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# River Shin sediment source tracing

## Kyle of Sutherland Fisheries Trust

## P00002604

## September 2020

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## Revision and Amendment Register

| Version Number | Date | Section(s) | Page(s) | Summary of Changes | Approved by |
|---|---|---|---|---|---|
| 1.0 | 29/09/2020 | 4 | 13 | Draft issue for client approval | DEC |
| 2.0 | 23/11/2020 | 4 | 13 | Final incorporating client comments | DEC |

## Executive Summary

Excess fine sediment in river channel beds has a negative impact on salmonid habitat and it is, therefore, necessary to determine the provenance of fine sediment to enable targeted mitigation at source.

Sediment source tracing was undertaken in the River Shin using channel bed sediment and surface material from potential terrestrial sources, sampled in September 2019. A sediment fingerprinting approach was applied whereby samples were first characterised for their geochemistry using X-ray fluorescence spectrometry with subsequent geochemical fingerprints selected following standardised range testing and Principal Component Analysis procedures. A Bayesian mixing model (MixSIAR) was applied to determine the key subcatchments and land cover type acting as sources of fine sediment to the lower River Shin.

The upper River Shin and Allt Tomich subcatchment were found to be the main contributors of fine sediment to the lower River Shin receptor site, with coniferous forest the dominant land cover source. Fine sediment risk mapping suggested that high risk areas were associated with forestry upstream of the upper River Shin sampling site. Such sediment inputs appear most likely to arise from episodes of forest establishment and harvesting, which are widely attributed to causing pulse inputs of elevated fine sediment loads.

Fine sediment inputs from forestry upstream of the upper River Shin sampling site are likely to feed into Loch Shin above the dam. Consideration should, therefore, be given to the potential for sediment transmission at the dam and to the capability of flow releases to mobilise sediment in Loch Shin and compensation to the downstream river reaches. Further study during the winter period would offer additional information with regard to seasonality and monitoring of turbidity and flow relationships across the loch – river interface would offer further clarity with regard to sediment mobilisation from the loch. Sediment dating of loch cores would also provide useful insight into historical sedimentation rates in relation to known land-use activities.

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# 1. Introduction

## 1.1. Project Background

Successful spawning and recruitment of salmonid fish, including Atlantic salmon (S*almo salar*) and brown and sea trout (*Salmo trutta*), depends upon access to sediment that has an open, well-oxygenated structure, enabling clear exchange of oxygen and nutrients between the interstices and the overlying water column and removal of waste products. It is widely accepted that excess fine sediment (silt and clay fractions <63 µm) negatively impacts upon salmonid spawning habitat by embedding in coarser material and preventing exchange between interstices and surface (Geist and Auerswald, 2007).

In recent years, increased fine sediment loading in river systems has become more common and is linked to impacts upon salmonid recruitment, as well as more widespread effects on river biota. Whilst most obvious in intensively managed lowland catchments, impacts of excessive fine sediment deposition is not restricted to such environments and in upland catchments is often linked to high erosion risk landuse and to changes to river flow regimes.

Identifying sources of fine sediment to salmonid spawning habitats is crucial to targeting appropriate mitigation. This report describes the use of sediment fingerprinting and a mixing model approach to identify key subcatchments and land cover types contributing fine sediment to the lower River Shin in Sutherland, Scotland. The River Shin is an important salmon and trout fishery and fine sediment is considered to have potential impacts on the productivity on the river.

## 1.2. Site Description

The River Shin in Sutherland is a relativity short river reach of around 11 km, characterised by steep descents from Loch Shin, down to the lower reaches (Figure 2-1). The flow regime in the River Shin is heavily modified owing to Lairg Dam which was erected at the outlet of Loch Shin in the 1950s as part of the Shin hydropower scheme. A smaller dam a short distance downstream of Lairg Dam impounds Little Loch Shin and is used to divert water to another hydropower station at Inveran. Mean flow at Inveran between 1981 and 2011 was approximately 5 $m^3/s$ (NRFA, 2020).

The catchment area is around 575 $km^2$ with underlying geology primarily of psammite and micaceous psammite overlain by deposits of diamicton and peat. Land cover is characterised by areas of open moorland and rough pasture with coniferous forest plantations also a significant feature of the landscape. Under the Water Framework Directive, overall status of surface waters upstream of Loch Shin is generally poor, largely owing to biological elements and barriers to fish passage, while downstream waterbodies are maintaining good overall status.

# 2. Methodology

## 2.1. Field Sampling & Laboratory Analysis

Channel bed sampling was undertaken in September 2019, located at the outlets of key subcatchments and along the main channel. At each location, channel bed sediment was sampled from the upper 5 cm of the gravel bed following the stilling well approach of Lambert and Walling (1988). Samples were taken in triplicate at each site to account for spatial variability across the channel bed, with a total of 10 L (4 x 2.5 L samples) taken for each replicate. Bulk samples were allowed to settle for a minimum of 48 hours to enable overlying water to be decanted. Sediment was separated from the remaining sample by centrifugation, with the sediment then freeze dried prior to sieving to <63 μm.

Land cover source samples were taken from representative areas across the catchment and were grouped according to land cover type (coniferous forest; pasture; peat bog; moorland and heathland) (Figure 2-1). These samples were air dried at 40 °C prior to sieving to <63 μm.

Dried samples were analysed in triplicate for major and trace elemental concentrations using an XL3t 950 He GOLDD+ X-ray fluorescence instrument (Thermo Fisher Scientific Niton, UK). Instrument drift was monitored following laboratory quality control procedures with measurements validated using a suitable certified reference material (GBW07318).

In addition to measurement of elemental concentrations, estimates of fine sediment storage, S (g/m$^2$), in the channel bed were derived using:

$$S = \frac{C_s \times W_v}{A}$$

Where the sediment concentration in the water samples, $C_s$ (g/L), is considered in relation to the volume of water in the cylinder, $W_v$ (L), and the sampled channel bed area, A (m$^2$).

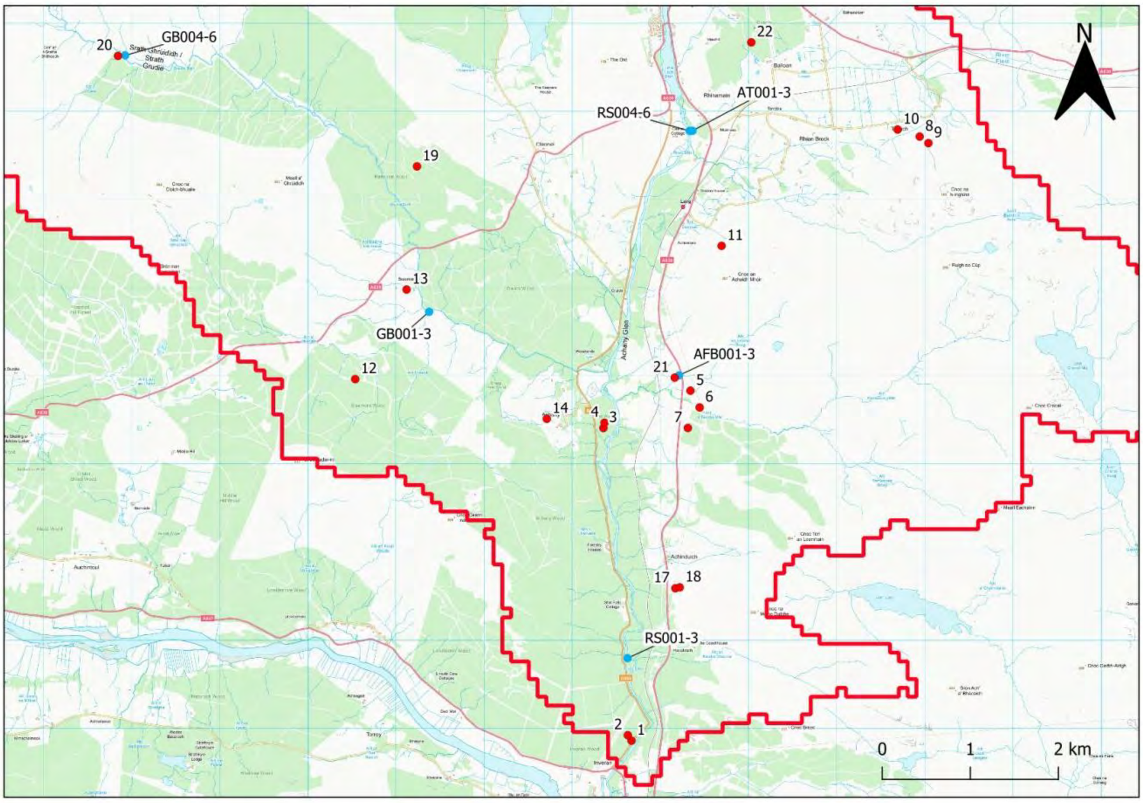


**Figure 2-1** Sampling locations in the River Shin catchment.
Blue markers indicate channel bed sampling sites and red markers show the location of source material sampling.

## 2.2. MixSIAR Modelling

Sediment source apportionment was derived using a Bayesian mixing model approach detailed by Blake *et al*. (2018). Within this approach, the geochemical profile associated with the downstream channel bed sediment 'mixture' is compared to the fingerprints of potential sources, with the downstream profile then 'unmixed' against the upstream fingerprints to determine the relative contributions from all sources. The downstream mixture at the receptor site of interest can conceivably receive sediment material direct from terrestrial runoff and from channel bed sediment stored upstream.

Here, the downstream receptor site of interest was the lower River Shin (RS001-3 in Figure 2-1). The MixSIAR model was applied using two separate approaches:

- Model 1: The contribution of channel bed sediment upstream of the lower River Shin receptor site was modelled using samples from subcatchment outlets and the upper River Shin as sources.

- Model 2: Discrete source samples from across the catchment were pooled according to land cover group, and contributions from each group to the downstream receptor were modelled.

Prior to running the model, data were scrutinised to compare the element concentration ranges in the (upstream) sources relative to the downstream channel bed mixture, with elements falling outside of the mixture range excluded from the model dataset. Range testing of this manner highlights potential non-conservative tracer behaviour or contributions from sources, which have not been sampled. Principal component analyses (PCA) undertaken both before and after element exclusion were used to assess clustering of source types and potential for discrimination.

# 3. Results

## 3.1. Model 1

PCA following element exclusion for Model 1 is shown in Figure 3-1. The PCA depicts generally good clustering between the source groups with the MixSIAR model output showing Allt Tomich and the upper River Shin as the dominant sources to the lower River Shin, with mean contributions of 25 % and 62 % respectively (Table 3-1). Boxplots and concentrations for the elements used in the model are provided in the appendices.

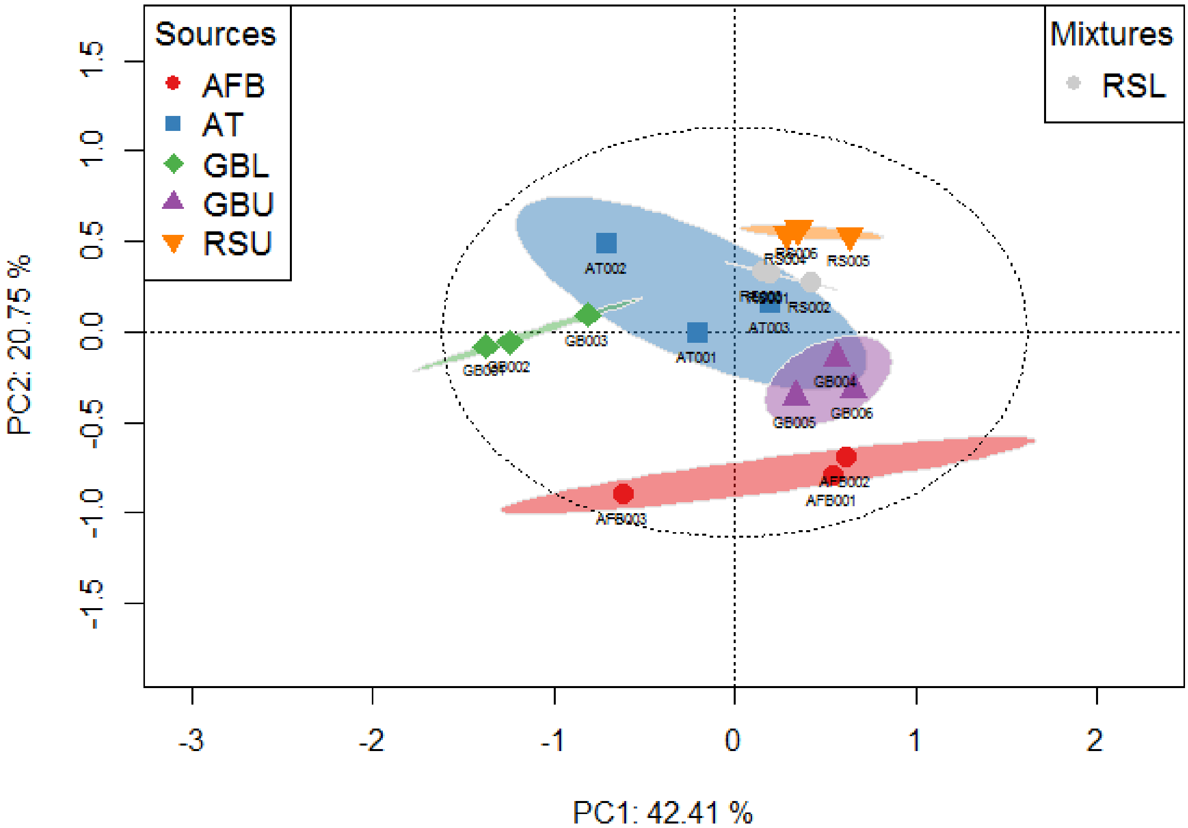


**Figure 3-1** Principal Component Analysis (PCA) for Model 1 following element exclusion. Sources are grouped according to Allt na Fearna Beag (AF); Allt Tomich (AT); Grudie Burn lower (GBL); Grudie Burn upper (GBU); the upper River Shin (RSU). The receptor is the lower River Shin (RSL).

**Table 3-1** Mean modelled sediment contribution to the lower River Shin (RSL).

| Sample site | Mean (%) |
|---|---|
| AFB | **3** (5) |
| AT | **25** (9) |
| GBL | **3** (4) |
| GBU | **7** (8) |
| RSU | **62** (9) |

Sources are grouped according to Allt na Fearna Beag (AF); Allt Tomich (AT); Grudie Burn lower (GBL); Grudie Burn upper (GBU); the upper River Shin (RSU). Uncertainty (in parentheses) presents one standard deviation of the mean (most likely) model output where a smaller relative uncertainty indicates greater confidence in model output.

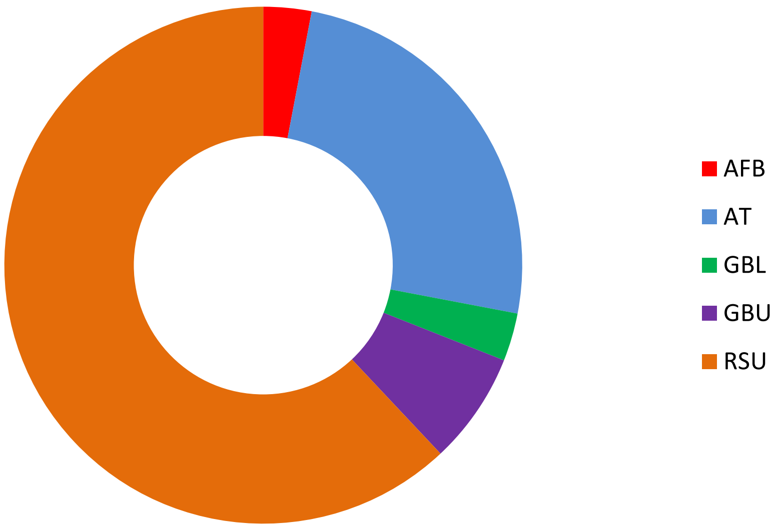


**Figure 3-2** Proportional representation of sediment contributions to the lower River Shin. Allt na Fearna Beag (AF); Allt Tomich (AT); Grudie Burn lower (GBL); Grudie Burn upper (GBU); the upper River Shin (RSU).

## 3.2. Model 2

PCA and results for model 2 are provided in Figure 3-3 and Table 3-2. Modelled contributions were largely associated with coniferous forest at 81 %. Boxplots and concentrations for the elements used in the model are provided in the appendices.

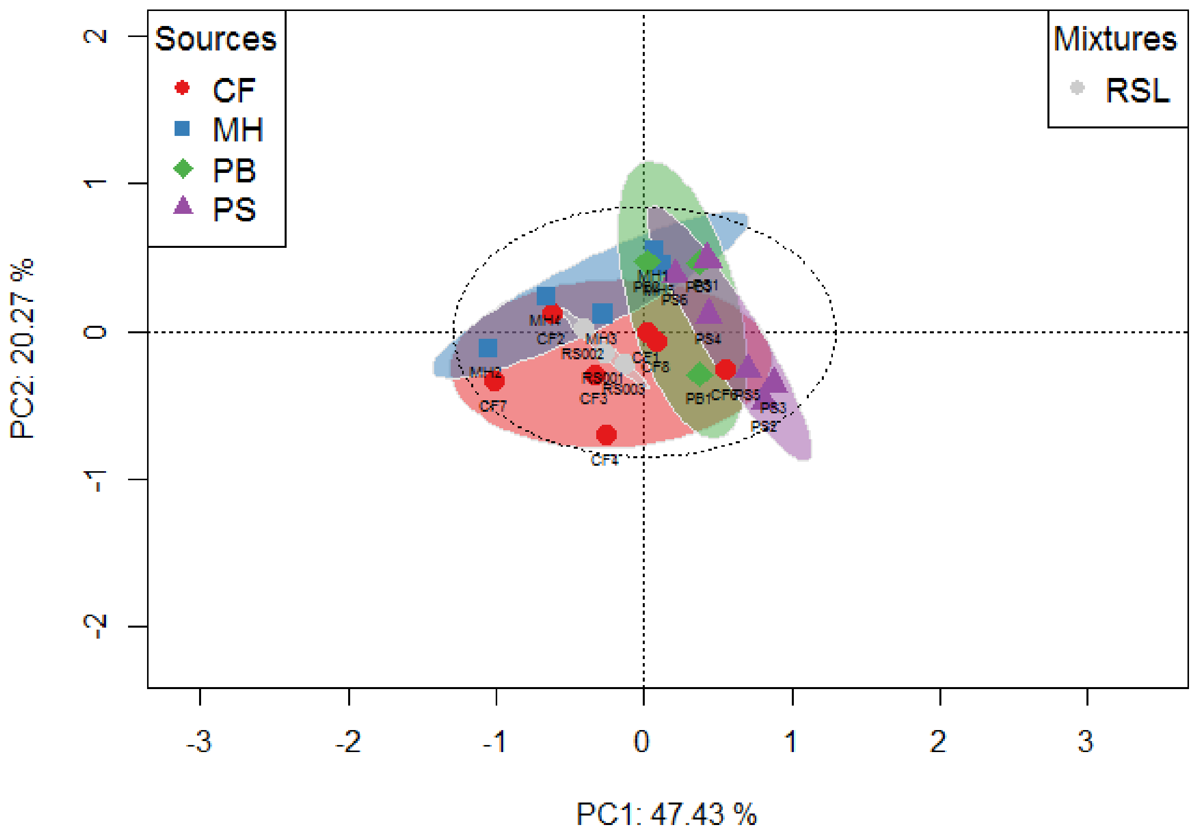


**Figure 3-3** Principal Component Analysis (PCA) for Model 2 following element exclusion. Sources grouped according to coniferous forest (CF); pasture (PS); Moors & heath (MH); peat bog (PB). The downstream receptor if the lower River Shin (RSL).

**Table 3-2** mean modelled source contribution to the lower River Shin.

| Sample site | Mean (%) |
|---|---|
| CF | **81** (25) |
| MH | **8** (17) |
| PB | **8** (17) |
| PS | **3** (8) |

Sources are grouped according to coniferous forest (CF); pasture (PS); Moors & heath (MH); peat bog (PB). Uncertainty (in parentheses) presents one standard deviation of the mean (most likely) model output where a smaller relative uncertainty indicates greater confidence in model output.

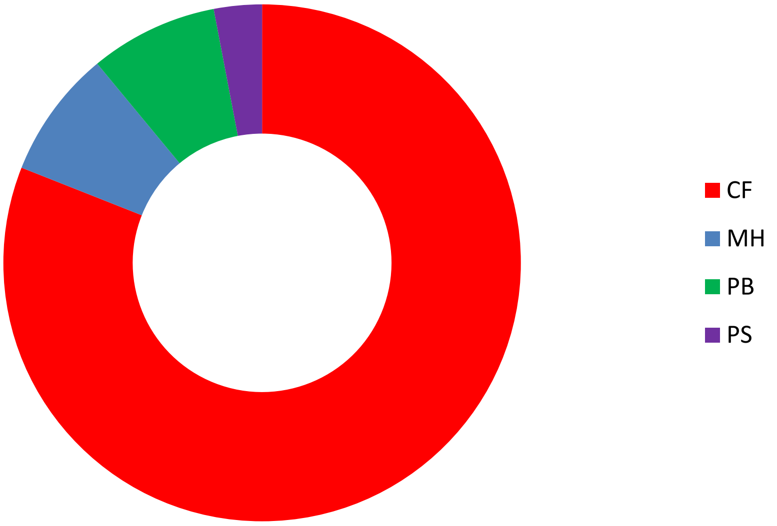


**Figure 3-4** Proportional representation of sediment contributions to the lower River Shin. Sources are grouped according to coniferous forest (CF); pasture (PS); Moors & heath (MH); peat bog (PB).

## 3.3. Channel Fine Sediment Storage Mass

Estimates of the mass of fine sediment stored in the river channel are shown in Table 3-3, with the upper River Shin and Allt Tomich displaying the greatest storage mass compared with other sources upstream of the lower River Shin.

**Table 3-3** Mean mass of fines (<63 µm) stored in the channel bed by sampling location.

| | Sample Code | | | | | |
|---|---|---|---|---|---|---|
| | RSU | AT | GBU | GBL | AFB | RSL |
| Mean g/m$^2$ | 75 | 78 | 4 | 7 | 9 | 108 |
| SD g/m$^2$ | 37 | 49 | 2 | 3 | 8 | 31 |

Data are ordered upstream to downstream (left to right). The upper River Shin (RSU); Allt Tomich (AT); Grudie Burn upper (GBU); Grudie Burn lower (GBL); Allt na Fearna Beag (AF); lower River Shin (RSL).

# 4. Discussion

The two key source subcatchments identified were the upper River Shin (RSU) and Allt Tomich (AT) with 62 % and 25 % mean contributions to the lower River Shin (RSL) respectively (Table 3-1). The upper River Shin and Allt Tomich also had the highest mass of stored fine sediment in comparison to the other subcatchment sample areas. At all sites, however, calculated mass storage is low compared with other UK rivers where values exceeding 9,000 g/m$^2$ have been reported (e.g. Walling *et al*.,1998; Owens *et al*.,1999; Wilson *et al*., 2004; APEM 2015), although Walling *et al*. (1998) and Owens *et al*. (1999) report storage for a slightly broader range of grain sizes (<0.15 mm).

For comparison, in-channel sediment risk was mapped using SCIMAP, which considers sediment risk to be a function of rainfall, topography, landcover type and hydrological connectivity. Using the default landcover risk weightings, the Allt Tomich subcatchment shows elevated risk (yellow-red shading). Areas of higher in-channel risk associated with the upper River Shin appear to be less extensive and mainly to the northeast of the sampling location, encompassing pasture, open moorland and coniferous forest (Figure 4-1).

Model 2 assessed the contribution of sediment from pooled landcover groups to the lower River Shin, with the output clearly identifying coniferous forest as the key source type with a mean contribution of 81 % (Table 3-2). This finding is apparently at odds with the SCIMAP default risk weightings for landcover type which set coniferous forest risk at the lowest level (a risk value of 0.05). However, bed sediment composition reflects the relative contributions of sources over time, and the effect of coniferous plantation forest on erosion and sediment yields in the UK uplands varies with the forest establishment, mature forest and timber harvesting phases of the forest cycle (Stott and Mount, 2004). Mean sediment yields are high at the initial ground disturbance phase, reduce as the forest matures and increase again more significantly at the timber harvesting phase, with the first and last phases creating pulses or waves of downstream fine sediment transport. It was, therefore, pertinent to examine the potential risk derived from coniferous forest in the two key sub-catchments highlighted by the Model 1 output.

To assess the potential future risk associated with the current distribution of coniferous forest in this catchment during higher sediment-export phases of the forestry cycle, a second map was therefore derived using a higher risk weighting for coniferous forest (Figure 4-2) whereby the default value was increased by a factor of 10 to 0.5. This adjusted value remains at half the default value for the highest risk landcover type (arable) but higher than the default value for rough pasture (0.15). Although the adjusted value is arbitrary, it nevertheless highlights areas with potential for greater risks associated with coniferous forest. The adjusted map shown in Figure 4-2 shows reduced risk associated with Allt Tomich, and increased risk for the subcatchment upstream of the upper River Shin sampling site, with notably high risk of channels flowing into the western areas of Loch Shin. It is evident from aerial imagery that felling has occurred in recent years in the catchment of the River Tirry on the eastern shore of Loch Shin (not included in the SCIMAP modelling extent), and at Sallachy on the Loch's western shore. These represent possible sources of fine sediment to the upper River Shin and, subsequently, to the lower reaches of the river.

For timber harvesting or forest establishment to affect sedimentation in the lower River Shin, there is also a key question regarding the connectivity between the lower river and the sampling location in the upper River Shin, given that these channels ultimately flow into Little Loch Shin where any fine sediment would be expected to settle due to the impounding effect of the dam. The results reported here suggest that there is potential for connectivity between the upper River Shin and the loch, either due to fine sediment contributions to the loch remaining in suspension, rather than settling out into lake sediments, or due to their settling and subsequent remobilisation. Alternatively, this might plausibly be an artefact of sediment inputs prior to the construction of the hydropower dam in the late 1950s. Thus, current degrees of and mechanisms for sediment connectivity has not been established and detailing the processes controlling the transfer of fine sediment across the loch – channel interface is outside of the scope of this report.

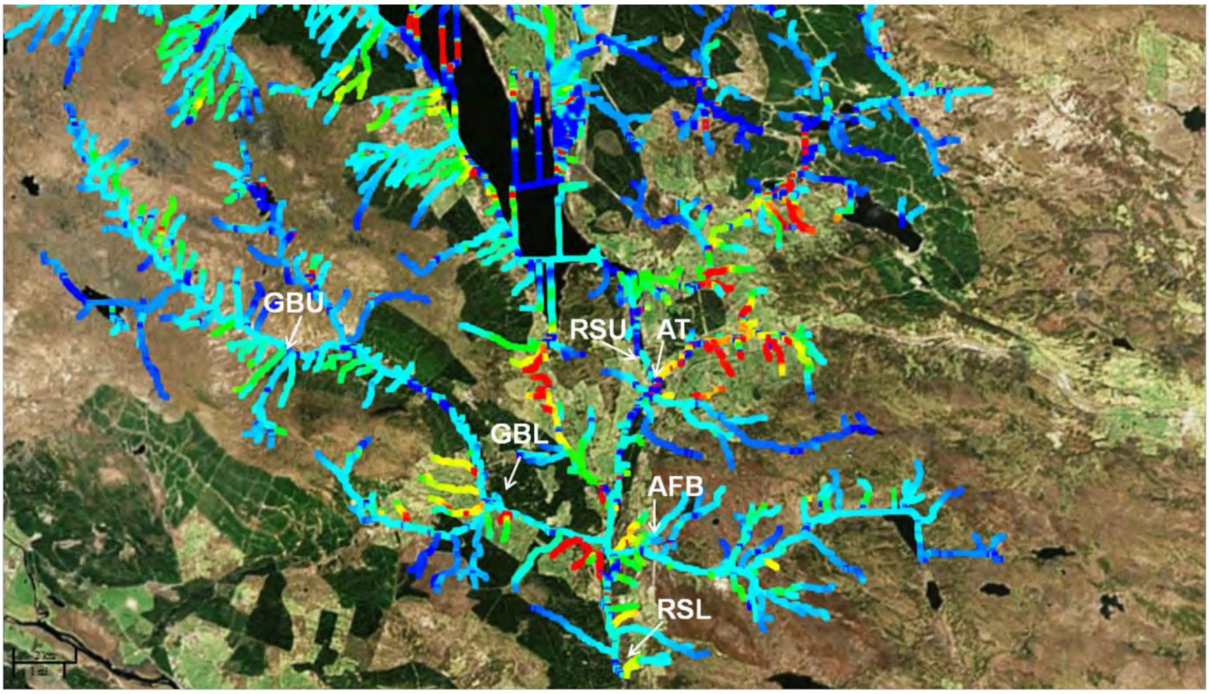


**Figure 4-1** SCIMAP output of in-channel sediment risk for the catchment area of interest.
Areas of low, moderate and high risk are highlighted in blue, green and red respectively. The risk shown here was derived using SCIMAP default landcover risk weightings.

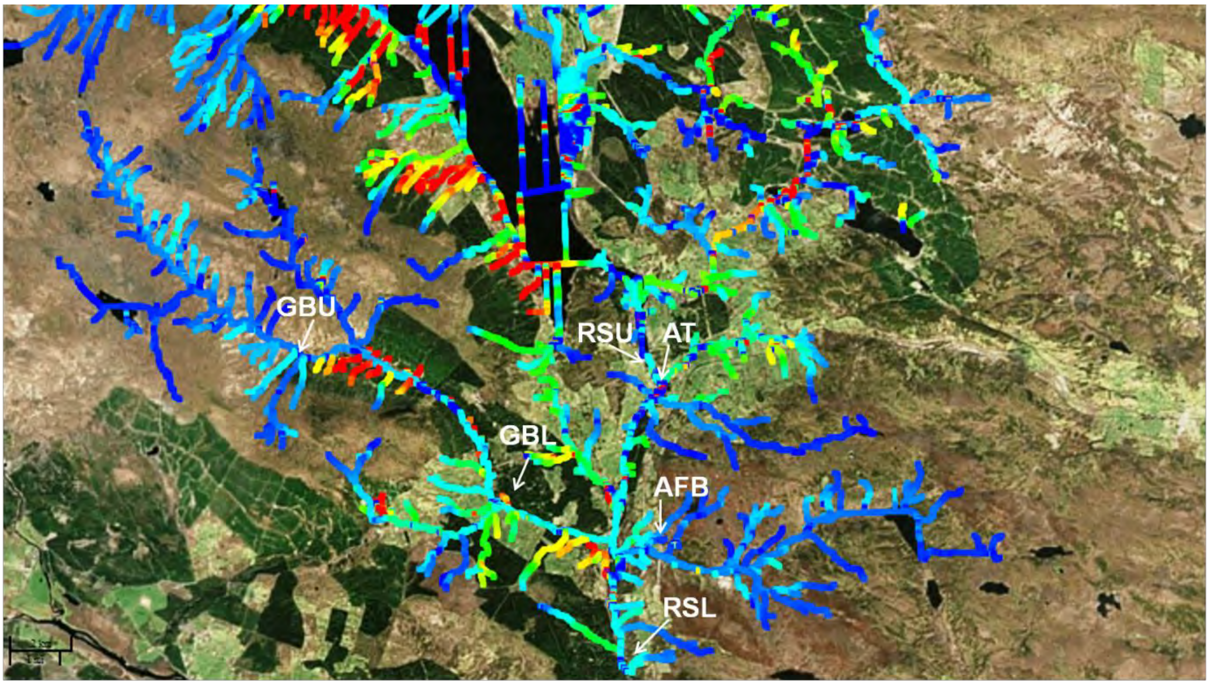


**Figure 4-2** SCIMAP output of in-channel sediment risk for the catchment area of interest. Areas of low, moderate and high risk are highlighted in blue, green and red respectively. The risk shown here was derived using an increased risk weighting for coniferous forest.

# 5. Conclusions and recommendations

## 5.1. Conclusions

Unmixing fine sediment fingerprints suggests the upper River Shin and Allt Tomich in the upper catchment are dominant sediment contributors to the downstream receptor in the lower River Shin with mean contributions of 62 % and 25 % respectively. Estimates of the mass of fine sediment stored in the channel bed were also highest for Allt Tomich and the upper River Shin.

Coniferous forest was shown to be the dominant land cover source delivering sediment to the lower River Shin. This may not be a continuous input and may not relate to current forestry activities but rather relate to elevated inputs during forest establishment and harvest.

High risk areas associated with coniferous plantations appear to be concentrated in the upper catchment, with transfer to Loch Shin above the dam. Results therefore suggest the potential for sediment derived from coniferous plantations to be mobilised and transferred from Loch Shin to the river channel during dam releases, although the degree of and mechanisms for such connectivity with the presence of the dam has not been demonstrated.

## 5.2. Recommendations

Mitigation should be targeted at reducing sediment inputs to the upper River Shin and Allt Tomich, with particular focus upon inputs from areas of forestry plantation during forest establishment and harvesting phases.

However, mitigation in the upper catchment may not be successful if connectivity of sediment transmission between the upper and lower catchment is impaired.

The following further work is therefore recommended:

- The potential connectivity of these source areas to the channel needs to be evaluated with local stakeholders to validate the above findings.

- Further supporting data would be required with regard to sediment – flow relationships from the loch, and the timing of any activities, such as dredging, which may serve to further mobilise fine sediment. Turbidity and flow monitoring at key sampling locations on a continuous basis across the seasons would help establish sediment – flow relationships and sediment loads, although such relationships are often imprecise.

- The application of sediment dating techniques (cf. Woodbridge et al., 2014) on sediment cores taken from Loch Shin would enable sedimentation rates to be estimated and provide clarity with regard to the relationship between sediment inputs and known forestry activities.

- Increases in the spatial resolution of sampling of landcover type would strengthen confidence in the assessment of landcover source contributions to the lower River Shin and enable unmixing of source contributions to be carried out on a subcatchment scale.

- Additional sampling after high flow events in the winter/spring period may provide further clarity with regard to seasonality.

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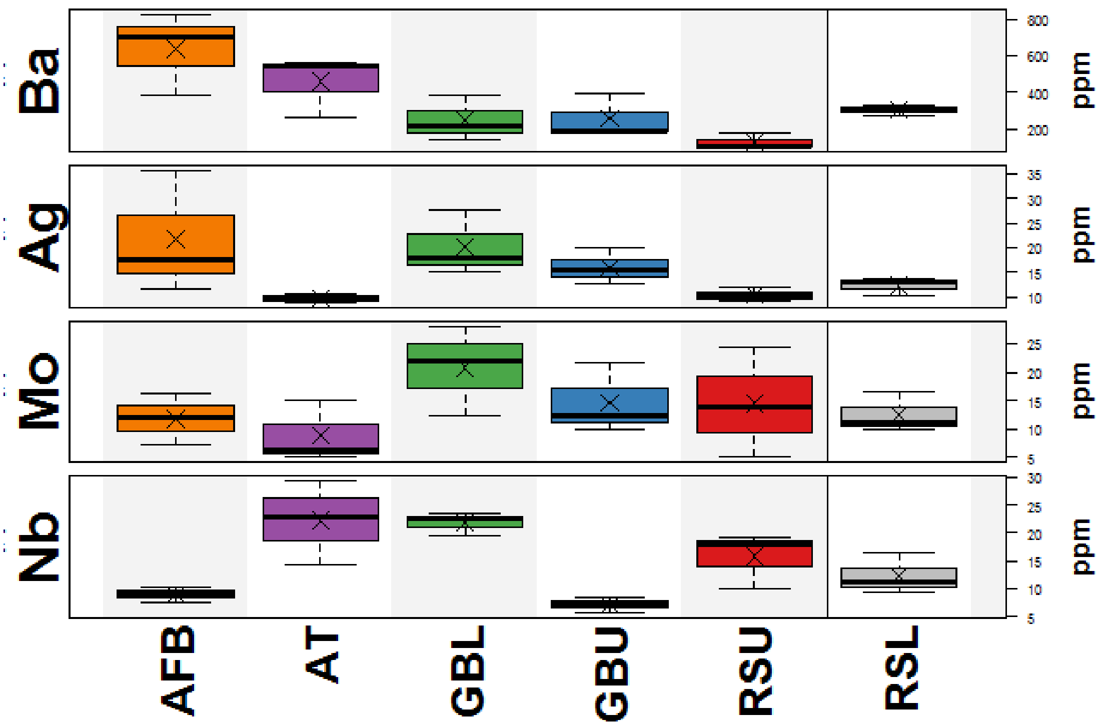
# Appendix A: Concentrations of elements selected for Model 1

| Sample | Type | Ba | Ag | Mo | Nb | Zr | Sr | Pb | Zn | Mn | Cr | V | Ti | Ca | K | Al | P | Si | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | mg/kg | | | | | | | | | |
| RSU | Mean | 125 | 10 | 14 | 16 | 116 | 144 | 45 | 248 | 27188 | 134 | 103 | 2781 | 7956 | 8407 | 7142 | 845 | 160023 | 1418 |
| | SD | 42 | 1 | 10 | 5 | 21 | 2 | 19 | 83 | 11262 | 25 | 49 | 616 | 1041 | 1157 | 1366 | 175 | 25789 | 249 |
| AT | Mean | 456 | 10 | 9 | 22 | 374 | 443 | 17 | 466 | 19860 | 183 | 215 | 4681 | 20603 | 12451 | 13783 | 1039 | 95369 | 1377 |
| | SD | 167 | 1 | 5 | 7 | 82 | 11 | 13 | 176 | 9730 | 71 | 121 | 1155 | 3955 | 2753 | 3489 | 277 | 10904 | 318 |
| GBU | Mean | 256 | 16 | 15 | 7 | 79 | 156 | 22 | 460 | 39754 | 251 | 157 | 1389 | 16831 | 6510 | 7158 | 198 | 48503 | 1825 |
| | SD | 119 | 4 | 6 | 1 | 82 | 31 | 9 | 196 | 1649 | 79 | 55 | 546 | 2751 | 1016 | 135 | 98 | 10403 | 442 |
| GBL | Mean | 247 | 20 | 21 | 22 | 230 | 332 | 70 | 890 | 43748 | 466 | 253 | 6490 | 31766 | 18499 | 24884 | 1394 | 115028 | 2140 |
| | SD | 125 | 7 | 8 | 2 | 51 | 7 | 29 | 67 | 12145 | 80 | 36 | 912 | 4905 | 4317 | 6453 | 156 | 16564 | 532 |
| AFB | Mean | 636 | 22 | 12 | 9 | 139 | 413 | 27 | 560 | 147396 | 290 | 102 | 2625 | 22797 | 7726 | 13193 | 289 | 56358 | 1780 |
| | SD | 225 | 12 | 5 | 1 | 72 | 88 | 9 | 288 | 44139 | 167 | 29 | 1733 | 9113 | 4873 | 8725 | 341 | 21416 | 676 |
| RSL | Mean | 304 | 12 | 13 | 12 | 216 | 219 | 49 | 384 | 16855 | 167 | 104 | 3228 | 10688 | 11359 | 8356 | 849 | 110825 | 1490 |
| | SD | 31 | 2 | 3 | 4 | 61 | 24 | 6 | 51 | 3600 | 25 | 16 | 529 | 1026 | 1769 | 1397 | 150 | 864 | 295 |

## Appendix B: Boxplots of elements selected for Model 1



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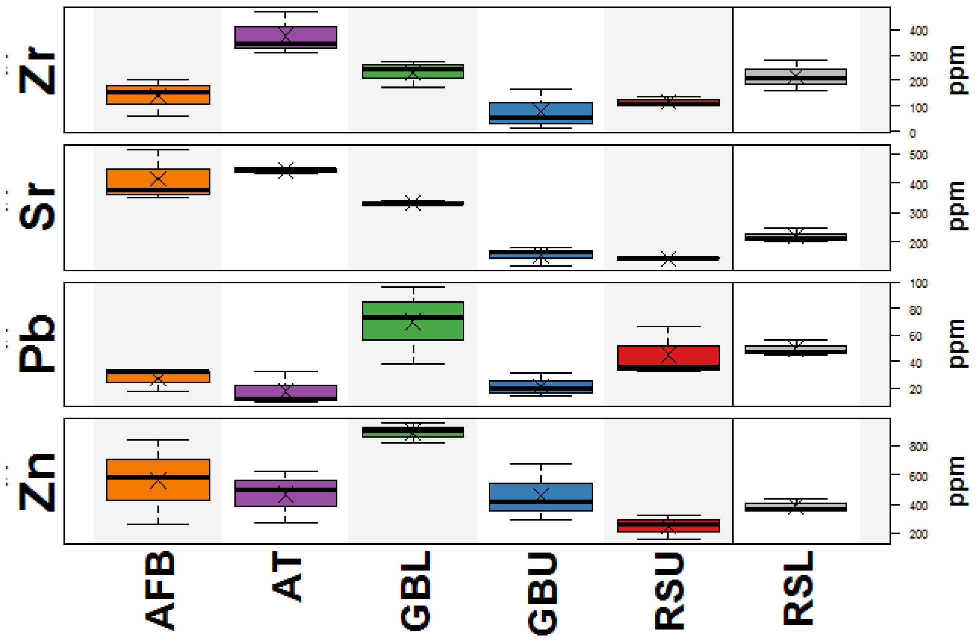
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RSU
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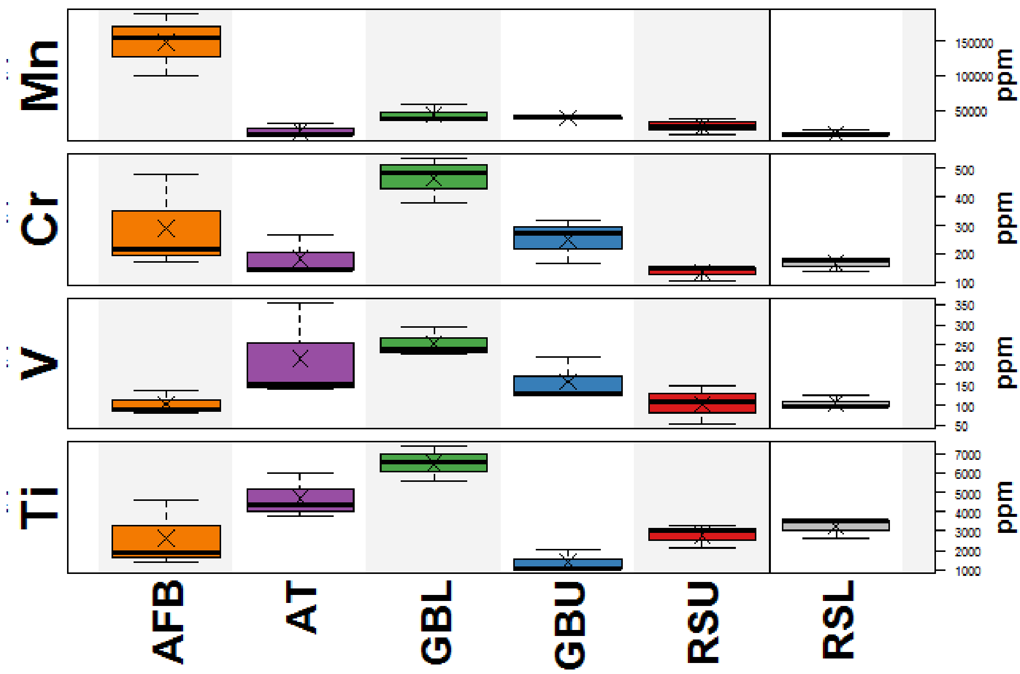
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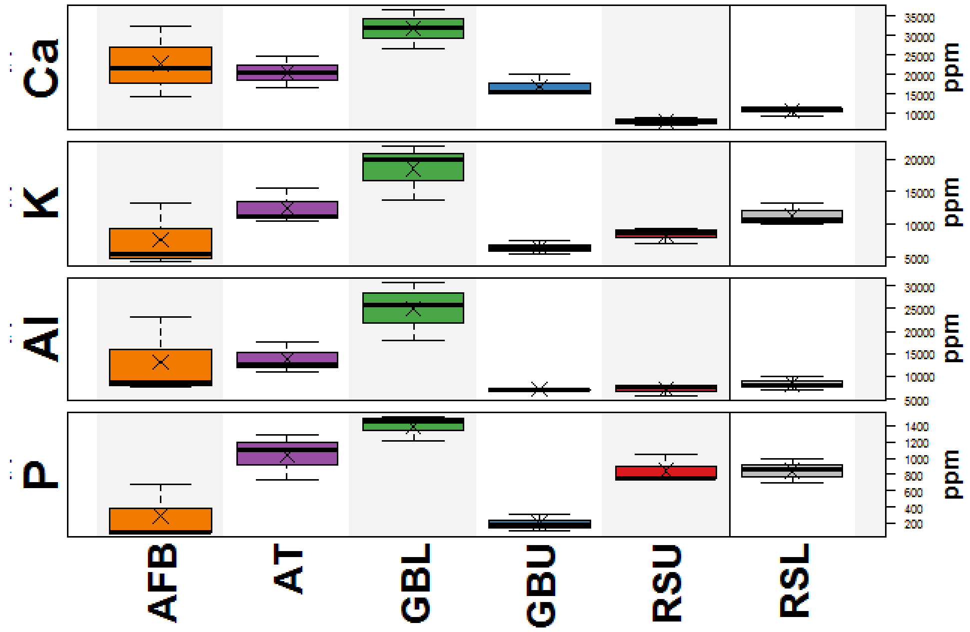
RSU
RSL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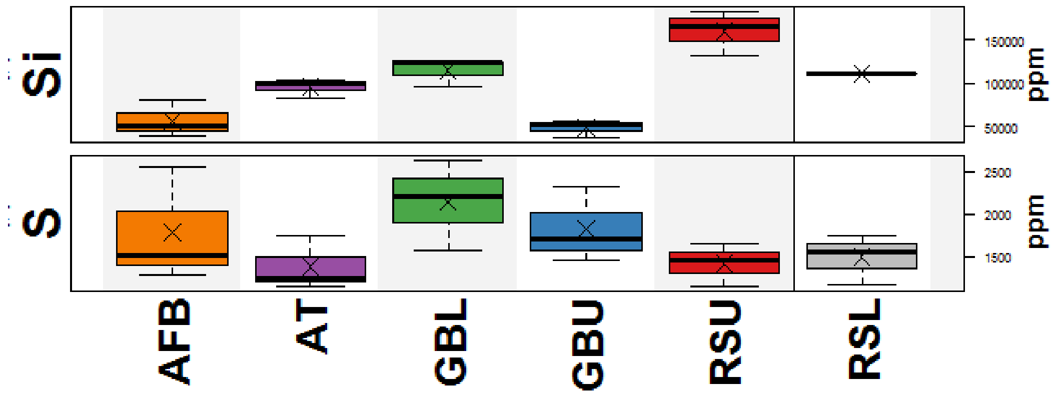
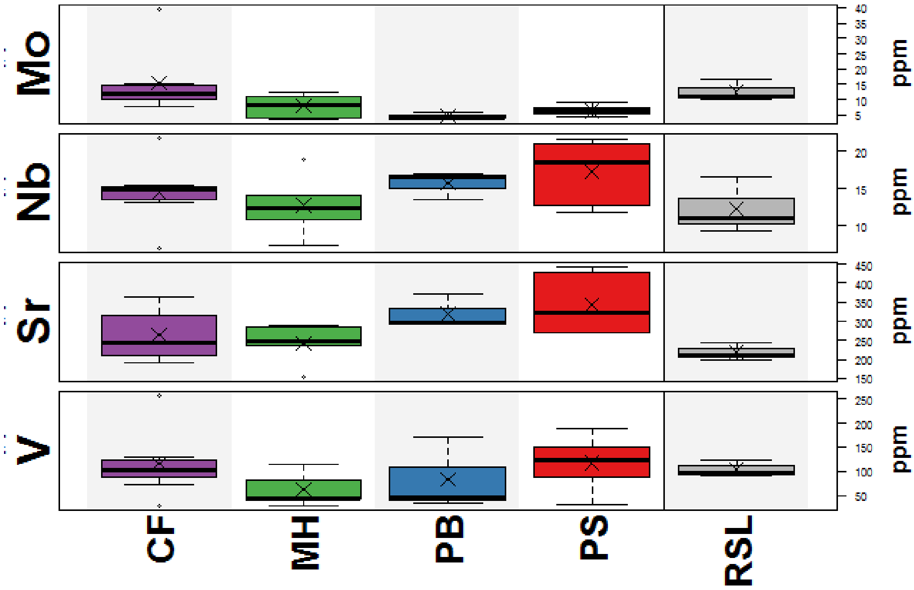

Si
S
ppm
150000
100000
50000
2500
2000
1500
AFB
AT
GBL
GBU
RSU
RSL

# Appendix C: Concentrations of elements selected for Model 2

| Sample | | Mo | Nb | Sr | V | Ca | P | Si | Cl |
|---|---|---|---|---|---|---|---|---|---|
| CF | Mean | 16 | 14 | 265 | 115 | 9539 | 1756 | 112630 | 331 |
| | SD | 11 | 4 | 72 | 70 | 2660 | 1436 | 27774 | 163 |
| PS | Mean | 6 | 17 | 343 | 117 | 12686 | 4678 | 151863 | 54 |
| | SD | 2 | 4 | 77 | 55 | 3393 | 674 | 23801 | 49 |
| MH | Mean | 8 | 13 | 243 | 63 | 6075 | 914 | 128938 | 258 |
| | SD | 4 | 4 | 54 | 35 | 1129 | 516 | 61416 | 274 |
| PB | Mean | 5 | 16 | 320 | 84 | 9642 | 2902 | 156993 | 124 |
| | SD | 1 | 2 | 46 | 76 | 904 | 2463 | 37487 | 96 |
| RSL | Mean | 13 | 12 | 219 | 104 | 10688 | 849 | 110825 | 162 |
| | SD | 3 | 4 | 24 | 16 | 1026 | 150 | 864 | 32 |

# Appendix D: Boxplots of elements selected for Model 2



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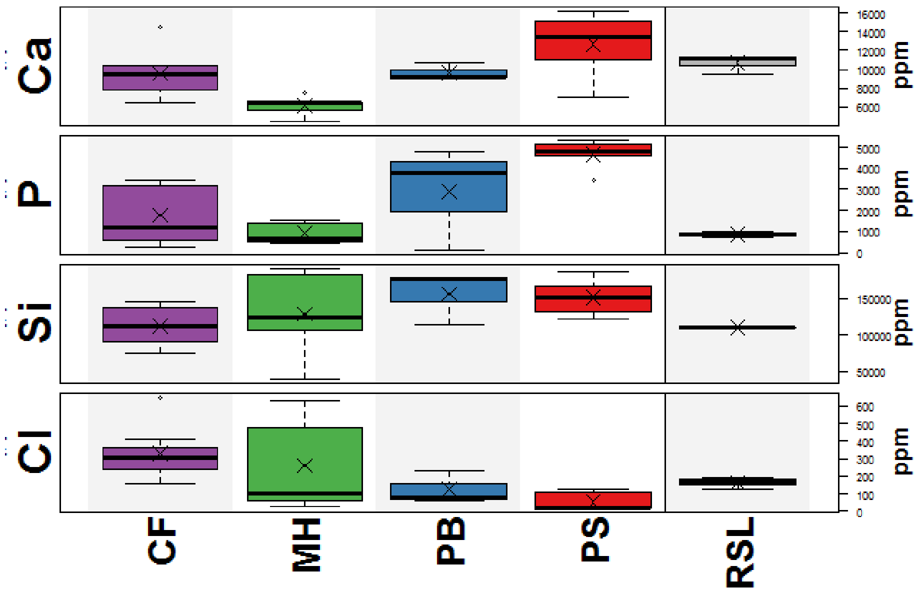




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