

Precipitation, runoff and nutrient losses from cultivated Histosols in western Iceland

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ABSTRACT

From May 2001 to June 2002, regular measurements were done on the volume of water runoff from the fields of the Agricultural University of Iceland's farm at Hvanneyri, western Iceland. Precipitation and other weather factors were continuously monitored. The following components were analysed in the runoff water: total N, ammonia N (NH₄-N), oxidized N (TON), phosphate (PO₄-P), soluble phosphorus (TSP), K, Ca, Mg, Na, and S. Results show that nutrient runoff varied considerably over the year, highest in winter but low during the summer months. Losses of Ca, Mg, K and Na were relatively high, but N and P runoff was low considering that we are dealing with fertilized organic soils with a high content of soluble P in the top 10 cm and high total N in the whole soil profile. Results showed that major fluctuations and peak runoff events were confined to the winter months. Nutrient losses in relation to field management practices require further studies.

Keywords: Fertilizer, Nutrient losses, Open ditch draining, Precipitation events, Water runoff.

YFIRLIT

Úrkoma, afrennsli og tap af næringarefnum af mýrartúnum á Hvanneyri.

Reglulegar mælingar voru gerðar frá maí 2001 til júní 2002 á afrennslismagni og styrk efna í afrennslisvatni af túnum á Hvanneyri í Borgarfirði. Einnig var veðurgagna aflað frá sama svæði. Efnagreiningar voru gerðar á eftirtöldum þáttum í afrennslisvatni: heildarstyrk köfnunarefnis (N), fosfórs (P), kalís (K), kalsíums (Ca), magnesíums (Mg), natríums (Na) og brennisteins (S). Einnig var mælt magn ólífræns köfnunarefnis (NH₄-N+ heilda oxað N (TON), fosfats (PO₄P) og leysanlegs fosfórs (TSP). Niðurstöður sýndu að útskolun er sveiflukenndust og mest yfir vetrarmánuðina. Heildarútskolun Ca, Mg, K og Na reyndist frekar mikil en útskolun köfnunarefnisþátta og fosfórs var lítil með tilvísun til þess að um er að ræða áborið ræktarland.

INTRODUCTION

Agricultural soils are enriched in plant nutrients, although their quantities and form depend on climate and soil parent material, together with tillage, crop history and nutrient inputs (McLauchlan 2006). Fertilizers added annually to the soils, either in organic or inorganic form, are usually only partly absorbed and utilized by plants, whereas a part of the nutrients may

be immobilized in the soil or leached away with runoff and drainage water (Edwards et al. 2012, Schröder et al. 2004). Nitrogen (N) is the nutrient most at risk of being lost from agricultural fields, as the available N is usually in soluble form and applied in large quantities with potentially serious environmental implications for groundwater and ecosystems (Brouwer 1998,

Zhang et al. 2015). Although not as soluble as nitrogen, phosphorus (P) runoff from agriculture has also been identified as a major ecological problem through potential eutrophication of lakes and coastal waters (MacDonald et al. 2011, Sims et al. 1998). In most freshwater systems P is the limiting factor for enrichment (Schoumans et al. 2014). In Iceland, however, N is usually the limiting factor in geologically younger zones where any extra input into water and river systems potentially boosts primary production (Óskarsdóttir et al. 2011).

Chemical runoff has also significant sources other than fertilizer, as can be expected from the volcanic rocks of Iceland that weather rapidly (Gíslason 2008). Icelandic soils, including organic soils, contain considerable amounts of Ca and Mg and other elements, making them generally fertile (Gudmundsson et al. 2005, Guðmundsson 2018). Together with the Andosols the organic soils, Histosols, are the most fertile agricultural soils in Iceland. The natural chemical runoff in Iceland has been reviewed thoroughly by Gíslason (2008) who found that the total chemical denudation rate is in the range 19 to 146 t km⁻² yr⁻¹, excluding bicarbonate. This corresponds to 190 to 1,460 kg ha⁻¹ yr⁻¹.

The inorganic parent material of the soils in Iceland is predominantly basaltic which is low to very low in potassium (K). This is reflected in the soils and as potassium fertilization may be lower than the uptake and removal from agricultural fields, the potassium content of the soils may decrease (Gudmundsson et al. 2005). Therefore, large amounts of potassium are not expected to leach through the soils. However, potential leaching also depends upon soil type and timing of fertilizer application (Óskarsson & Eggertsson 1991). Bog drainage and cultivation increases oxygen access to the soil and mineralizes soil organic matter, releases soil nutrients and improves soil fertility. Risk of nutrient losses increases at the same time, especially outside the growing season (Björnsson 2001).

The intensive nutrient-use in traditional agriculture has been of major international

concern for decades and calls for enhanced sustainability in agriculture, a demand that will continue and intensify (Glibert 2017, Withers et al. 2014). This topic has been addressed in many countries through regulations and guidelines for more sustainable management practices to combat nutrient losses through drainage and surface waters (Stoate et al. 2009, Fiener et al. 2011, Pärn et al. 2012).

Iceland has clearly been lagging behind in collecting data and undertaking research in this field. However, nutrient runoff from agricultural land in Iceland is believed to be rather limited (Pálmason et al. 1989). Earlier estimates of fertilizer losses by runoff in Iceland range from 5-20% for N and 2% for P (Pálmason et al. 1989). Fertilizer experiments on the Histosols in Hvanneyri showed that about 2/3 of the applied nitrogen was removed by the harvested hay crop (Björnsson & Óskarsson 1978) when fertilization was below 140 kg N ha⁻¹. The soils had been drained in 1960 and cultivation and the experiments started in 1965. The results showed that during the first years after cultivation and fertilization between 20 and 40 kg N ha⁻¹ were released from the soils and taken up by crops. However, with increased age of drainage, cultivation, fertilization and apparently increased decomposition, the release of N increased. During the warmer years in the early 1970's up to 100 kg N ha⁻¹ were taken up in plots without N fertilization (Björnsson & Óskarsson 1978). Phosphorus applied can be accounted for either by uptake or that it is bound in the soil, mostly in the top 5 cm of permanent grassland. This also applies for the present study area (Gudmundsson et al. 2014).

Several studies have been done in Iceland on element fluxes in relation to weathering in unmanaged catchments (Eiríksdóttir et al. 2015, Eiríksdóttir et al. 2016, Moulton et al. 1998, Moulton et al. 2000) and from forest land (Sigurðsson et al. 2005, Sigurðsson et al. 2017), where fluxes have been low. Nutrient runoff from wetlands has also been measured in few studies and was found to be rather low (Pálmason 1980, Friðriksson et al. 1977), but data on total nutrient runoff from agricultural land is lacking.

Icelandic oligotrophic waters and sub-arctic ecosystems are fragile and the relatively short term of human presence in Iceland has already caused major ecological changes (e.g. Möckel et al. 2017). Further, there are indications that climate change will result in increased runoff by streams and rivers in Iceland due to higher precipitation volumes and intensity (Björnsson et al. 2018) that likely also will impact agricultural land in Iceland.

The aim of this study was to assess the amount of nutrients lost from cultivation of drained agricultural land in Iceland and to identify patterns and major influences of that loss. This is the first study quantifying nutrient runoff from Icelandic agricultural soils which are unique, both due to the location in the subarctic geographic region and to their high organic matter concentration and volcanic parent material.

MATERIALS AND METHODS

The study area

The study catchment is located at the Research Farm of the Agricultural University of Iceland, Hvanneyri, western Iceland (64.564°N, 21.748°W), 10-15 m above sea level. The fields, 61.0 ha, were in mixed use, mainly for grass, 6-8 ha for barley cultivation, 1.8 ha for forestry and 6.7 ha for shelterbelts, roads and an open ditch drainage system. The total catchment area was 69.4 ha.

Climate data for Iceland is published on the home page of the Icelandic Meteorological Office (2019).

The soils of the area are organic, consisting of poorly decomposed sedge peat (Fibric Hyperdystric Histosols; IUSS Working Group 2014) overlying fine-grained marine sediments, as the area was below sea level at the end of the Ice Age. The soil depth is mostly 2–3 m but shallower in some places due to undulating bedrocks. The soil pH was relatively low for Icelandic Histosols, i.e. 4.2–4.6 without liming, and the bulk density was mostly 0.3–0.4 g cm⁻³. The organic C content of the soil ranged from 25–30% close to the surface but increased to 30–40% at greater depth. The N content was

about 1.6% at surface but varied between 1.5 - 1.7% at greater soil depth and the C/N ratio was 15–18 at the surface and 20–25 at greater depths. Ammonium lactate extractable nutrients (AL extraction) were highest in the top 5 cm in a fertilized permanent grass field with about 300 mg K kg⁻¹ and 380 mg P kg⁻¹ but below the plough layer the values only reached 10–50 and 8–20 mg kg⁻¹ for K and P, respectively (Þórðardóttir & Guðmundsson 1994).

The typical fertilizing scheme that has been used for many years on grass fields was 110 kg N, 24 kg P and 45 kg K ha⁻¹ and barley fields 70 kg N, 70 kg P and 70 kg K ha⁻¹ applied in spring and 15–20 t ha⁻¹ manure applied in the autumn. Nutrient content of the manure was about 9 kg N, 15 kg P and 25 kg K ha⁻¹.

Field sampling

All runoff from the measurement catchment collected into ditches that end up in a single brook. The water collected at the sampling site originated both from runoff from the soil surface and drainage water from the soil. A triangular notch thin plate weir was installed into the brook and used to calibrate a pressure gauge that continuously monitored the volume of the runoff, operated by Iceland Geosurvey (ISO standards 1983, Shen 1981). Two water samples were collected in plastic bottles at 2–3 day intervals from May 2001 to June 2002. One sample was used to measure temperature, conductivity and pH, and the second sample was frozen immediately after it was collected for later chemical analysis. Meteorological data was collected on site by the Icelandic Meteorological office. In 2018, 10 to 20 soil samples were taken from the top 10 cm of selected fields within the catchment area using a 10 cm sample auger. The samples were mixed, dried at 30°C and sieved to 2 mm prior to analysis

Chemical analysis

Water samples were thawed and filtered through 0.45µm syringe filters just before analysis. Prior to analysis samples were acidified by adding 0.5 mL of 65% nitric acid to a 50 mL aliquot. Concentrations of Ca, Mg, K, Na and

S in the acidified samples were determined by Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES). Ammonia nitrogen ($\text{NH}_4\text{-N}$), total oxidized nitrogen (TON) and orthophosphate phosphorus ($\text{PO}_4\text{-P}$) were determined colorimetrically in filtered samples using Flow-Injection Analysis (FIA). Ammonia was determined using the absorbance change of an acid-base indicator (bromothymol blue) when sample ammonia passes over a teflon membrane from an alkaline carrier stream through gas-diffusion into the indicator stream. TON is measured as nitrite after pre-reduction in a column with solid copper-coated cadmium granules. The nitrite is diazotized with sulfanilamide and coupled with N-(1-naphthyl)-ethylenediamine dihydrochloride to form a highly coloured azo dye which is measured colorimetrically. This measures the combined concentration of nitrite and nitrate ions, respectively. $\text{PO}_4\text{-P}$ was measured by quantifying the absorbance of a phospho-molybdenum blue complex formed after reduction with Sn(II) ions and reaction with ammonium molybdate. All colorimetric determinations were estimated as heights of transient absorbance peaks. Total phosphorus (TSP) and total oxidized nitrogen (TON) were determined as $\text{PO}_4\text{-P}$ and $\text{NO}_2\text{-N}$, respectively, following an autoclave digestion at 120°C with peroxodisulphate of filtered samples. Organic nitrogen was determined by subtracting inorganic nitrogen ($\text{NH}_4\text{-N} + \text{TON}$) from the total nitrogen. Available soil nutrients were extracted with an ammonium lactate-acetic acid mixture (AL-extraction, Egnér et al. 1960). To dissolve nutrients that could be released with time, soil samples were digested in nitric acid (U.S. EPA. 1996) by boiling in 65% (w/w) nitric acid, under reflux, in test tubes in an aluminium block, heated to about 135°C for at least 40 hours. Quantitation of the nutrients in both solutions was done by Inductively-Coupled-Plasma Mass Spectrometry (ICP-MS). Extractable amounts of nutrients were calculated to kg ha^{-1} using depth and bulk density (Table 6) in order to enable comparison with the nutrients lost.

The pH was measured using a glass electrode in a 1:2 soil/deionized water suspension. Bulk

density was measured by weighing 200 cm^3 air dried and sieved samples and corrected to oven dry weight.

Instrumentation

For the colorimetric determinations a FIALab3500b instrument (FIALab, USA) and for ICP-OES determinations a Spectroflame D instrument (Spectro, Germany) were used. For the ICP-MS determinations a Thermo X-series 2 instrument, equipped with a collision cell which was used here both for interference removal and for a gas phase dilution. All chemicals used were of analytical grade. All calculations and graphs were made in Microsoft Excel.

RESULTS

Meteorological data and runoff quantity for the study period are summarized in Table 1 and Figure 1. The weather during the period included in this study is regarded as normal. Peaks in precipitation occur in all seasons, but with more intensity during the winter months except during an extreme freezing episode that froze all runoff from the fields from 21 January to 25 February, which was also a very dry period with very few precipitation events. Larger runoff volumes and nutrient losses occur from fall to spring. Lower volumes occur during the growing season, June to September, which are the months with the highest evapotranspiration (Figure 1). Comparison of the precipitation and runoff volumes shows that about 83% of the

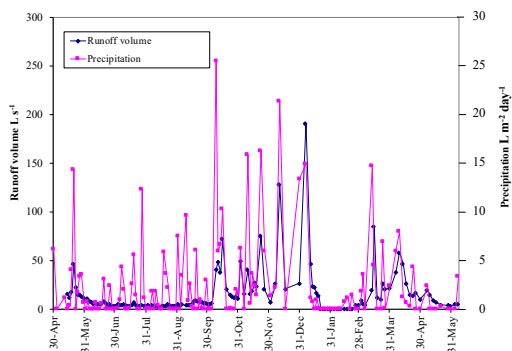


Figure 1. Monitoring of precipitation and surface runoff and drainage water volume from the Hvanneyri fields in May 2001 to June 2002.

Table 1. Summary of meteorological data and surface runoff volume from Hvanneyri fields in May 2001 to June 2002.

	n	Average	St.dev.	Min	Max
Average temperature (°C)	558	5.4	5.8	-12.5	16.4
Max daytime temperature (°C)	558	9.0	6.0	-10.9	21.3
Min daytime temperature (°C)	558	1.7	6.2	-17.3	13.3
Precipitation (L m ⁻² day ⁻¹)	560	2.4	5.1	0.0	44.4
Runoff volume (L s ⁻¹)	448	16.0	25.7	0.0	256.7

annual precipitation flows through the weir in the outflow from the area.

In the present study, the effects of rain events indicated considerable water infiltration and minimal nutrient losses during the growing season, June to September, but larger runoff volumes and nutrient losses from autumn to spring (Figure 1). For example, one day rainfall events of 12 mm and 10 mm in July and August 2001 had no effect on the discharge or surface water nutrient content, while 26 mm rainfall in an intense October autumn storm increased discharge 3.5-fold within hours. Runoff kept increasing to over 11-fold (6.4 to 72.6 L s⁻¹) for 4 days, after an additional 23 mm of rainfall. This rapid response of runoff volumes to rainfall amounts was intensified when winter

thaws occurred, as in December 2001 when a rainstorm delivered 21.4 mm of rain in one day at air temperature of 7°C. This caused a discharge peak during the same day from 27 to 129 L s⁻¹. An additional 13.4 mm of rain 2 days later increased the discharge to 191 L s⁻¹ (Figure 1).

Nutrient concentrations in the runoff (Table 2) were in the range 3.4 to 33.6, 3.3 to 43.5 and 1.1 to 7.2 mg L⁻¹ for Ca, Mg and K, respectively which is within or close to the range found in Icelandic rivers. However, the Na concentrations of 8.5 to 27.8 mg L⁻¹ were considerably higher than found in Icelandic rivers and the nitrate concentrations in the range of 0.01 to 20 mg L⁻¹ were much higher than found in Icelandic river systems.

Soil samples from the top 10 cm of selected fields within the catchment area in 2018 had a pH from 4.8 to 6.0, loss on ignition from 43 to 62% and bulk density from 0.35 to 0.43 kg l⁻¹ (Table 5). We assume that this represents the soil properties as they were in 2002.

Phosphorus concentrations were very low in the runoff samples (Figure 3). In total 94 out of 149 samples had phosphorus below the detection limit of 0.02 mg P L⁻¹. The other 55 samples above detection limits originated from events of heavy rain during winter.

The total loss of nutrients increased with increasing runoff volume, including those nutrients that simultaneously dropped in concentration. Average nutrient runoff values

Table 2. Nutrient concentrations (mg L⁻¹) in surface runoff water from Hvanneyri fields in May 2001 to June 2002.

	n	Average	St.dev.	Min	Max	Conc. range River water*	Average River water*
Ca	149	17.0	5.0	3.4	33.6	0.3-26.5	4.0
Mg	149	22.7	6.9	3.2	43.5	0.3-17.7	1.6
K	149	2.6	1.0	1.1	7.2	0.1-8.8	0.5
Na	149	19.5	3.9	8.5	27.8	0.9-9.6	9.1
S	149	6.8	2.1	2.2	15.0	0.1-13.9	4.7
TON	136	1.9	2.8	BDL	19.6	BDL**-0.2	0.1
Inorganic N	137	0.7	1.0	0.0	7.6		
Total N	149	1.0	1.0	0.2	7.4		
pH	140	7.1	0.3	6.1	8.5		
Conductivity µS/cm	141	352	82	118	577		

*Gislason et al. 1998 **BDL: below detection limit

Table 3. Nutrients in runoff water from Hvanneyri fields in May 2001 to June 2002 ($\text{kg ha}^{-1} \text{ day}^{-1}$). Phosphorus is not included due to high number of samples below analytical detection limits.

	n	Average	St.dev.	Min	Max
Ca	132	0.26	0.34	BDL	2.15
Mg	132	0.32	0.35	BDL	2.56
K	132	0.05	0.08	BDL	0.44
Na	132	0.31	0.37	BDL	2.22
S	132	0.12	0.18	BDL	1.07
TON		0.02	0.06	BDL	0.46
$\text{NH}_4\text{-N}$		0.01	0.06	BDL	0.55
Organic N	120	0.01	0.02	BDL	0.16
Total N	132	0.04	0.11	BDL	0.98

BDL: below detection limit

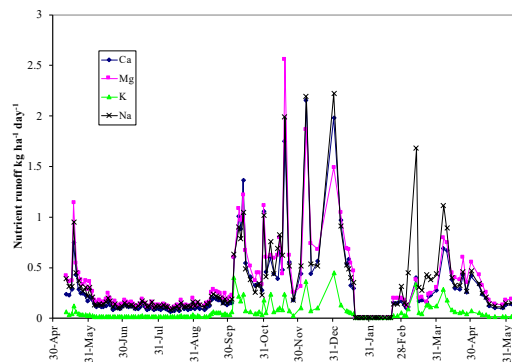


Figure 2. Runoff quantities for Ca, Mg, K, Na, and S $\text{kg ha}^{-1} \text{ day}^{-1}$ from the Hvanneyri fields in May 2001 to June 2002.

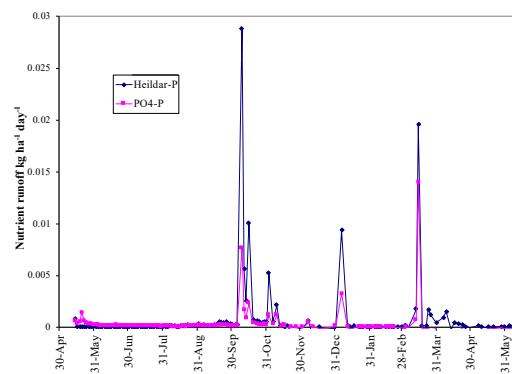


Figure 3. Runoff quantities for $\text{PO}_4\text{-P}$ and total P $\text{kg ha}^{-1} \text{ day}^{-1}$ from the Hvanneyri fields in May 2001 to June 2002.

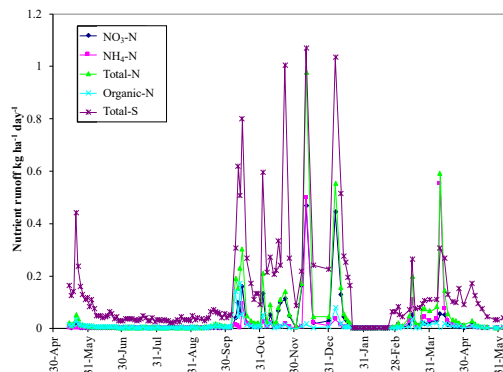


Figure 4. Runoff quantities for $\text{NO}_3\text{-N}$, $\text{NH}_4\text{-N}$ organic N, total N and total S ($\text{kg ha}^{-1} \text{ day}^{-1}$) from the Hvanneyri fields in May 2001 to June 2002.

($\text{kg ha}^{-1} \text{ day}^{-1}$ are summarized in Table 3, but graphs showing results from individual samples are shown in Figures 2–4. Runoff data are lacking between January 22 and February 25 when the pressure gauge was frozen and runoff very limited due to weather conditions. Figures 2–4 show that the major runoff events occur during the winter months in association with rainstorms. That is in contrast to the summers which are characterised by low and stable runoff volumes and low nutrient concentrations.

DISCUSSION

Although soil depth in the study catchment area is largely >2 m, most nutrient cycling takes place in the biologically most active top 10 cm of the soil, especially in grass swards and forages (Griffin et al. 2002, Tampere et al. 2015) which were dominant in the study area. In open ditches drainage systems, as in this study area, surface runoff is a probable source of water losses outside the short growing season, especially when the ground is frozen. The infiltration capacity of grassland soils can be considerable and may be comparable to crop field soils; however, the capacity is dependent on the time of year (Bharati et al. 2002). In a Swedish study on losses of rainwater by surface runoff were estimated to be 82% in the spring and 22% in the autumn. The other losses were through leaching (Bengtsson et al. 2003). Only

one published study in Iceland has measured the whole water cycle. It was done for an area with recently planted tree saplings in a grassland ecosystem and it found that 75% of the annual precipitation left the area as runoff (Sigurðsson et al., 2004).

Losses of N in this study were relatively low; the highest measured nitrate level of 20 mg L⁻¹ was below the maximum values allowed in drinking water (50 mg L⁻¹) (WHO 2017). However, for general conditions in Icelandic lakes and rivers these values are high. In west Iceland, Sigurðsson et al. (2005) reported nitrate values of 0.01 – 0.91 mg L⁻¹ from an unmanaged catchment. The positive correlation between N losses and runoff water volumes was likely due to the high solubility of inorganic soil N and oxidation of NH₄⁺ to NO₃⁻, which is more susceptible to leaching (Cameron et al. 2013). This, along with high additions of N from fertilizer and manure and mineralization of soil N, leads to an elevated risk of N losses from agricultural land outside of the growing season, when rainfall is also most intense (Jiang et al. 2011). Indeed, up to 65% of applied N in crop production can be expected to be lost by leaching or volatilization (Cameron et al. 2013, Lentz & Lehrs 2018). The short growing season in Iceland with low biological activity due to relatively low soil temperatures, and the practice of early spring fertilizer application, and in particular late autumn or winter manure spreading, increase the risk of N loss from cultivated soils. However, this study showed relatively low losses of N from the drained and fertilized fields of 13.1 kg ha⁻¹yr⁻¹ or about 11% of applied N. Yet, it must be kept in mind that oligotrophic waters are very sensitive to any fertilizer contamination.

It is well known that soluble phosphorus in runoff water does not correlate well with phosphorus in soils due to strong binding of phosphorus to organic and mineral constituents of the soil (Gudmundsson et al. 2014, Magdoff et al. 1999). It must be kept in mind, however, that water sampling strategies may give somewhat varying results (Robertson & Roerisch 1999). That almost no P was lost with the effluent

water shows the high capacity of the Icelandic soils to bind or fix phosphorus (Gudmundsson et al. 2014), which is building up in the soils as the HNO₃-extraction values of 370 to 770 kg ha⁻¹ show (Table 6). These low losses of P are most probably explained by the uniqueness of Icelandic soils, and they are in contrast with many other agricultural areas where P-induced eutrophication from over-fertilization is a persistent problem (MacDonald et al. 2011). An urgent need for reduced P losses has been identified in both Europe and North America (Schoumans et al. 2014, Smil 2000), and climate change is expected to increase this risk (Forber et al. 2018). Some of the HNO₃ extractable P in this study might become mobile through the combined effect of increased temperature and precipitation in the future. However, the P fixing properties of the Icelandic soils counter this effect.

Nutrient concentrations in the runoff for Ca, Mg and K (Table 2) had minimum values considerable higher than in Icelandic rivers. However, the maximum and mean values were only somewhat higher for Ca and K, whereas all Mg values were higher in our runoff than found in the rivers (Gislason 1993).

The Ca content varied depending on liming that is done at long intervals to correct falling pH values (Óskarsson & Eggertsson 1991). The AL-soluble Ca in the soil in the present study ranged from 560 to 5,300 kg ha⁻¹ and the HNO₃-soluble Ca from about 6,000 to 15,000 kg ha⁻¹ (Table 6). These high values were not reflected in annual Ca loss from the catchment area,

Table 4. Total loss of nutrients in runoff water per year (kg ha⁻¹ year⁻¹) from Hvanneyri fields from May 2001 to June 2002.

Element	Loss kg ha ⁻¹	Element	Loss kg ha ⁻¹
Na	101	Total P	0.3
Ca	86	PO ₄ -P	0.1
Mg	105	Total N	13.1
K	17	TON	6.3
Total S	41	NH ₄ -N	4.2
		Organic N	2.7

Total amount of chemical constituents in effluents from the fields: 377 kg ha⁻¹ yr⁻¹

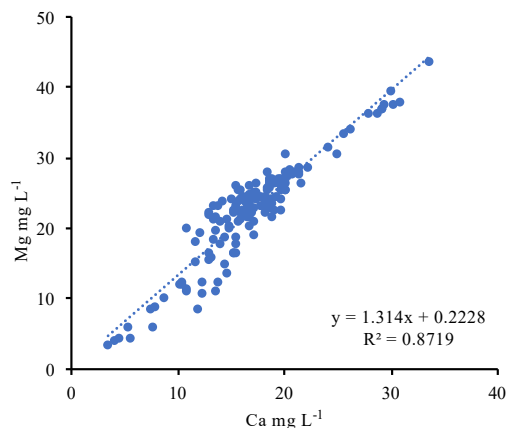


Figure 5. The correlation between Ca and Mg concentrations in surface runoff from the Hvanneyri fields in May 2001 to June 2002.

which were only 86 kg ha⁻¹ (Table 4). When the runoff data for Na, Ca and Mg is analysed, their concentrations are shown to be highly correlated ($P < 0.001$) as shown in Figure 5. All these three elements drop in concentration with increasing runoff volume ($P < 0.001$) which can be seen as dilution effect at high rainfall. Variations in K concentration were subjected to a different pattern. It increased simultaneously to N and P in the effluent water. The relatively low potassium levels in the soils reflected the comparatively low potassium content of Iceland's basaltic bedrock (Björnsson 2001), although varying (0.05-4.0% K by weight), depending on the petrology and geochemistry of the basalt (Heier et al. 1966, Sigmarsson & Steinthórsson 2007). The AL- and HNO₃-soluble K was 140 to 360 and 290 to 510 kg ha⁻¹, respectively, in the top 10 cm of the soil (Table 6). Considering that K application by fertilizers is in the range of 70 kg ha⁻¹ and around the same amount is removed with the hay, the loss of 17 kg K ha⁻¹ annually with the effluent water, which equals 25% of the applied K, indicates opportunity for improved K management.

There are indications that Mg as a plant nutrient has been underestimated in the past (Gransee & Führs 2013). In an extensive review, Metson (1974) reported up to 50-fold difference in Mg leaching losses in trials (2–100 kg ha⁻¹ yr⁻¹)

Table 5. pH, loss on ignition (LOI) and bulk density (BD) in the top 10 cm of the soil in selected fields of the catchment area.

Field no.	pH	LOI %	BD g cm ⁻³
61	4.8	60	0.35
60	6.0	43	0.43
57	5.1	53	0.39
31	5.5	62	0.39

Table 6. Ammonium lactate (AL) (Egner et al. 1960) and nitric acid (HNO₃) (ISO standards 2013) extractable nutrients in soil in selected fields of the catchment area in the top 10 cm of the soil.

Field no.	Ca	Mg	K	Na	P					
						AL extraction (kg ha ⁻¹)				
61	880	280	150	150	55					
60	5300	390	150	160	48					
57	900	390	140	120	47					
31	560	680	360	570	20					
						HNO ₃ extraction (kg ha ⁻¹)				
61	6000	2300	290	1000	370					
60	15000	5000	350	1800	490					
57	9800	4800	380	1600	560					
31	12400	2800	510	870	770					

depending on soil type, levels of exchangeable Mg in soil, drainage condition and fertilizer additions. An antagonistic relationship between K application and Mg uptake in plants is known (Jakobsen 1993). Further, there seems to be a relationship between K-additions in fertilizer and Mg losses by leaching, where increased K or Ca application increases Mg leaching losses (Metson 1974, Mikkelsen 2010). These findings may explain the relatively high losses of Mg and Ca in this study (105 and 86 kg ha⁻¹, respectively; Table 4). Icelandic hayfields may contain high levels of exchangeable K in the top few cm of the soils (Guðmundsson 2018) and in this study fertilizer and manure supplied significant amounts of K to the soil. Further, it is known that available Mg in younger, less developed soils of basaltic parent material, a condition that many Icelandic soils meet, will partly depend on the acidity of the reagent used (Metson 1974).

The amounts of Mg extracted are also affected by the acidity of the soils themselves and levels of available Mg, where low pH yields high Mg. Thus AL extraction may overestimate available Mg and lack correlation with other extraction methods, especially in the top 10 cm soil (Järvan et al. 2017, Staugaitis & Rutkauskienė 2010). It would be interesting to study further the varying amounts of available Mg and Ca, which ranged 4-fold for AL extractable Mg (280-680 kg ha⁻¹) and 11-fold for the quantity of Ca (560-5,300 kg ha⁻¹, Table 6) despite similar soil properties (Table 5).

The lack of correlation between runoff volumes and lost K, S, organic N and P in this study may have different explanations. The high solubility of K in soil, especially manure K, increases risk of losses where the available pool of K is exhausted in initial rainfall without a steady supply of K for subsequent losses (Alfaro et al. 2006, Haynes & Williams 1993, Kayser & Isselstein 2005). The availability of S, organic N, and P is to a larger extent dependent on mineralization of organic matter than K and therefore less directly a function of precipitation and runoff volumes (Bittman et al. 2007, Haynes & Williams 1993). Hence, as previously mentioned, seasonal variations in temperatures and precipitation will influence the risk of nutrient losses. Plants assimilate sulphur in the form of sulphate that is very mobile in the soil (Mengel & Kirkby 2001), which explains current data on sulphur in this study.

All measured constituents in the effluent water from the Hvanneyri fields gave a grand sum of 400 kg ha⁻¹ yr⁻¹. This is within the range that can be expected to be runoff under a variety of Icelandic conditions, which is according to Gíslason & Arnórsson (1988, 190-1460 kg ha⁻¹) from unmanaged catchments. Their findings suggest that average weathering in Iceland releases about 1 tonne ha⁻¹ yr⁻¹. Here it should be kept in mind that Si, Al and Fe were not included in the present study, but they, especially Si, have a considerable share in total chemical weathering in Iceland.

Possible sources of errors in the present data were evaluated in the runoff volume

measurements. Considerable efforts were made in calibrating the pressure gauge in the weir. Some uncertainty was suspected for high flow rates. A closer look at the precipitation data indicates that in the present study 83% of the annual precipitation was delivered to the weir at the water outflow from area. That was a slightly higher runoff ratio than was found by Sigurdsson et al. (2004) in southern Iceland.

As groundwater flows and levels were not monitored in this study, we lack data on the actual path of the water from the precipitation at soil surface to the ditches. Which part of the soil was actually affecting runoff water chemistry must, among other things, depend on variation in precipitation, temperature, and winter soil ice thickness in and on the soil. Interaction of precipitation and wind velocity have mechanical effects on the soil surface. Winter storms with heavy rain were showed to be the events of highest chemical runoff. The effects of other aspects such as interaction between soil and effluent water chemical composition are not so clear.

Although negative effects to ecosystems were unlikely from the relatively low nutrient losses in this study, no actual assessment was made of adjacent ecosystem condition, as it was considered outside of the study scope.

Considering the rapid mineralization of the relatively young igneous rocks prevalent in Iceland (Gíslason 2008, Gíslason et al. 1996), it is plausible that climate change induced rising temperatures and precipitation levels will increase background mineral concentration in streams and stimulate production of primary aquatic producers. Research in agriculture has shown that higher temperatures, and in particular precipitation levels, correlate strongly with increased nitrate losses (Jabloun et al. 2015). Phosphorus has historically been applied in agronomic excess in Icelandic agriculture and, as is the case for the study area, frequently accumulates in the soil surface (Björnsson 2001) where it is biologically and chemically retained (Table 6). While low amounts of P were lost in this study, there were large quantities of loosely bound P in the soils that could become

mobile through increased rain events and mineralization of organic matter associated with rising temperatures. Although eutrophication is a complex process (Glibert 2017), temperature is the most limiting factor for biological activity in Iceland (Björnsson et al. 2018). A study of SW-Icelandic streams showed that controlled fertilization caused increased primary producer activity that was closely connected with water temperature and was expected to intensify with the effects of climate change (Gudmundsdottir et al. 2011). Icelandic river catchment areas seem to act as N sinks and display increasing negative fluxes (net consumption) of NO_3 and NH_4 with increasing P concentration (Table 6, Fig. 1, Gislason et al. 1996). Further research suggests that P, as dissolved inorganic phosphorus (DIP), is limiting in vegetated areas of Iceland, while dissolved inorganic nitrogen (DIN) is likely limiting in less vegetated, volcanic areas of Iceland (Oskarsdottir et al. 2011). This would suggest that P, along with N, is a limiting factor in cultivated areas of Iceland and that increased P losses in those areas could contribute to ecological changes or deterioration of water quality. Global estimations for N and P cycles support this conclusion, although N is estimated to be more limiting for terrestrial ecosystems at higher latitudes (Wang et al. 2010).

Our results thus show the need for a more detailed study of chemical runoff, from other homogeneous areas, with a detailed track of land use and with different soil types.

We only have one year of monitoring discharge and chemical analysis of the discharge water. This is certainly a limitation and we would like to stress the necessity to continue or repeat the measurements in order to get more reliable results and also that the nutrient discharge may change in quantity and quality if management practices change with milder climate and increasing cereal production.

CONCLUSIONS

About 83% of the precipitation was accounted for in the discharge of the area which allows us to conclude that we have representative values for the catchment area. The discharge

of the main nutrients (N, P and K) which are applied as fertilizers were relatively low and do not constitute serious losses of nutrients from the fields. The low nitrate concentration in the discharge water and in particular the very low P content allow us to conclude that eutrophication due to the discharge from the fertilized grassland of the catchment area is unlikely or at least not a major problem.

The year-long study thoroughly characterized water runoff volumes and range of nutrient contents from a catchment area consisting of fields under farming regimes typical of the animal-based agriculture in Iceland. Losses of macronutrients amounted to about 11% of applied N, 17% of applied K, and negligible losses of P from the catchment area.

Although runoff and leaching losses were relatively low, the estimated soil nutrient pools in the main rooting zone were large, and up to 5-10 times annual nutrient uptake of grasses is loosely bound or subject to soil biological mineralization. With rising temperatures in Iceland and the expected increase in extreme weather events, the risk of nutrient losses increases. Needed research includes improved understanding of soil properties such as infiltration capacity and groundwater flows throughout the year, under different management and cropping cycles.

ACKNOWLEDGEMENTS

Icelandic Agricultural Productivity fund for financial support. Iceland Geosurvey for operating runoff volume measurements (Páll Jónsson, Gunnar Sigurðsson). Iceland Meteorological office for providing meteorological data (Hreinn Hjartarson, Trausti Jónsson). Chemical Analysis Lab of Innovation Centre Iceland for chemical analyses (Baldur Vigfússon). Efnagreining ehf - Chemical analysis lab at Hvanneyri (Elísabet Axelsdóttir). Staff of Agricultural University of Iceland Laboratory and farm management Hvanneyri (Jófríður Leifsdóttir, Guðmundur Hallgrímsson).

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Manuscript received 15 May 2019

Accepted 16 October 2019