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The influence of land cover, including Nootka lupin, on organic carbon exports in east Icelandic rivers

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Abstract

Fluvial dissolved and particulate organic carbon concentrations, [DOC] and [POC], were measured weekly in two contrasting catchments in east Iceland in June and July 2016. Sampling was carried out at ten sites in each catchment, including the outlets. [DOC] ranged from 2.1 to 6.6 mg L^{-1}, and [POC] from 0.4 to 3.1 mg L^{-1}. Mean TOC fluxes over the sampling period amounted to 0.46 µg m^{-2} s^{-1} from the West catchment and 0.42 µg m^{-2} s^{-1} from the East catchment. Concentration and flux data were used to analyse the relationship between organic carbon budgets and different land cover: heathland, wetland, sparse vegetation and dense Nootka lupin (*Lupinus nootkatensis*). Wetland area, associated with C-rich Histic Andosols, was found to have a significant positive influence on in-stream organic carbon concentrations and fluxes, and the opposite was found with sparsely vegetated areas, likely due to limited soil development. Areas with dense lupin cover were associated with relatively-low organic carbon fluxes in the East catchment, possibly because lupin stabilises its substrate, reducing mobilisation of DOC and POC. In the West catchment this influence was not clear, but this is likely due to the co-location of wetland, causing increased C exports.

Keywords: Organic carbon; River; Soil; *Lupinus*; Iceland; Skálanes

Highlights

- This research addresses the data gaps in fluvial carbon export in Iceland.
- Total organic carbon (TOC) concentrations ranged between 3.0 and 8.5 mg L^{-1}.
- Two streams export similar TOC (0.09–0.97 µg m^{-2} s^{-1}) despite different vegetation.
- Wetland areas are associated with higher organic carbon exports.

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1. Introduction

Fluvial networks are an important pathway for the transport of terrestrial carbon to the oceans (Drake et al., 2018; Pawson et al., 2012, Hope et al., 1994). It is estimated that 5.1 Pg C yr^{-1} are transferred globally from the terrestrial environment to inland waters (Drake et al., 2018). The further export of C to the oceans has been estimated at 0.95 Pg C yr^{-1} (Regnier et al., 2013). The dissolved organic carbon (DOC) flux (0.25 Pg C yr^{-1}) has been identified as the largest transfer of reduced carbon, followed by the particulate organic carbon (POC) flux (0.18 Pg C yr^{-1}), from the terrestrial environment into the world's oceans (Battin et al., 2008). Exports from 550 catchments worldwide were found to range between 1.2 and 56,946 kg C km^{-2} yr^{-1} of DOC and between 0.4 and 73,979 kg C km^{-2} yr^{-1} of POC (Alvarez-Cobelas et al., 2012).

The main sources of organic carbon in headwater streams are (allochthonous) terrestrial inputs of organic matter, such as plant litter, through soil leaching and erosion (Pawson et al., 2012; Dawson and Smith, 2007) and (autochthonous) in-stream biological production (Hope et al., 1994). While some organic carbon is transported to the ocean where it can be sequestered in ocean sediments (Benner et al., 2005), most in-stream organic carbon is thought to be mineralised to CO_2 through microbial respiration, thus forming a source of carbon to the atmosphere (Pawson et al., 2012; Tank et al., 2012). Quantifying these budgets can give us an indication of terrestrial carbon sources and sinks and allow further estimates of global carbon fluxes between the terrestrial, atmospheric and marine environments.

Carbon exports are largely controlled by the dominant soil and vegetation types, hydrology and climate. By fixing atmospheric carbon within its biomass, vegetation regulates the soil organic carbon (SOC) pool, thereby forming a key influence on fluvial organic carbon fluxes (Tank et al., 2012). Soils with a larger SOC pool, such as the peaty Histosols and Histic Andosols found in Iceland's wetlands, generally lead to higher in-stream DOC concentrations (Tank et al., 2012; Ågren et al., 2007; Kardjilov et al., 2006). This relationship is particularly apparent in small catchments under 5 km^2 (Dawson and Smith, 2007; Aitkenhead et al., 1999). In contrast, sparse vegetation cover, by producing little biomass, has been shown to limit SOC development and organic carbon export (Jantze et al., 2015).

High latitude soils can store relatively high amounts of carbon due to low temperatures and low rates of degradation (Kardjilov et al., 2006). In Iceland, the dominant soil order, Andosols, store the second highest amount of carbon (31 kg C m^{-2}), after Histosols (197.5 kg C m^{-2}) (Óskarsson et al., 2004). The main characteristics of Andosols are low bulk density, high porosity, large soil water retention and a lack of cohesion, making them highly susceptible to wind and water erosion (Óskarsson et al., 2004).

In Iceland, soil erosion has been a widespread and long-term issue, as a result of widespread deforestation following the settlement of the island (Arnalds, 2015). Seeding of the Nootka lupin (*Lupinus nootkatensis*), a highly productive, nitrogen-fixing legume (Arnalds, 2015), has been shown to significantly increase SOC in areas experiencing severe erosion (Tanner et al., 2015; Aradóttir et al., 2000). The Nootka lupin is a non-native species to Iceland and was introduced in 1885 (Hiltbrunner et al., 2014) to address erosion by rapidly revegetating eroded and nutrient poor lands (Arnalds, 2015). It has been cultivated for revegetation since the 1980s (Aradóttir et al., 2000). The Nootka lupin is renowned for its ability to germinate on barren ground (Benediktsson, 2015), with net primary productivity ranging between 400 and 800 g C m^{-2} yr^{-1} during its thicket stage (Hiltbrunner et al., 2014).

Iceland experiences relatively high runoff, estimated to average 1460 mm yr^{-1} based on the water years 1961–1990 (Jónsdóttir, 2008), compared with the global average of 299 mm yr^{-1} (Fekete and Vörösmarty, 2002). The combined effects of high runoff and extent of carbon-rich Andic Histosols, could make Iceland a significant contributor of the global fluvial carbon flux. While many studies on fluvial carbon fluxes in temperate and sub-arctic regions in Europe have been published, limited research exists for this component of the carbon cycle for Iceland. Rather, most research concerning the terrestrial carbon cycle has focused on carbon sequestration potentials through revegetation, particularly with lupin (e.g. Bjarnadottir et al., 2009; Ritter, 2007; Tanner et al., 2015), carbon storage in basalt (e.g. Matter et al., 2009; Snæbjörnsdóttir et al., 2014), and carbon losses through erosion (e.g. Óskarsson et al., 2004). DOC and POC fluxes from a drained peatland in west Iceland (Borgarfjörður region) were quantified at 11.65 (± 1.98) and 9.57 (± 6.21) g m^{-2} yr^{-1}, making up 2.82 and 2.31% of the local carbon budget, respectively (Ólafsdóttir, 2015). In 13 proglacial streams in central and southwest Iceland DOC concentrations ranged from 0.11 to 0.94 (mean: 0.226) mg L^{-1} and POC concentrations ranged between 0.67 and 84.67 (mean: 0.37) mg L^{-1} (high POC concentrations were linked to high anthropogenic influences), resulting in an estimated DOC flux of 0.008 ± 0.002 Tg yr^{-1} from Icelandic glaciers (Chifflard et al., 2019). Kardjilov et al. (2006) quantified fluvial organic carbon fluxes from three large inland catchments in NE Iceland, where DOC (0.23–0.30 g C m^{-2} yr^{-1}) and POC (0.23–0.44 g C m^{-2} yr^{-1}) fluxes were relatively low and close to detection limits. Despite these low fluxes, an increase in DOC and POC between the catchments was linked to increases in net primary productivity with greater wetland cover and SOC development (Kardjilov et al., 2006).

Here, we investigate DOC and POC export in small, runoff-driven Icelandic stream catchments, and how this is influenced by land cover, including the Nootka lupin. Two stream catchments which flow into the Norwegian Sea were selected as this helps to understand the extent to which terrestrial C may be delivered to the ocean. These catchments were adjacent but differed in discharge and land cover. We had the following objectives: (1) to quantify summertime organic carbon concentrations and fluxes from these catchments and (2) to examine the influence of different vegetation covers on concentrations and fluxes of DOC and POC.

2. Method

2.1. Study area

The Skálanes Nature & Heritage Centre (65.294257, –13.705330) is a 12.5 km^2 nature reserve situated on a peninsula in the eastern region of Iceland. Weekly water sampling and discharge measurements were carried out on two adjacent catchments, referred to as the West catchment and the East catchment (Fig. 1), on the reserve between 10.06.2016 and 14.07.2016. The two catchments were chosen for their remote location and absence of sheep-grazing to minimise human disturbance to the catchments and their vegetation. Their adjacent position means relative homogeneity in terms of their underlying geology, rainfall and temperature. Sampling was undertaken during the summer season to ensure peak vegetation cover, and connectivity between subsurface waters and the upper soil horizon (e.g. Jantze et al., 2015).

The two study catchments are situated on the northern side of the central peninsula ridge, draining northwards into the Seydisfjördur fjord and are, like most other valley catchments in eastern Iceland (Arnalds, 2015), driven by surface runoff. Elevation ranges between 0 m above sea level (a.s.l.) at the catchment outlets to 372 m a.s.l. at the West catchment and 655 m a.s.l. at the East catchment. The hydrological year 2016 had a mean temperature of 4.8 °C and total rainfall of 1794.6 mm, compared with the mean of 4.6 °C and 1666.0 mm of the preceding ten hydrological years (2006–2015) (Dalatangi weather station, Icelandic Meteorological Office). The months June and July 2016, during which this study took place, exhibited mean monthly temperatures of 7.7 °C and 9.1 °C and total monthly rainfall of 87.4 mm and 201.4 mm, respectively. They were thus slightly warmer and wetter than average June and July temperatures (7.0 °C and 8.7 °C) and rainfall (62.7 mm and 114.8 mm), based on mean temperatures from the preceding ten summers (2006–2015) (Dalatangi weather station, Icelandic Meteorological Office). The runoff rate on our study area is estimated at 1000–2000 mm yr^{-1} and at 100–400 mm over the summer period of June, July and August, with 100–200 mm at high altitudes and 200–400 mm in the lowlands (Jónsdóttir, 2008).

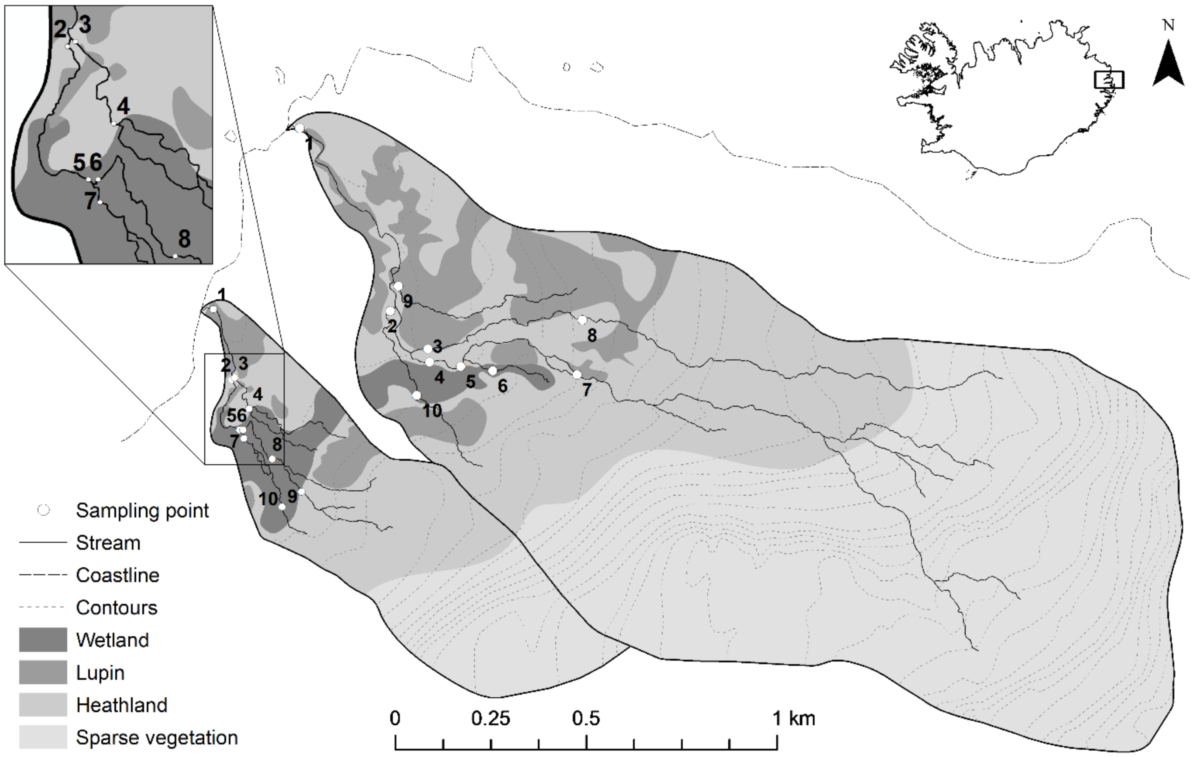

Fig. 1. The West catchment and the East catchment, with sampling sites, stream networks and vegetation distributions of heathland, wetland, sparse vegetation and dense lupin.

The underlying geology is predominantly composed of tertiary basalt with some andesites, known as the Tertiary Formation (Arnalds, 2015). The main soil classes found here are Histic Andosols (HA), Brown Andosols (BA), Gleyic Andosols (WA) and Vitrisols (V) (Arnalds and Grétarsson, 2001). Across both catchment areas, land cover was classified into four categories: (1) heathland, (2) wetland, (3) sparse vegetation and (4) dense lupin. Heathland was dominated by dwarf heathland vegetation, such as *Betula nata* (dwarf birch) and *Calluna vulgaris* (common heather). Wetland areas contained various species of *Carex* (sedges) and *Juncus* (rushes), most notably *Juncus arcticus* (arctic rush), and species *Agrostis capillaris* (common bent grass), *Deschampsia caespitosa* (tussock grass) and *Eriophorum angustifolium* (common cotton grass). Sparsely-vegetated areas were characterised by scattered vegetation among rock outcrops and steep scree slopes, where willow and heath species formed small isolated patches. Large expanses of the study area, particularly the East catchment, were densely vegetated by lupin (Fig. 1).

The sub-catchment basin areas of the West catchment and the East catchment were mapped and calculated using a digital elevation model (DEM) provided by the National Land Survey of Iceland (http://www.lmi.is/en/) and the Hydrology toolset in ArcGIS. The spatial distributions of heathland, wetland, sparse vegetation and dense lupin were mapped using GPS on site and matched with satellite imagery of the study area (provided as supplementary material with this paper). Most notably, the West catchment drains larger proportions of wetland and heathland area and smaller proportions of sparsely vegetated areas than the East catchment. Both catchments drained similar proportions of dense lupin (Table 1). Within the study area, wetlands and dense lupin were found at up to 150 m a.s.l., while heathlands extended further up to 260 m a.s.l. Sparsely vegetated areas covered the upland regions down to 100 m a.s.l. (Fig. 1).

Table 1
Spatial characteristics of the West catchment and East catchment.

	West catchment	East catchment
Catchment area, km²	0.43	2.01
Average elevation, m a.s.l.	127	274
Maximum elevation, m a.s.l.	344	660
Minimum elevation, m. a.s.l.	0	0
Land cover, km² (% catchment area)		
Heathland	0.18 (42.2)	0.62 (30.6)
Wetland	0.06 (12.9)	0.03 (1.6)
Dense lupin	0.04 (8.5)	0.20 (10.1)
Sparse vegetation	0.16 (36.4)	1.16 (57.7)

2.2. Water sampling and discharge measurements

Ten sampling sites were selected each on the West catchment and the East catchment using the following rationale, used by many others (e.g. Hope et al., 1997; Jantze et al., 2015). Sampling sites were situated near the catchment outlets, to determine total discharge and carbon exports from the entire catchments. Sites were also placed on tributaries near junctions to the main stream, to allow discharge and carbon export data for individual tributaries to be estimated. Sampling sites were also situated higher up on the main stream and tributaries, to quantify downstream changes in discharge, carbon concentrations and exports. All sites on both catchments were sampled on a weekly basis over the six-week period. The two catchments were sampled on different days within a week due to time constraints, but sites on one catchment were all sampled on the same day to reduce variations in hydrological conditions. Sampling days within a week could not be fixed, as site access was weather dependent.

At each sampling site, 250 ml of water were collected and filtered using an ashed 0.7 μm glass-fibre filter paper and a hand-pump. 50 ml polypropylene vials were rinsed three times with filtrate before use for sample storage. The filter papers were stored in low-density polyethylene petri-dishes for later POC analysis. A source of error, especially for [POC], can be vertical and horizontal variations in concentrations within the river profile (Hope et al., 1994). To minimise this, water samples were collected consistently from the vertical and horizontal centre of the stream. After sampling, instantaneous stream discharge was calculated from cross-channel area profiling and cross-channel changes in flow velocity. A *Geopacks Stream Flowmeter* was used – a device commonly used to measure discharge in small streams (Jantze et al., 2015). Over the study period, 53 samples were collected from the East catchment and 60 samples were taken from the West catchment.

2.3. Laboratory analysis

Samples were stored in a fridge at 4 °C until DOC analysis for up to 17 weeks. This storage time is not considered to affect filtered DOC samples (Gulliver et al., 2010). Prior to analysis, the filtrate was acidified to pH 3.9 using a Mettler Toledo G20 Compact Titrator, to remove any inorganic carbon present in the samples. [DOC] was quantified as non-purgeable organic carbon (NPOC) using a Thermalox TOC Analyser, which utilises high-temperature catalytic-oxidation to convert DOC to CO_2, which is subsequently detected using an infra-red analyser. A primary calibration using four potassium hydrogen phthalate (KHP) standards of known concentration, spaced at 5 mg L^{-1}, accompanied each sample run.

[POC] was quantified using the loss on ignition technique (e.g. Dawson et al., 2002). The filter papers were exposed to 105 °C for 4 h to evaporate any water, then weighed and subjected to 375 °C for 16 h for dry combustion of organic matter, after which they were again weighed. The loss of dry weight of organic matter was corrected using the van Bemmelen factor 0.58, following the procedure from Pallasser et al. (2013).

2.4. Summertime DOC and POC fluxes

For each (sub-) catchment, instantaneous DOC and POC fluxes per unit area (μg m^{-2} s^{-1}) were quantified by multiplying concentrations of DOC or POC (μg L^{-1}) by their associated discharge (m^3 s^{-1}) and dividing by the (sub-) catchment area (m^2). Instantaneous fluxes at each sampling site were averaged over the study period to obtain mean fluxes for each site. The resulting mean flux estimates were used for correlation analysis with land cover categories (%).

Mean fluxes were also extrapolated to daily fluxes and multiplied by 94 (days in June, July and August) to estimate summer fluxes (g m^{-2}).

2.5. Statistical analysis

A p-value < 0.05 was considered statistically significant, as this is generally applied with geographical data (Ebdon, 1985). As land cover data was non-normally distributed, the non-parametric Spearman's rank correlation test (Spearman's rho) was used to determine correlations between different land covers and mean organic carbon concentrations and fluxes. The validity of these correlations was tested in two ways: (1) by adjusting for multiple comparisons using the False Discover Rates (FDR)-based analysis, following the procedure by Pike (2011) and (2) by examining potential correlations between different land covers (where likewise p-values were tested using FDR-based analysis), as such a correlation could lead to an indirect, secondary correlation between a land cover and mean C concentrations and fluxes. A 2-sample t-test was applied to test for significant differences in concentrations and fluxes between the West catchment and East catchment.

3. Results

3.1. Summer organic carbon concentrations and fluxes

Sampling site characteristics and DOC, POC and TOC concentrations and fluxes are summarised in Table 2. The East catchment had more variable and significantly higher mean discharge ($p < 0.001$) across sampling sites than the West catchment (Fig. 2). [DOC] and [POC] ranged from 2.1 to 6.6 mg L^{-1} and from 0.4 to 3.1 mg L^{-1} respectively in the West catchment, and between 2.1 and 6.3 mg L^{-1} and 0.6 and 2.3 mg L^{-1} respectively in the East catchment. DOC and POC fluxes near the West catchment outlet (site W01) averaged at 0.34 and 0.12 (µg m^{-2} s^{-1}) respectively, and near the East catchment outlet (site E01) at 0.31 and 0.11 (µg m^{-2} s^{-1}) respectively, over the study period. A two-sample t-test, including all data from both catchments, showed significantly higher [DOC]s in the West catchment (mean = 4.4 mg L^{-1}, $\sigma = 0.9$) than across the East catchment (mean = 3.5 mg L^{-1}, $\sigma = 0.9$) ($p < 0.001$) (Fig. 3). Similarly at the catchment outlets, W01 (mean = 4.7 mg L^{-1}, $\sigma = 1.0$) had significantly higher [DOC]s than E01 (mean = 3.3 mg L^{-1}, $\sigma = 0.9$), over the study period ($p < 0.05$). [POC] as well as DOC, POC and TOC fluxes did not differ significantly between the two catchments ($p > 0.05$). However, mean DOC fluxes in the West catchment were more responsive to a peak in discharge on 21.06.2016 whereas mean fluxes in the East catchment remained relatively stable throughout the study period (Fig. 4).

Across all sampling sites, TOC concentrations and fluxes were made up mostly of DOC (56.0–89.2 %). A two-sample t-test showed that in the West catchment, TOC concentrations and fluxes consisted of proportionally significantly more DOC than in the East catchment ($p < 0.01$). At the catchment outlet sites, DOC made up 73.7% ($\sigma = 8.1$) of TOC at W01 and 72.1% ($\sigma = 8.9$) of TOC at E01.

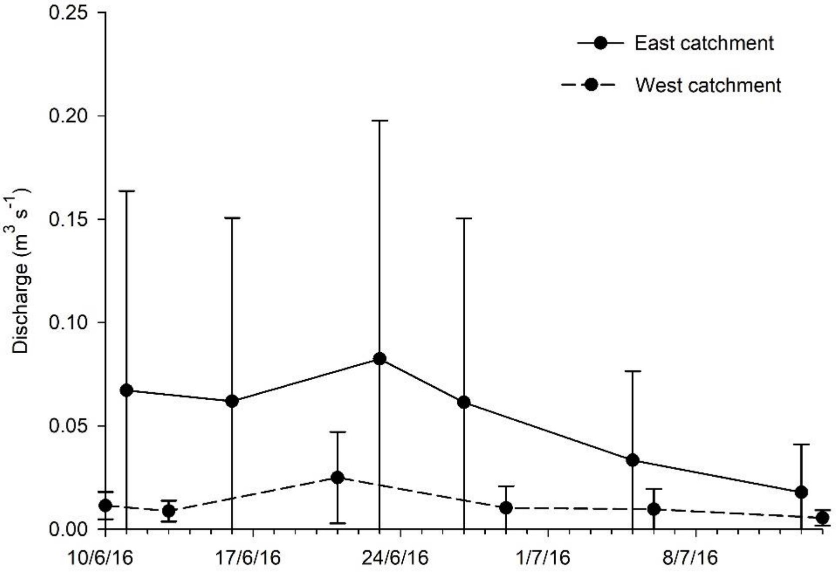

Fig. 2. Mean discharge (m^3 s^{-1}) measured across sampling sites in the West catchment and the East catchment over the sampling period.

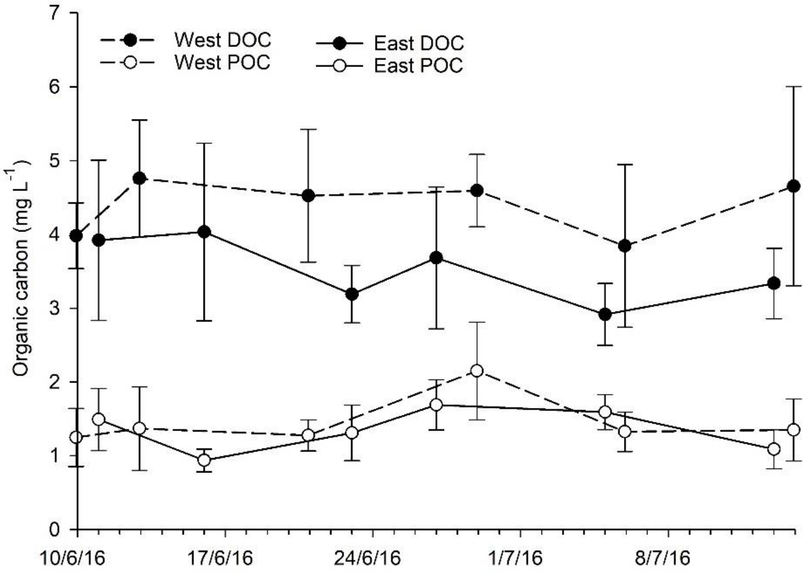

Fig. 3. Mean [DOC] and [POC] (mg L^{-1}) across sampling sites in the West catchment and East catchment over the sampling period.

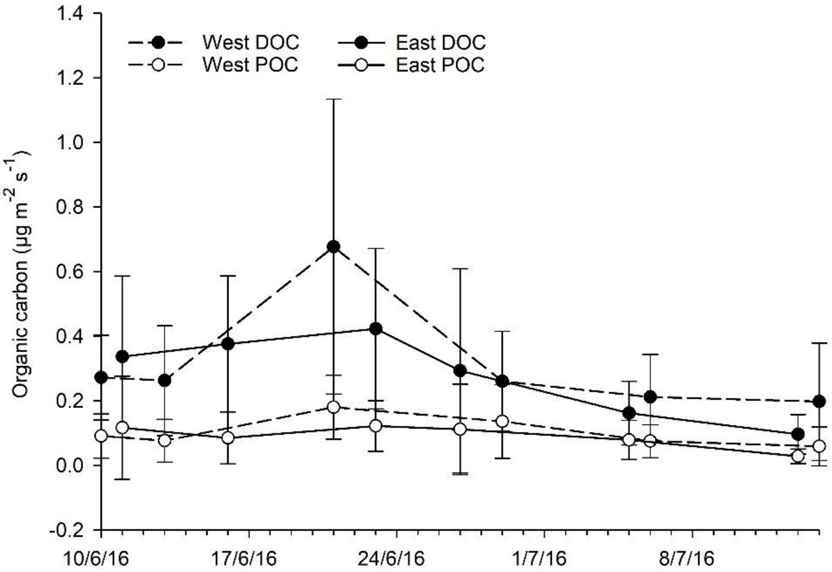

Fig. 4. Mean DOC and POC fluxes (µg m^{-2} s^{-1}) across sampling sites in the West catchment and East catchment over the sampling period.

3.2. The influence of land cover on organic carbon budgets

Spearman rho correlation coefficient between DOC, POC and TOC concentrations and fluxes and catchment characteristics, with associated significance, as well as FDR-adjusted significance, for the West catchment, East catchment and both catchments combined are shown in Table 3. In the West catchment, DOC, POC and TOC concentrations and fluxes increased significantly with wetland cover (Spearman rho, $p < 0.05$) (Fig. 5). The correlations between wetland cover and [POC], [TOC] and DOC, POC and TOC fluxes remained significant after FDR-adjusted p-values (Table 3). In addition, [POC] in the West catchment increased significantly with lupin cover and decreased significantly with larger areas of sparse vegetation (Spearman rho, $p < 0.01$) (Fig. 5) – both of these correlations remained significant ($p < 0.05$) after p-values were adjusted using FDR analysis (Table 3). DOC and POC fluxes also increased significantly with lupin cover in the West catchment (Spearman rho, $p < 0.05$) (Fig. 5), though this correlation didn't remain significant after FDR-adjusted p-values. In the East catchment, DOC and POC fluxes increased significantly with discharge (Spearman rho, $p < 0.05$) and reduced significantly with greater lupin cover (Spearman rho, $p < 0.05$) (Fig. 5), though neither of these correlations remained significant after FDR-adjusted p-values. Significant correlations and their coefficients between different land cover categories (Table 4) were examined to account for third factor causation, where a significant correlation between two land cover categories could lead to a misinterpretation of correlations between organic carbon exports and land cover. A significant positive correlation (a rise in one vegetation cover coinciding with a rise in another vegetation cover) was found between wetland and lupin cover in the West catchment ($p < 0.05$) (although this correlation was no longer deemed truly significant after FDR analysis). Significant negative correlations existed between sparse vegetation and heathland in the East catchment ($p < 0.001$), and between sparse vegetation and lupin in the West catchment ($p < 0.001$), both of which remained significant when p-values were adjusted using FDR analysis.

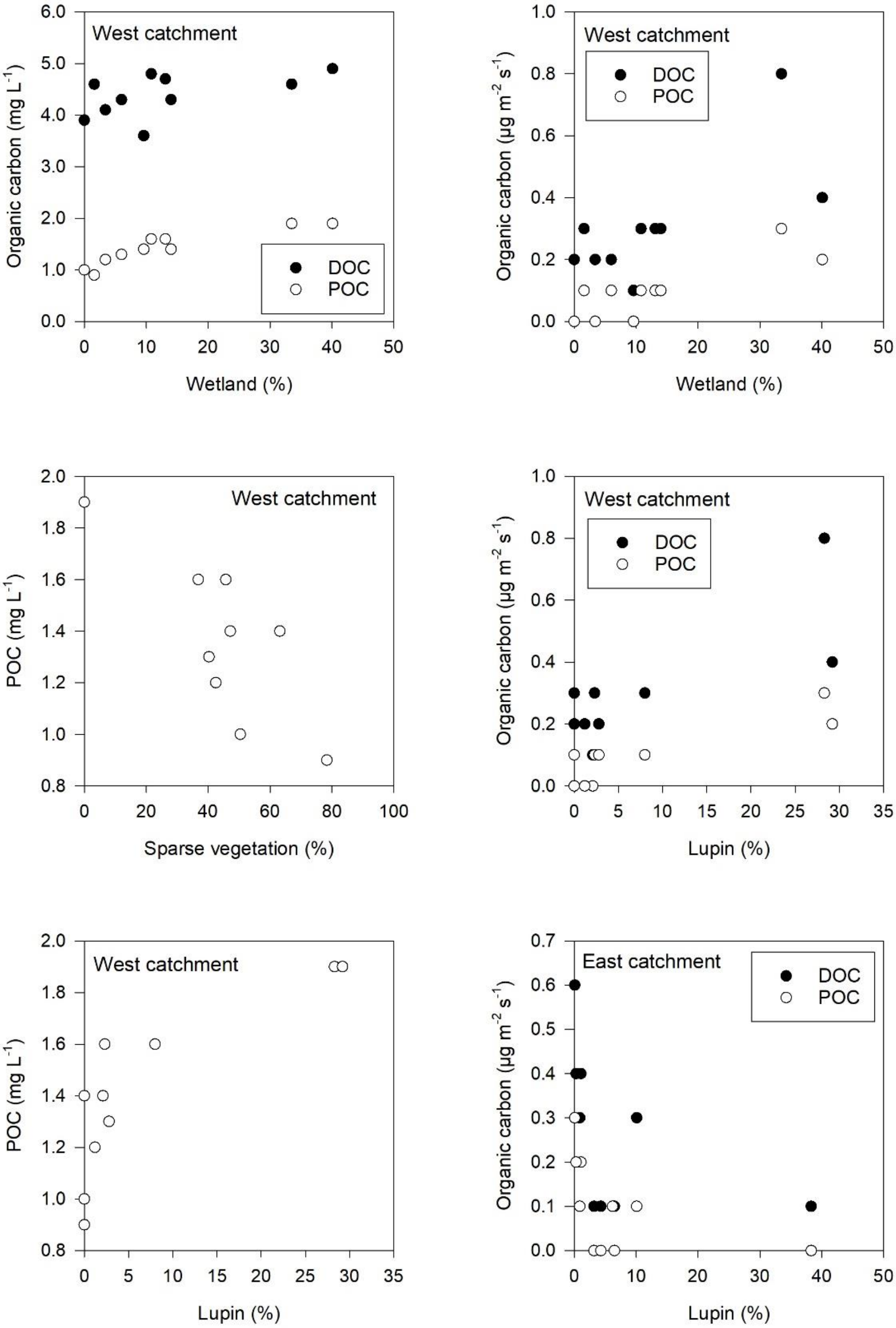

Fig. 5. Significant correlations ($p < 0.05$) between organic carbon concentrations (mg L^{-1}) or fluxes (µg m^{-2} s^{-1}) and vegetation cover (%).

Table 2

Sub-catchment characteristics and mean DOC, POC and TOC concentrations and fluxes (±standard deviation) at sampling sites in the East catchment and West catchment.

Site	Number of samples	Area (km^2)	Mean discharge ($m^3 s^{-1}$)	Land cover (%)				Concentration (mg C L^{-1})			Flux (µg C $m^{-2} s^{-1}$)		
				H	L	SV	W	DOC	POC	TOC	DOC	POC	TOC
East catchment													
E01	6	2.00	0.184	30.3	10.1	58.0	1.6	3.3 (±0.9)	1.2 (±0.4)	4.5 (±0.7)	0.31 (±0.17)	0.11 (±0.06)	0.42 (±0.21)
E02	6	0.31	0.009	28.2	6.5	60.4	4.9	3.9 (±0.5)	1.2 (±0.4)	5.1 (±0.5)	0.11 (±0.05)	0.04 (±0.02)	0.15 (±0.07)
E03	6	0.34	0.014	40.0	6.2	53.8	0.0	3.5 (±0.9)	1.4 (±0.4)	4.9 (±0.9)	0.14 (±0.06)	0.06 (±0.04)	0.20 (±0.10)
E04	6	1.02	0.151	20.2	1.1	77.6	1.1	2.8 (±0.5)	1.4 (±0.5)	4.2 (±0.5)	0.39 (±0.14)	0.02 (±0.01)	0.41 (±0.15)
E05	6	0.07	0.006	79.8	0.9	7.5	11.8	3.9 (±1.0)	1.3 (±0.3)	5.3 (±0.9)	0.34 (±0.17)	0.11 (±0.04)	0.45 (±0.19)
E06	5	0.06	0.007	80.3	0.3	9.6	9.9	3.3 (±0.5)	1.4 (±0.3)	4.6 (±0.5)	0.43 (±0.21)	0.18 (±0.07)	0.60 (±0.27)
E07	6	0.90	0.154	12.8	0.1	87.1	0.0	3.5 (±0.9)	1.5 (±0.6)	4.3 (±1.4)	0.60 (±0.34)	0.25 (±0.18)	0.86 (±0.49)
E08	4	0.32	0.006	38.9	3.2	57.9	0.0	3.9 (±0.6)	1.4 (±0.3)	5.2 (±1.4)	0.08 (±0.05)	0.03 (±0.01)	0.10 (±0.05)
E09	5	0.12	0.002	61.7	38.3	0.0	0.0	3.5 (±0.6)	1.6 (±0.4)	5.1 (±0.8)	0.06 (±0.04)	0.03 (±0.02)	0.08 (±0.06)
E10	3	0.26	0.005	24.8	4.3	70.6	0.3	3.3 (±0.7)	1.5 (±0.6)	4.7 (±1.1)	0.06 (±0.01)	0.03 (±0.01)	0.08 (±0.02)
West catchment													
W01	6	0.43	0.032	42.1	8.0	36.8	13.1	4.7 (±1.0)	1.6 (±0.5)	6.3 (±0.8)	0.34 (±0.22)	0.12 (±0.07)	0.46 (±0.27)
W02	6	0.35	0.025	41.2	2.3	45.7	10.8	4.8 (±0.3)	1.6 (±0.5)	6.4 (±0.3)	0.34 (±0.28)	0.11 (±0.08)	0.46 (±0.35)
W03	6	0.04	0.007	38.2	28.3	0.0	33.5	4.6 (±0.8)	1.9 (±0.6)	6.5 (±0.9)	0.76 (±0.50)	0.27 (±0.09)	1.03 (±0.57)
W04	6	0.03	0.003	30.7	29.2	0.0	40.1	4.9 (±0.8)	1.9 (±0.7)	6.8 (±1.3)	0.44 (±0.29)	0.16 (±0.09)	0.60 (±0.37)
W05	6	0.33	0.011	41.1	2.1	47.2	9.6	3.6 (±0.9)	1.4 (±0.7)	5.0 (±1.4)	0.12 (±0.06)	0.05 (±0.04)	0.17 (±0.09)
W06	6	0.21	0.010	51.0	2.8	40.3	6.0	4.3 (±0.6)	1.3 (±0.3)	5.6 (±0.7)	0.19 (±0.12)	0.06 (±0.04)	0.25 (±0.15)
W07	6	0.11	0.009	22.9	0.0	63.2	14.0	4.3 (±0.7)	1.4 (±0.2)	5.7 (±0.8)	0.33 (±0.08)	0.11 (±0.03)	0.44 (±0.11)
W08	6	0.20	0.008	53.0	1.2	42.5	3.4	4.1 (±1.5)	1.2 (±0.3)	5.3 (±1.6)	0.18 (±0.14)	0.05 (±0.02)	0.22 (±0.16)
W09	6	0.17	0.007	49.6	0.0	50.4	0.0	3.9 (±0.7)	1.0 (±0.3)	4.9 (±0.9)	0.17 (±0.17)	0.05 (±0.05)	0.22 (±0.21)
W10	6	0.09	0.006	20.0	0.0	78.4	1.6	4.6 (±1.4)	0.9 (±0.1)	5.5 (±1.4)	0.26 (±0.12)	0.06 (±0.03)	0.32 (±0.15)

H = heathland; L = lupin; SV = sparse vegetation; W = wetland

Table 3
Spearman Rho correlation coefficients between vegetation cover (%) and DOC, POC and TOC. Concentrations are in mg C L^{-1} and fluxes are in µg C m^{-2} s^{-1}. Area is in m^2 and discharge is in m^3 s^{-1}. * = $p \leq 0.05$, ** = $p \leq 0.01$, and *** = $p \leq 0.001$. † signifies truly significant correlations after FDR-adjusted p-values, following the method by Pike (2011).

		Area	**Discharge**	**H**	**L**	**SV**	**W**
Concentration							
DOC	East	-0.273	-0.297	0.236	0.152	-0.358	0.019
	West	-0.188	-0.115	-0.382	0.607	-0.486	* 0.661
	Both	-0.389	-0.185	0.084	0.092	-0.393	**† 0.627
POC	East	-0.115	-0.297	-0.188	-0.188	0.091	-0.557
	West	-0.055	0.103	-0.188	***† 0.865	**† -0.778	***† 0.915
	Both	0.012	-0.006	-0.033	* 0.505	-0.39	0.348
TOC	East	-0.442	-0.491	0.552	0.236	-0.624	0.119
	West	-0.273	-0.115	-0.37	* 0.755	* -0.657	***† 0.867
	Both	-0.430	-0.245	0.164	0.23	* -0.511	***† 0.691
Flux							
DOC	East	0.188	* 0.685	-0.067	* -0.721	0.236	0.319
	West	-0.345	-0.200	-0.418	* 0.644	-0.571	**† 0.782
	Both	-0.152	0.284	-0.12	-0.154	-0.188	* 0.552
POC	East	0.236	* 0.697	-0.224	* -0.745	0.394	0.313
	West	-0.273	-0.103	-0.503	* 0.718	-0.596	***† 0.867
	Both	-0.003	0.406	-0.177	-0.092	-0.116	* 0.495
TOC	East	0.285	* 0.721	-0.164	* -0.697	0.309	0.281
	West	-0.345	-0.200	-0.418	* 0.644	-0.571	**† 0.782
	Both	-0.078	0.349	-0.143	-0.175	-0.137	* 0.514

Table 4
Spearman Rho correlations between different vegetation covers. * = $p \leq 0.05$, ** = $p \leq 0.01$, and *** = $p \leq 0.001$. † signifies truly significant correlations after FDR-adjusted p-values, following the method by Pike (2011).

		Lupin	Sparse vegetation	Wetland
Heathland	Both	0.108	†***-0.774	0.142
	East	0.091	†***-0.952	0.331
	West	0.067	-0.267	-0.418
Lupin	Both		*-0.481	0.132
	East		-0.285	-0.200
	West		†***-0.948	*0.706
Sparse vegetation	Both			*-0.499
	East			-0.169
	West			-0.620

4. Discussion

4.1. Organic carbon concentrations and fluxes

Across the study site, [DOC] and [POC] ranged between 2.1 and 6.6 mg L^{-1} and from 0.4 to 3.1 mg L^{-1}, respectively. [DOC]s from our catchments were higher than average concentrations (1.2 ± 0.8 mg L^{-1}) from 32 sites in the 576 km^2 subarctic Abiskojokka catchment in northern Sweden (Jantze et al., 2015), but resembled mean summer [DOC]s in three headwater streams, HP3A (3.6 ± 0.8 mg L^{-1}), HP4 (7.0 ± 1.0 mg L^{-1}) and PC1-08 (2.0 ± 0.3 mg L^{-1}) from the Harp Lake and Plastic Lake catchments in central Ontario, Canada (Eimers et al., 2008). These three stream catchments contained similar proportions of % peatland cover (3%, 8% and <2%, respectively) to the % wetland cover of the West catchment, at W01, and East catchment, at E01 (Table 2). However, estimated summer DOC fluxes (June, July, August) from the West catchment (2.7 ± 1.7 g m^{-2}) and the East catchment (2.5 ± 1.3 g m^{-2}) were relatively higher than summer DOC fluxes from these three headwater streams, HP3A (0.18 ± 0.20 g m^{-2}), HP4 (0.36 ± 0.26 g m^{-2}) and PC1-08 (0.029 ± 0.021 g m^{-2}) (Eimers et al., 2008), which could have been due to differences in catchment characteristics, runoff and climate.

If our summer DOC and POC fluxes were extrapolated over the length of the snow-free season, annual TOC fluxes would be 14.4 g m^{-2} yr^{-1} (DOC 10.6 g m^{-2} yr^{-1}; POC 3.8 g m^{-2} yr^{-1}) for the West catchment and 13.3 g m^{-2} yr^{-1} (DOC 9.8 g m^{-2} yr^{-1}; POC 3.5 g m^{-2} yr^{-1}) for the East catchment. Organic carbon fluxes in subarctic and boreal catchments tend to be highest during the spring snowmelt, leading to flushing of DOC-rich organic soils (Jantze et al., 2015, Ågren et al., 2007), and during the summer snow-free season, when vegetation cover is at its maximum and high temperatures lead to greater degradation of plant litter (Köhler et al., 2009; Ågren et al., 2007). In addition, surface runoff rivers, such as ours, in Iceland are known to have extremely fluctuating flow, being generally low in winter and during dry conditions, but having the potential to increase to more than ten times the average flow during spring floods and sudden thaw events in winter (Arnalds, 2015). These fluxes are therefore very likely to be overestimates of annual exports and should therefore be taken purely as very rough estimates.

These rough estimates are, nevertheless, considerably higher than those from three larger river catchments, Jökulsá á Fjöllum (0.48 g C m^{-2} yr^{-1}), Jökulsá á Dal (0.74 g C m^{-2} yr^{-1}) and Fellsá (0.48 g C m^{-2} yr^{-1}), situated in northeast Iceland, of which the first two catchments drain northwards from the Vatnajökull glacier (Kardjilov et al., 2006). The three catchments were considerably larger, at 5179 km^2, 3338 km^2 and 124 km^2, with higher mean annual discharges of 164 m^3 s^{-1}, 130 m^3 s^{-1} and 6 m^3 s^{-1} (data from 1998), respectively, compared with our catchments (Table 2). However, similarly as with our study, these larger river budgets were quantified using a small sample size of 10 samples per year between 1998 and 2003 and their estimates may similarly lack resolution and have led to underestimates. Smaller catchments, such as the West catchment and East catchment can be more variable in C exports than larger catchments (Alvarez-Cobelas et al., 2012). Firstly, organic carbon concentrations and fluxes, particularly of DOC, tend to show a stronger connectivity to the SOC pool within smaller catchments (Dawson and Smith, 2007; Aitkenhead et al., 1999). Secondly, in-stream DOC concentrations tend to be higher in lowlands (<700 m) than in uplands due to changes in SOC production associated with land cover and slope (Parry et al., 2015; Aitkenhead et al., 1999). In Iceland, both wetlands and heathlands are predominantly found in lowland areas, with 87% of heathlands and 95% of wetlands occurring between 0 and 600 m a.s.l. (Arnalds, 2015). The West catchment and East catchment had mean elevations of 127 m and 274 m, while the Jökulsá á Fjöllum, Jökulsá á Dal and Fellsá had higher mean elevations of 883 m, 897 m and 703 m, respectively (Kardjilov et al., 2006), and considerably less vegetation cover than the West catchment and East catchment. Compared with our study catchments, the three catchments in NE Iceland contained lower proportions of vegetated land (heath, grassland, cultivated land, wetland and moss heath) and larger expanses of little to no vegetation cover (sparsely vegetated land, rivers, lakes and glaciers). The Jökulsá á Dal catchment, with 11% wetland cover, resembled our West catchment, where site W01 contained 13.1% wetland cover (Table 2). The two catchments differed however in their proportions of total vegetated cover, with only 32% of the Jökulsá á Dal catchment covered in wetland, heath, grassland and cultivated land, while our site W01 was made up of 63.2% vegetated area (heathland, dense lupin and wetland) (Table 2).

Rough estimates of annual TOC fluxes from the West catchment and East catchment were of similar magnitude to annual fluxes measured at temperate peat moorland catchments of comparable size and discharge in the UK and Sweden. The Brocky Burn in NE Scotland, with a catchment area of 1.3 km^2 and mean discharge of 0.036 m^3 s^{-1}, drains an area largely composed of heather moorland with rushes and grasses, and exported 18.8 g TOC m^{-2} yr^{-1} (Dawson et al., 2002). The Upper Hafren in mid-Wales, with a catchment area of 0.93 km^2 and mean discharge of 0.062 m^3 s^{-1}, exported 11.1 g TOC m^{-2} yr^{-1} from an area of acid moorland with acidic grassland and peaty mires (Dawson et al., 2002). Similarly, in southern Sweden, a catchment (0.57 km^2), dominated by approximately 40% open minerotrophic fen, exported

18.8 g C m^{-2} yr^{-1} of DOC, while an adjacent catchment (0.48 km^2), consisting of over 90% forest, exported 11.9 g C m^{-2} yr^{-1} of DOC, based on 115 and 97 samples taken between April and December (2012 and 2013), respectively (Wallin et al., 2015). This, again, suggests the strong dependency of organic carbon exports on high percentage vegetation cover and greater soil connectivity in small catchments.

4.2. The influence of land cover on organic carbon budgets

The West catchment had significantly higher mean [DOC]s (mg L^{-1}) at 4.4 ± 0.9 mg L^{-1}, than the East catchment (3.5 ± 0.9 mg L^{-1}) ($p < 0.001$) (Fig. 3), and DOC fluxes were generally more variable over time across the West catchment sampling sites (Fig. 4). The significant positive correlation between [DOC] and wetland area, as found in the West catchment, has been observed elsewhere (Jantze et al., 2015, Monteith et al., 2015 and Ågren et al., 2007). In Iceland, wetlands, including those in our study area (Arnalds and Grétarsson, 2001), are largely associated with SOC-rich Histic Andosols (Arnalds 2015). Wetlands are highly productive ecosystems, where waterlogged conditions ensure constant connectivity for the leaching of humic components from the SOC pool to exporting waters (Jantze et al., 2015; Aitkenhead et al., 1999). In addition, eroding C-rich wetland soils can be significant contributors to the export of POC (Pawson et al., 2012), which could explain the significant positive correlation between wetland area and POC concentration and fluxes in the West catchment. Sparsely vegetated areas occurred mainly on steep scree slopes, associated with SOC-poor Leptosols (Arnalds, 2015). Differences in vegetation cover (Table 1) and soil, due to elevation, were likely drivers of higher estimated fluxes in the West catchment compared with the East catchment.

The Nootka lupin has been shown to be highly effective in increasing SOC content (Tanner et al., 2015; Aradóttir et al., 2000) and stabilising the soil (Tanner et al., 2015; Hiltbrunner et al., 2014). In the East catchment, DOC, POC and TOC fluxes decreased significantly with greater lupin cover (Table 3). This is consistent with the stabilising effect of dense lupin cover on the soil which could lead to reduced mobilisation of DOC and POC. However, in the West catchment, [POC] increased significantly with lupin cover, and so did DOC, POC and TOC fluxes (Table 3). This could be due to the greater amounts of litter associated with the plant's size, in contrast to smaller wetland and heathland vegetation. Lupin grew mainly in the higher, south-eastern areas of the West catchment and near the outlet site W01 (Fig. 1). Areas covered with dense lupin formed significant parts of the sub-catchments of sites W03 and W04, which also contained relatively high wetland cover (Table 2). A Spearman's rank correlation test showed this correlation between wetland and lupin cover in the West catchment to be significant ($p < 0.05$) (Table 4). The positive correlation between lupin and organic carbon fluxes in the West catchment could therefore have been an artefact of the correlation between lupin and wetland cover.

5. Conclusions

This research reports new data on DOC and POC concentrations and exports from stream catchments in Iceland, an area lacking in C flux data. Wetland cover, associated with SOC-rich Histic Andosols, was found to be a driving force in enhancing DOC, POC and TOC fluxes. The role of Nootka lupin in influencing C fluxes seemed inconsistent between the two catchments, but this may be because the West catchment wetland cover exerted a positive control on increased flux and was co-located with Nootka lupin.

The West catchment and East catchment differed in discharge and vegetation cover, which may have led to the significant difference in their [DOC]s, although they did not differ significantly in flux. The significantly higher [TOC]s in the West catchment were likely driven by its larger wetland area, while [TOC]s in the East catchment were limited by proportionately larger areas of SOC-poor sparse vegetation.

Jónsdóttir (2008) predicts a 2.8 °C rise in temperature and a 6% increase in precipitation by the period 2071–2100, estimated to lead to a 25% increase in runoff on average across Iceland, with unknown implications for soil erosion, biomass production and organic carbon exports. With limited data on fluvial C export from Iceland, this research provides better understanding of the magnitude and controls on organic carbon budgets in Icelandic stream catchments, and thus the drivers of terrestrial C export. It thereby contributes to global estimates of organic carbon exports and provides a baseline for further study of organic carbon budgets in Iceland.

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