biomass. Accounting for the fact that carbon constitutes only about 50% of that biomass (Devine et al., 2013), the loading of carbon to the stream channel from riparian litterfall might only be 68 ± 24% t/year. However, that litterfall estimate was calculated only for the Fanno Creek channel and did not account for the many contributing tributaries, which might nearly triple the annual litterfall loading directly to the stream channel based on the total stream network in the watershed. Given the much smaller annual POC load estimated at the Durham Road site (83 ± 5 t/year), it seems that riparian litterfall is large enough to account for and be the main source for much of the POC in the system. Taking into account all litterfall to the floodplain (496 ± 22% t/year of carbon, Table 3) but allowing for much of that material to remain outside the stream channel, riparian litterfall must be recognized as a substantial annual loading of carbon that is larger than the measured instream loads and likely the ultimate source of carbon to the stream, even after years of processing in the soils of the floodplain.

The fraction of the Fanno Creek carbon load measured in dissolved and particulate forms is consistent with previous studies. Kraus et al. (2010) and Carpenter et al. (2013) reported that most of the organic carbon in their studies was in the dissolved fraction; this study is no exception, with 74% of the total carbon load being dissolved. The annual suspended sediment load exported from Fanno Creek during the same time period was about 1909 tonnes (Table 3), but only about 4% of that suspended material was organic. That percentage is consistent with the range of organic carbon contents measured on sediment-deposition plates in the Fanno Creek channel by Keith et al. (2014) during the same time frame, but higher than the organic carbon content measured in eroding bank material. Therefore, although the number of bank material samples was limited, it appears that bank material is not sufficiently rich in organic carbon to account for most of the particulate OM being transported in Fanno Creek. The carbon-rich

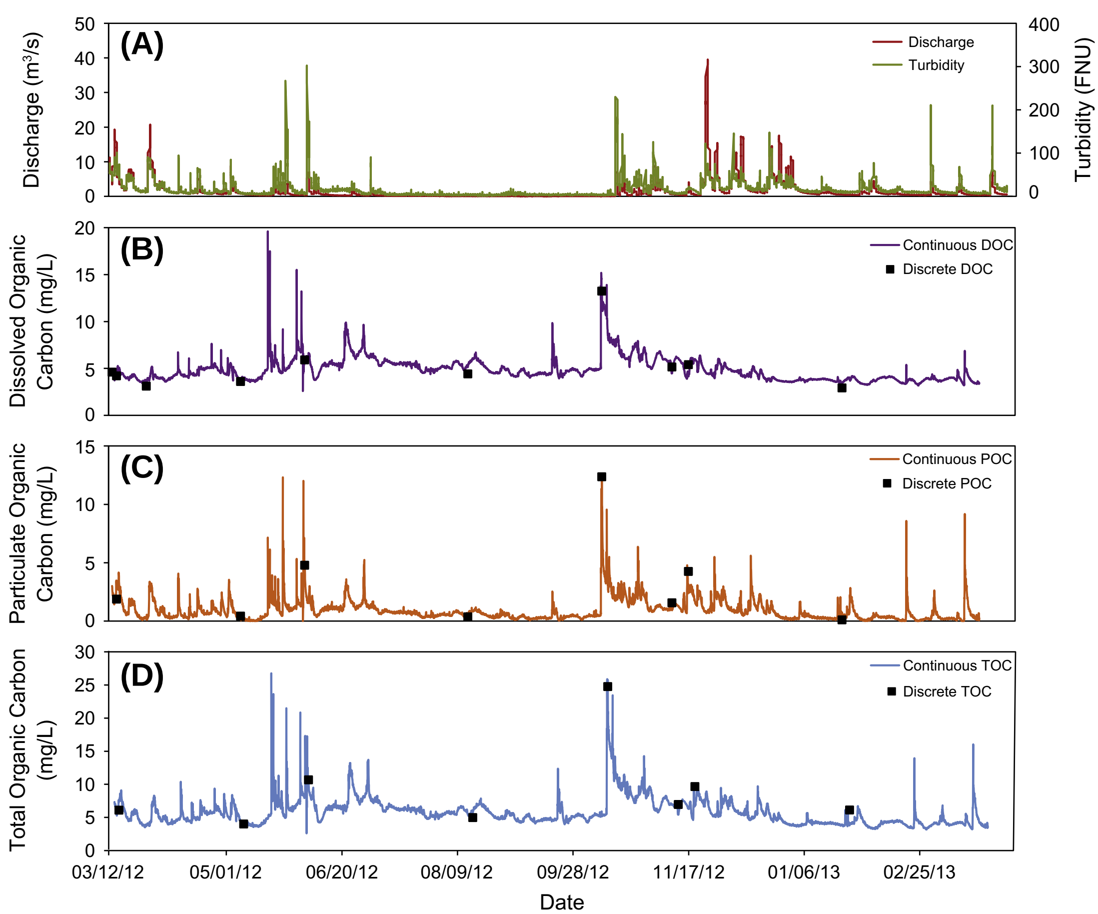

Fig. 2. Continuous estimates of dissolved, particulate, and total organic carbon in Fanno Creek at Durham Road (station 14206950) along with measured streamflow and turbidity data during the deployment period of the FDOM sensor. (A) Discharge (m^3/s) and Turbidity (FNU). (B) Continuous estimated and discrete measured DOC. (C) Continuous estimated and discrete measured POC. (D) Continuous estimated and discrete measured TOC.

Table 3
Calculated annual riparian litterfall, monthly mean discharge, suspended sediment export loads, and carbon export loads occurring in Fanno Creek at Durham Road during the study period. (Riparian litterfall fluxes adapted from Sobieszczyk et al. (2014) using a 0.5 carbon to biomass ratio. Suspended sediment loads are as calculated by Keith et al. (2014)).

Full FDOM deployment	Date	Discharge	Riparian litterfall		Turbidity correlation	FDOM-correlation			Statistics		
		Monthly mean discharge (m^3/s)	Metric tons of carbon (t)		Suspended sediment loads (SSL) metric tons (t)	DOC loads-C metric tons (t)	POC loads-C metric tons (t)	TOC loads-C metric tons (t)	% DOC in TOC	% POC in TOC	% POC associated with SS
3/13/12 14:00	Mar-2012	140			459	39	18	57	68	32	4
	Apr-2012	39			89	18	3	21	86	14	3
	May-2012	24			83	13	4	17	78	22	4
	Jun-2012	18			81	11	4	16	73	27	5
	Jul-2012	6			10	4	1	5	84	16	7
	Aug-2012	2			1	1	0	1	95	5	7
	Sep-2012	1			1	1	0	1	98	2	3
	Oct-2012	30			175	26	11	37	70	30	6
	Nov-2012	84			393	47	18	66	72	28	5
	Dec-2012	118			509	61	21	82	74	26	4
	Jan-2013	23			57	10	1	11	87	13	3
	Feb-2013	17			34	6	1	7	88	12	2
3/13/13 14:00	Mar-2013	18	Floodplain	Channel	17	3	0	4	88	12	3
			Imports		*Exports*				*Averages*		
	Total		496	68	1909	241	83	324	74	26	4

material is mostly in the O (organic matter) and A (surface soils) horizons while the bank erosion soil samples are more consistent with organic-poor subsoils found in B soil-horizons.

Monthly loads of total carbon are positively correlated with higher monthly discharge averages, and not just because loads are a function of discharge (Table 3). Higher flows are associated with higher concentrations of DOC and POC. November and December produced the highest loads of carbon during this study. Several large storms during March, 2012 were associated with moderate concentrations of TOC, thus producing relatively high loads of carbon at that time of year as well. Of particular note, however, is the month of October, when relatively high carbon concentrations and moderate loads occurred (Fig. 2, Table 2) despite a lower monthly mean discharge. The increase in concentrations in the first-flush October storm primarily is due to the accumulation of OM in the stream during the 3–4 months of antecedent conditions with almost no precipitation. Particulate OM accumulates on the streambed as a result of some productivity by algae and microbial activity that decomposes and can mobilize OM in surficial sediments. After several months of low-flow conditions, the October 2012 "first-flush" storm(s) with moderate discharge was sufficient to mobilize dissolved organic matter as well as particulate material that had accumulated on the streambed and export it from the system.

3.1.3. Significance of the fall first-flush

The first-flush mobilization of OM in Fanno Creek has some timing characteristics that are indicative of sources and transport processes. Although carbon concentrations are highly correlated with turbidity and discharge (Fig. 2), the initial pulse of carbon in the first-flush storm preceded the turbidity and discharge peaks (Fig. 3A). This phenomenon has been reported elsewhere, in which rapid and significant increases in carbon concentrations during storm events were typical (Saraceno et al., 2009). During the initial fall flush event on October 12, 2012, carbon concentrations peaked at levels that were significantly higher than at almost any other time during the study. Discharge during that storm also was sufficient to mobilize particulate OM that had accumulated on the streambed during the previous months of low flow, as well as OM from other sources throughout the watershed. After the peak of the storm passed, both DOC and POC concentrations remained elevated and, unlike turbidity and discharge, did not return to baseline concentrations for many days. For the POC to remain suspended long after the turbulent energy of the storm receded, the particle size would need to be rather small. Keith et al. (2014) found that a high percentage of fine material was deposited in the Fanno Creek channel after the fall first-flush event.

The fall first-flush was important not only because it mobilized and transported large amounts of OM within the Fanno Creek watershed, but also because the OM exported downstream to the Tualatin River had significant water-quality effects. Once exported from Fanno Creek, the OM continues to decompose as it travels downstream, exerting a measurable oxygen demand in the Tualatin River at the Oswego Dam (station 14207200) located about 1.5 days of travel downstream (Fig. 3B). The small peak in turbidity at that station corresponds to suspended material transported from Fanno Creek during the storm, and the accompanying decrease in dissolved oxygen is restricted to that storm-related plume. This type of rain-induced water-quality problem is frequent in the September–October time frame in the Tualatin River (U.S. Geological Survey, 2013), occurring typically after the first-flush storm (late summer, early fall) or even a smaller late-summer rain event as a direct result of increased OM loading from the river's tributaries.

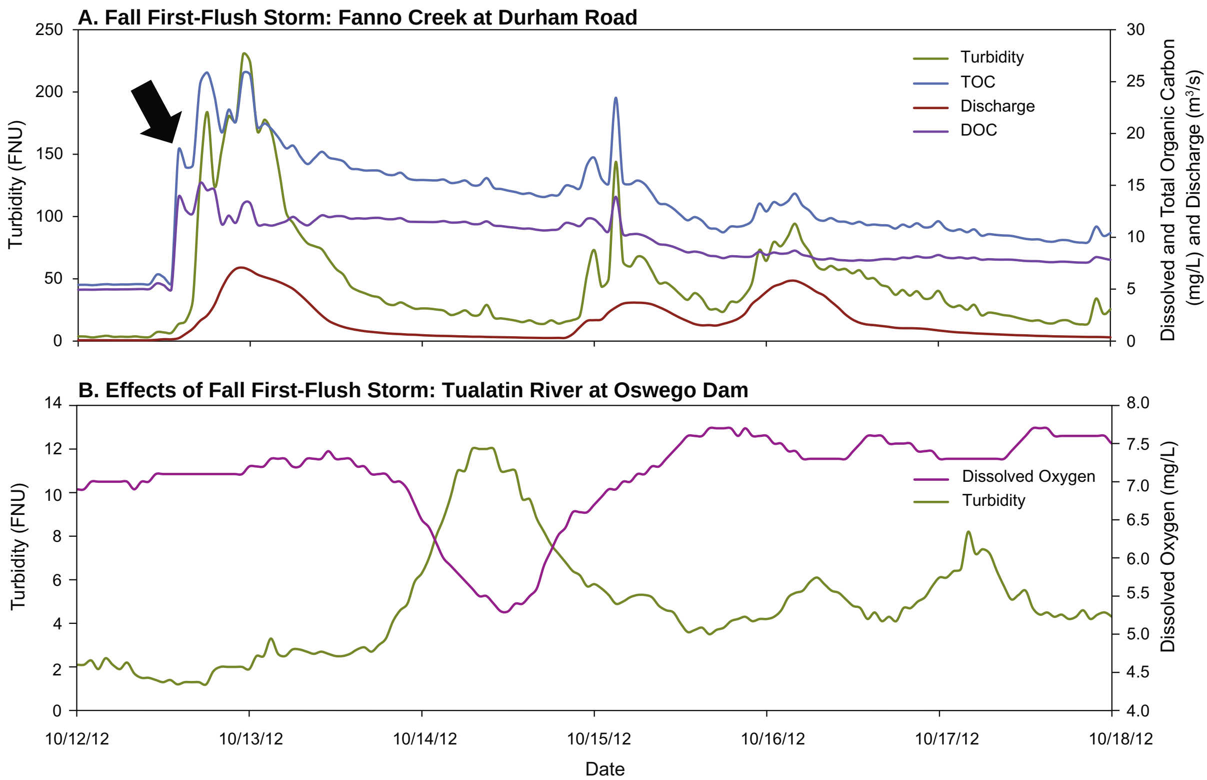

Fig. 3. Fall first-flush storm dynamics in Fanno Creek and the Tualatin River downstream in northwest Oregon. (A) Discharge, turbidity, and organic carbon patterns in Fanno Creek at Durham Road (station 14206950) over the course of a first-flush storm in October, 2012, with an arrow indicating that the peak in carbon preceded the peaks in discharge and turbidity. (B) Dissolved oxygen and turbidity in the Tualatin River at Oswego Dam (station 14207200), illustrating the effects of the first-flush storm downstream.

3.2. Sources and characteristics of OM

Data from the synoptic samplings were used to assess the characteristics of OM in the Fanno Creek watershed under a variety of hydrologic conditions and seasons. Results can be categorized into sources, seasonality, and OM composition.

3.2.1. OM sources

The carbon and nitrogen stable isotope data along with carbon-to-nitrogen ratios were used to assess the potential sources (soil, leaf litter, detritus, and algae) of particulate OM to Fanno Creek. Previous studies have shown that some of these sources, particularly algae, are easily distinguished on the basis of their isotopic signatures (Bonn and Rounds, 2010; Kendall et al., 2001). With the exception of samples from the summer synoptic (Table 1), the isotopic signatures of all the samples were indicative of terrestrial sources in various degrees of decomposition from leaf litter to soil, consistent with findings from a previous study in the same basin (Bonn and Rounds, 2010). The summer samples, however, were characterized by δ^{13}C ranging from −34 to −30 per mil and δ^{15}N ranging from 6 to 7 per mil, values that are more representative of plankton growth (Fig. 4A) (Kendall et al., 2001). Although the δ^{13}C values of the non-summer samples are similar to those of wastewater effluent particulate material (−28 to −24 per mil) documented by Bonn and Rounds (2010), the δ^{15}N values from this study are lower (wastewater δ^{15}N range from 7 to 12 per mil) and the C:N values are higher (wastewater C:N values range from 5 to 8) than those of wastewater samples, again pointing toward a soil OM source. Stormwater inputs can transport soil and leaf litter to the stream, particularly if that transport is via a ditch or other conduit that does not retain sediment and thereby decrease OM inputs. Consistent with these results, Keith et al. (2014) found that channel erosion via mass wasting likely contributes large amounts of sediment to the creek – sediment that contains organic-rich soil (O–A horizons) as well as organic-poor subsoil (B horizon). Although the isotopic results point to sediment and soil as important sources of OM to Fanno Creek, the ultimate source of much of that material most likely can be assigned to riparian litterfall.

3.2.2. Seasonality of OM characteristics

Three distinct periods of time emerged from an analysis of synoptic data collected throughout the watershed in terms of the quantity and characteristics of the OM in Fanno Creek. First, the base-flow conditions of the summer synoptic (S6) were different because the carbon content of the samples was lowest, with distinctly more microbial protein-like components as reflected through the samples' optical properties. Second, the fall first-flush conditions, with moderate flow conditions that were sufficient to transport a large amount of DOC and mobilize POC that had accumulated in the low-flow season, transported the highest concentrations of carbon, three times more than during other synoptics. Third, the post-fall-flush group, which includes all the remaining synoptics, all produced similar carbon concentrations and characteristics with subtle variations.

The summer synoptic (S6) had the lowest carbon concentrations during this study, with particulate carbon concentrations near zero (Fig. 5B). Concentrations of carbon varied slightly from one site to the next with the highest concentrations present at the Ironwood site located at Englewood wetlands. SUVA values in Fanno Creek were the lowest during this period with a gradual decreasing trend moving downstream, representing decreased aromatic carbon (Weishaar et al., 2003). However, the decreased SUVA for the summer synoptic is less pronounced in the tributaries, perhaps demonstrative of more aromatic carbon. Decreased SUVA

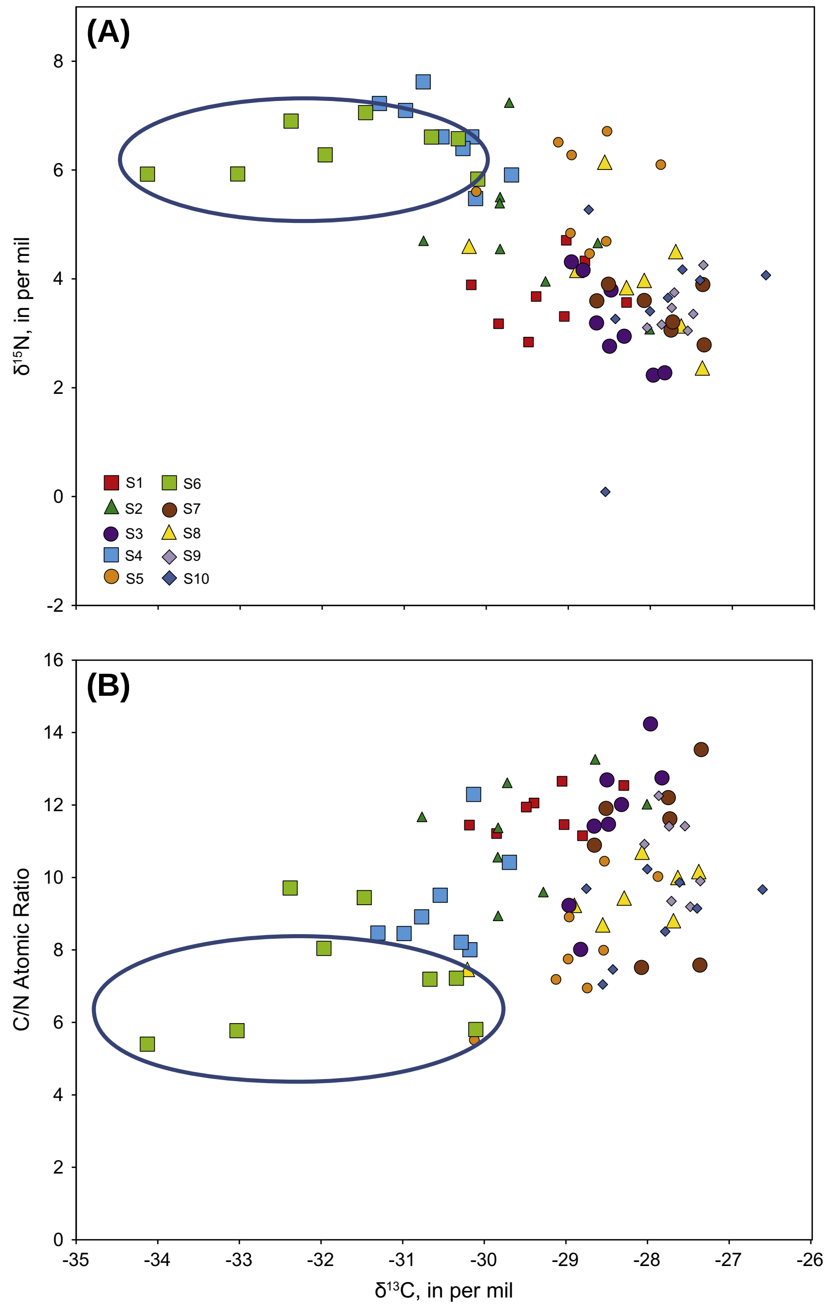

Fig. 4. Stable isotope ratios of carbon and nitrogen, along with carbon to nitrogen ratios from samples in Fanno Creek, with the colors representing the different synoptics (synoptic #1 [S1] through synoptic #10 [S10]). The group of samples from the summer base-flow synoptic (S6) is highlighted by the blue ellipse. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

values may also be reflective of source processing of the organic matter. As the material moves downstream, increased exposure to UV light can cause photochemical transformations to begin to alter the OM. Although photodegradation is a common process, Fanno Creek's riparian corridor offers substantial shade during the summer, which may minimize the photochemical transformation of the OM. In addition to SUVA, the FI value was slightly elevated in summer, potentially indicative of more microbially processed sources (McKnight et al., 2001). The HIX value also was elevated (Fellman et al., 2010), representing highly processed and humified material that is the result of terrestrial material that could be more microbially processed (Fig. 5A–F). Lastly, the stable isotope results (Fig. 4B) indicate a decrease in the C:N ratio for the summer sampling that has been linked to more processed OM (Bonn and Rounds, 2010).

The fall first-flush produced carbon concentrations that were three times as large as those observed during the other synoptics (Fig. 5A–C). The quantities varied slightly from site to site during this event, with the middle restoration site (Greenway Park) contributing a bit more particulate carbon (Fig. 5B). During summer months, that restoration site and nearby wetlands often act as a carbon sink, but once the rain begins and the flow increases, much of that material can be remobilized and transported downstream (Keith et al., 2014). Compared to the summer period, the characteristics of the OM shift to more aromatic carbon, terrestrially derived sources, and fresher and less humified materials as evidenced by the SUVA, FI, and HIX values respectively.

Lastly, the post-flush group includes all of the other eight synoptics. Although slight seasonal and flow variations were present in the grouped data, the quantity and characteristics of the OM

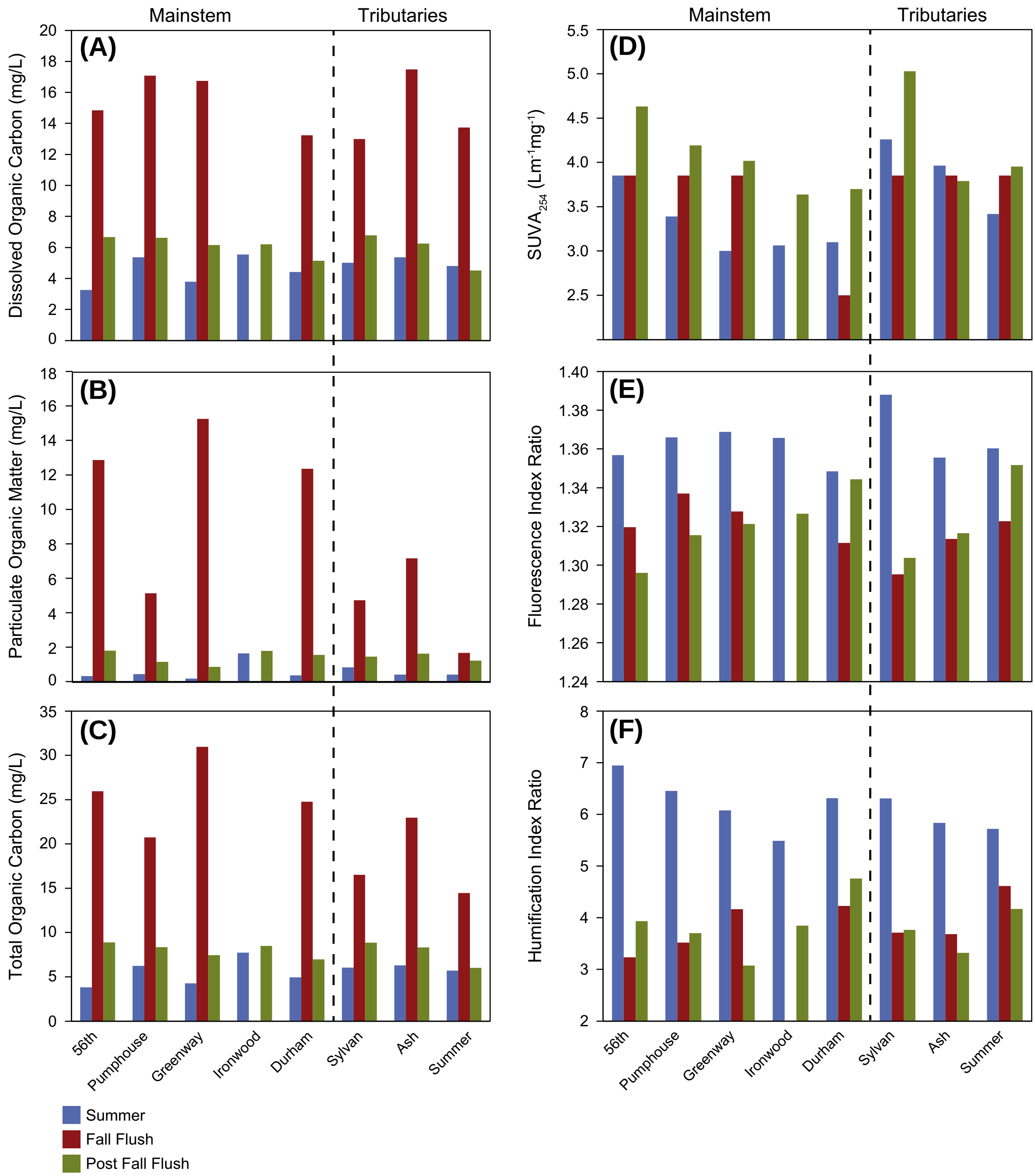

Fig. 5. Measurements of organic carbon, fluorescence, and absorbance in samples from Fanno Creek and its tributaries in northwest Oregon during three key time periods (summer, fall first-flush, and post-fall-flush): (A) DOC, (B) POC, (C) TOC, (D) SUVA, (E) FI value, and (F) HIX ratio. Sites are ordered from left to right in downstream order; tributary sites are separated from Fanno Creek sites but still are arranged in downstream order from left to right.

in this group are well represented by the data in Fig. 5. Despite changes in flow and season, the TOC concentration across all sites was approximately 5–10 mg/L. Photosynthetic activity was low based on daily variations in DO and pH, and the low temperatures in the stream caused biological reactions to slow, resulting in less microbial processing of the OM. During this time, transport and mobilization of the OM were primarily driven by hydrologic processes, with the highest concentrations measured during the mid-flow conditions. Qualitatively, the absorbance and fluorescence data indicate that mostly aromatic and less labile material entered the creek at the headwaters and became slightly more labile and less aromatic as it decomposed, moved downstream, and mixed with other tributary and stormwater inputs. According to Keith et al. (2014), geomorphic features in the channel such as low benches and log jams provide seasonal areas for the OM to deposit, begin decomposition, and become more bioavailable to the system. Leaf litter has been shown to have a high initial decomposition rate within days of moving into an aquatic environment (Cleveland et al., 2004). When storms occur, the high flow mobilizes the seasonally deposited material, consistent with a decline in SUVA and a slight increase in the FI value as the OM moves downstream (Fig. 5). In addition, inputs from impervious surface runoff, which increase with downstream distance, tend to input OM with lower SUVA values than OM coming from more forested areas found in the headwaters (Goldman et al., 2012).

3.2.3. OM composition

Parallel Factor Analysis (PARAFAC) helped to identify the composition of DOM in the synoptic samples through fluorescent response patterns. A four-component PARAFAC model applied to the full set of synoptic EEMs resulted in a good fit (90% or greater) between the measured and modeled EEMs. Analysis of model residuals revealed patterns that were mostly noise, with less than 10% of the samples containing any residual pattern. Splitting the data into two halves and modeling the sets independently showed that results from the two halves were consistent.

The four modeled PARAFAC components were drawn from previously documented PARAFAC results that linked the spectral characteristics in specific regions of the EEM domain to different OM pools that also were compared with model compounds (Table 4) (Coble, 2007; Cory et al., 2010; Hudson et al., 2007; McKnight et al., 2001; Stedmon et al., 2003; Stedmon and Bro, 2008). Component 1 (C1) is highly correlated to DOC and TOC and is commonly associated with terrestrially derived fulvic- and humic-like substances. Components 2 and 3 (C2, C3) also are strongly correlated to DOC and TOC but are representative of terrestrial humic-like substances. Compared to C1, C2 and C3 are slightly more aromatic and less labile. Component 4 (C4) represents fresher, more labile, and more representative of microbially processed material. On average, the PARAFAC model revealed mostly homogeneous results among samples, with most sites consisting of approximately 50–55% C1, approximately 30–40% as a mixture of C2 and C3, and about 10% C4 (Fig. 6A). Although differences among samples were slight, a subtle shift in composition was evident from the summer synoptic (S6) to the fall first-flush (S7), with the latter containing a higher percentage of C4, the protein-like material typically associated with plankton and increased microbial activity (Fig. 6B). Although the PARAFAC model does help to explain some overall general characteristic trends in OM composition, it was not able to detect any additional seasonal or site variations due to the limited sample size (87 samples) and relative homogeneity of the OM characteristics. Still, the relatively similar results are indicative of largely similar sources and processing of OM throughout the Fanno Creek watershed.

Principal Components Analysis (PCA) was used to delve deeper into the OM data and reveal patterns that may help explain the sources and composition of OM in Fanno Creek. Many potential inputs to PCA models were examined. The final model that explained the most variance (85%) and seemed to be most useful in illustrating patterns in the data contained the following as inputs: all PARAFAC component loadings, FI, HIX, SUVA, and the δ^{13}C values (Table 5). A plot of principal component 1 against principal component 2 shows a distinct separation of the summer and fall first-flush samples from the rest of the synoptic samples, again illustrating the strength of those seasonal differences (Fig. 7). Along the PC1 axis, the fall flush is positively influenced by the δ^{13}C variable with the highest eigenvalue of 0.776 (Table 5), while the summer synoptic is negatively influenced with the FI variable. Both parameters are indicative of a qualitative separation of distinctly different sources of organic matter during these particular events. In addition, the PC2 axis is heavily driven by the LC1 variable, demonstrative of the influence of carbon concentration on the synoptic results. Separation is evident between the fall flush and the summer synoptic because of (1) the qualitative differences in the summer of a more microbial and planktonic source of OM and (2) the much higher carbon concentrations in the fall first-flush with a source signature that is terrestrial and microbial mix, representing the microbially processed summer OM moving through the system and the fresh terrestrial inputs occurring during the storm event. All the remaining samples fall along a general trend line within their respective sampling groups, showing only subtle quantitative and qualitative shifts in OM composition that likely are driven primarily by hydrologic and seasonal patterns and predominantly terrestrial sources.

4. Conclusions and implications for monitoring and management

Results from this study show that OM inputs to Fanno Creek are primarily terrestrial, most likely originating ultimately from riparian litterfall, but partially decomposed and transformed through soil processing and decomposition. Sobieszczyk et al. (2014) estimated that hundreds of tonnes of riparian biomass are delivered to the stream and its floodplain each year, providing a large and continuing (over many years) source of OM to the stream ecosystem either as a direct input or as a source of OM to nearby O–A soil horizons that may later be transported into the stream. Many transport pathways can move this and other organic material into the stream, such as storm runoff, mass wasting, bank erosion, sewer overflows (rare), and intentional dumping. Once in the stream, the material decomposes and is transported through the system, with particulate material being mobilized or deposited as a result of hydrologic processes. Concurrent work by Keith et al. (2014) showed that large amounts of sediment, about 1900 t/year, are transported in Fanno Creek and that many reaches have rapidly eroding banks, but that the bank material has a relatively low OM content compared to the bulk OM transported in the stream. Clearly, erosion of bank materials provides a large and important source of OM to the stream, but additional inputs of OM-rich soil from the O–A horizons (partially from mass wasting and periods of flood inundation) and riparian litterfall are required to account for the higher loads and concentrations of OM instream. This research showed that several hundred tonnes of organic carbon are exported from the Fanno Creek watershed each year, often in pulses caused by storm events that have water-quality implications downstream in the Tualatin River.

Table 4
Component designations and descriptions from PARAFAC model results of samples from the Fanno Creek watershed in northwest Oregon. Parentheses indicate secondary peak locations.

Component	Excitation maximum (nm)	Emission maximum (nm)	Description	Probable source
1	250	440	Correlated strongly to DOC/TOC less aromatic and semi-labile	Terrestrial humic and fulvic-like substance
2	360 (270)	450 (320)	Correlated strongly to DOC/TOC more aromatic and less labile	Terrestrial humic-like substance, widespread
3	250 (390)	490 (340)	Correlated strongly to DOC/TOC more aromatic and less labile	Terrestrial humic-like substance, widespread
4	280	340	Less aromatic, more labile, fresher material-microbial processed OM	Amino acids, free or bound in proteins

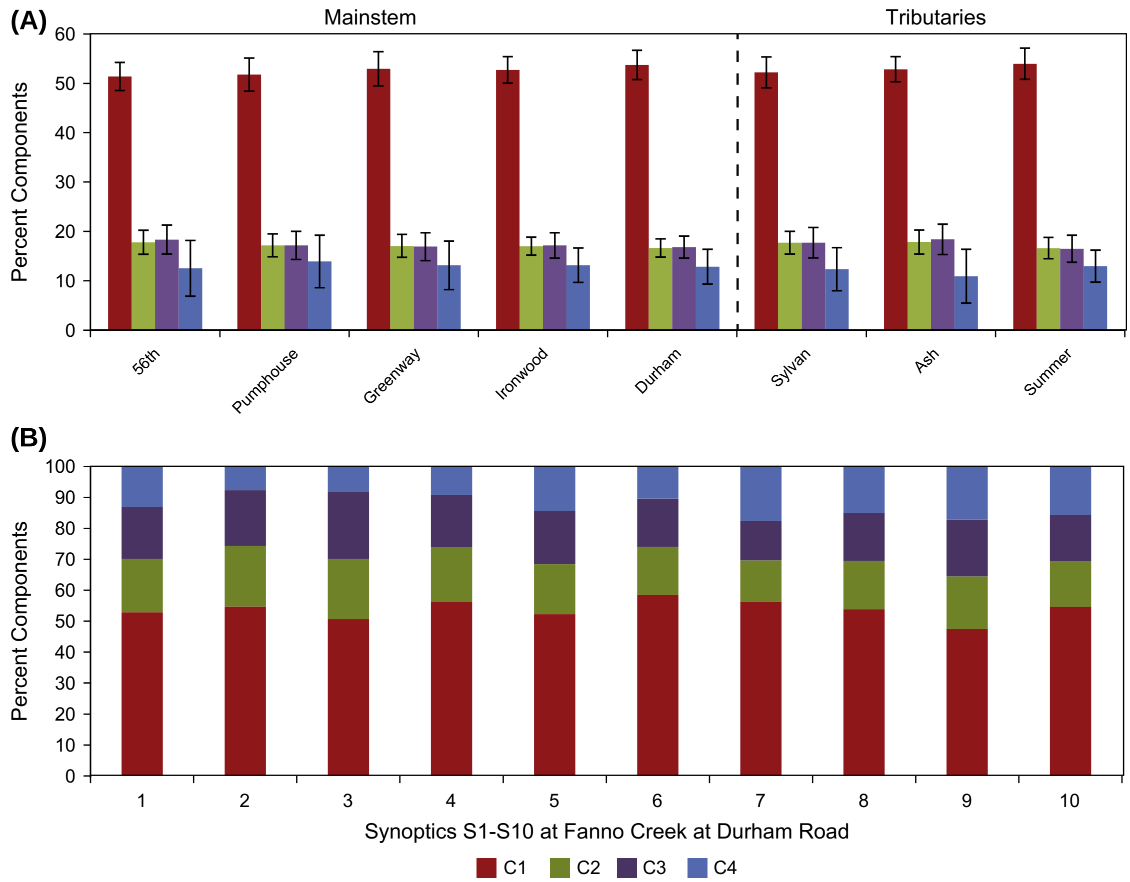

Fig. 6. PARAFAC component compositions across all synoptics in the Fanno Creek watershed, northwest Oregon: (A) average results at each site, and (B) PARAFAC component percentages at the Fanno Creek at Durham Road site for each synoptic.

Table 5
Results of the Principal Components Analysis using data from SUVA, FI, HIX, PARAFAC component loadings (LC1, LC2, LC3, LC4), and $\delta^{13}C$ values and their associated eigenvalues for PC1 and PC2.

Principal component	SUVA	FI	HIX	LC1	LC2	LC3	LC4	$\delta^{13}C$
1	0.074	−0.015	0.265	0.065	0.065	0.063	0.146	0.776
2	−0.513	0.014	−0.120	0.716	0.141	0.110	0.240	−0.346

Analysis of the OM in Fanno Creek revealed that it is composed of terrestrially sourced material, primarily humic- and fulvic-like components, that becomes less aromatic as it moves downstream and continues to decompose and mix with tributary inputs. Measurements of OM, fluorescence, absorbance, and stable isotope ratios were used to calculate carbon exports, characterize OM variations as a function of season and hydrologic condition, and describe the nature and sources of OM. Summertime OM is more planktonic and microbially processed, likely due to instream OM decomposition and the accumulation of the products of photosynthesis. The fall first-flush has the highest concentrations of OM of the entire year and likely represents a mobilization of accumulated OM in the stream over the summer period of low flows. Most of the particulate OM samples are relatively homogenous in their composition and similar in their isotopic signatures to some mixture of leaf litter, decomposing leaf litter, and soil, with the exception of some algal-derived material in late summer; overall, however, a terrestrially derived soil and leaf litter source appears to be dominant, which is consistent with the large inputs of riparian litterfall, bank erosion, and mass wasting. The mechanisms of transport into the stream via overland flow, mass wasting, erosion, and hydrologic dynamics are important to consider when formulating management strategies. Continued monitoring of the OM characteristics in Fanno Creek and their rate of export from the watershed will be useful as watershed managers continue restoration activities, enhance stormwater management to buffer the stream's hydrologic response to runoff, and modify riparian plantings to decrease OM loadings.

Acknowledgements

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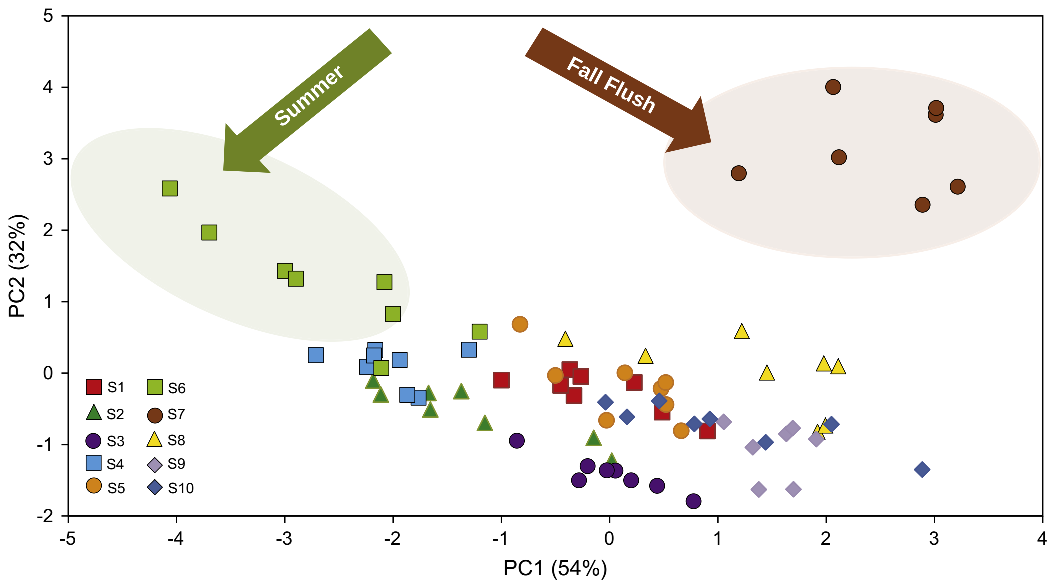

Fig. 7. Results of the Principal Components Analysis score plots for all the synoptic samples in the Fanno Creek watershed, northwest Oregon. Samples from the summer synoptic and the fall first-flush synoptic are highlighted as characteristically different from the other samples.

Kapur (CWS). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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