Forest Research

The effects of aerial and hand fertiliser applications on water quality in the North Forest Region: monitoring in sub-catchments of the River Oykel, Peffery Burn and Loch Shin

Final Report

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Summary

Many of Scotland's forests are growing on upland soils with low nutrient content and require fertilisation to improve tree establishment and growth. Fertilisation often has the desired effect of increasing forest productivity but it can have an adverse impact on the water environment if nutrient runoff enriches watercourses. This risk prompted the Scottish Environmental Protection Agency (SEPA) to express concerns over Forest Enterprise Scotland's (FES, now Forestry and Land Scotland) aerial and hand phosphorus fertiliser application programme in the North Highland District (now North Region), particularly in sensitive water body catchments. Whilst past evidence suggests that well designed and managed applications would not impair water quality, SEPA, FES and Forestry Commission Scotland (FCS) agreed that it would be prudent to undertake water quality monitoring in a few sensitive catchments to check that this was the case and hopefully demonstrate the effectiveness of current good practice measures.

A programme of water quality monitoring was established in selected sub-catchments around Loch Shin, the River Oykel and the Peffery Burn to determine the phosphorus response to aerial and hand fertiliser treatments. Aerial fertiliser applications were carried out in the Craggie and Inveroykel sub-catchments of the River Oykel in May 2014, followed by a second application to another site at Craggie in May 2015. In the Peffery Burn sub-catchment, an aerial fertiliser application was made in May 2016. Hand fertiliser applications were undertaken in sub-catchments of Loch Shin at South Dalchork in August-September 2014 and at North Dalchork in September-October 2018.

The results show that both orthophosphate (the reactive form) and total phosphorus concentrations in stream waters increased following all of the aerial fertiliser applications. However, annual mean concentrations of orthophosphate remained < 7 µg P l^{-1} in the Craggie streams, < 11.3 µg P l^{-1} in the Inveroykel streams and < 12.4 µg P l^{-1} in the Torrachilty streams, below the 13 µg l^{-1} high ecological status standard for annual mean reactive phosphorus in upland, low alkalinity rivers (UKTAG, 2013). In contrast, it was difficult to discern any response in phosphorus levels to the hand fertiliser applications in the S. Dalchork and N. Dalchork sub-catchments, confirming that this method of treatment poses a minor risk of fertiliser runoff. Phosphorus levels spiked at 16.1 µg P l^{-1} at mid-Dalchork in September 2015 but this was thought to be unrelated to the earlier fertiliser application and possibly associated with forest felling at the time.

At all sites, the absence or short length of baseline data made it difficult to separate out the effect of the fertiliser application from the background variation in phosphorus concentrations, especially for total phosphorus. Data from the few pre-fertiliser samples collected, together with the results for the River Tirry control stream, showed significant seasonal variation in stream concentrations and marked responses to storm events. The source of this phosphorus could be natural (weathering), a result of historic fertiliser applications, forest felling activity, increased erosion and suspended sediment transport, or the release of dissolved organic matter (Mayora et al., 2018). Further investigation of the

soils, past land use and management, and phosphate concentrations within local moorland streams would be needed to help identify the main source.

Following the aerial application of NPK fertiliser to a sub-catchment of the Peffery Burn there was an immediate but short-lived increase in ammonia-N in all three monitored streams, although concentrations in two of the streams (Allt Dearg and Peffery Burn) remained below the 0.5 mg l^{-1} high status threshold for short-term and intermittent changes in total ammonia concentration (99th percentile). The third stream, the Peffery Tributary, varied between good (0.7 mg l^{-1}) to moderate (1.8 mg l^{-}1) status indicating a short-lived deterioration in water quality in this watercourse; however, the impact was localised as there was no deterioration downstream in the Peffery Burn.

A low-level increase in nitrate-N was recorded in the Peffery Tributary in the month after fertilisation, but no such increase was seen at the other two streams indicating a localised nitrate release. Further low-level increases were seen in early 2017 in the Peffery Tributary and Peffery Burn, but not in the Allt Dearg, and could be related to meteorological conditions, namely snowfall and subsequent snowmelt at the time. The key point is that NO_3-N concentrations remained very low, never exceeding 0.51 mg l^{-1}.

The overall results of the study indicate that a good standard of forestry practice, including buffer widths of up to 50 m for aerial applications and 10 m for hand applications, was sufficient to protect water quality from fertiliser treatments. With respect to phosphorus, concentrations in all of the streams remained below the 13 µg l^{-1} high ecological status WFD standard for annual mean reactive phosphorus, even when up to 63% of the catchment was aerially fertilised. In terms of nitrogen, no issues were identified for nitrate but the total ammonia concentration (99th percentile) in one stream (the Peffery Tributary) varied between good and moderate status, albeit for a short time. This was thought to be related to over-flying of a section of the stream, highlighting the need for care in identifying and avoiding the treatment of buffer areas, especially where the treated area drains to nutrient-sensitive waters.

Based on the results, routine monitoring of fertiliser applications is not required, but it may be prudent to monitor water quality in particularly sensitive areas. One research need is to explore the apparently high background level of phosphorus within some nutrient sensitive catchments to determine whether the source is mainly natural or linked to recent or past land management activities, including forest felling and ground preparation. Consideration could be given to the use of stable isotope analysis or chemical fingerprinting techniques to help determine the sources of phosphorus.

Finally, it is recommended that the results of this monitoring are used to inform future updates to UKFS Water Guidelines and GBRs related to fertiliser use in forestry (GBR 18).

1. Objective

To monitor the effects of aerial and hand forest fertiliser applications on water quality in nutrient sensitive water catchments.

2. Background

Many of Scotland's forests are growing on upland soils with low nutrient content therefore forest fertilisation is undertaken to improve tree establishment and growth. Fertilisation often has the desired effect of increasing forest productivity but it can have an adverse impact on the water environment if nutrient runoff, especially of phosphate, enriches local watercourses. This nutrient transport, a form of diffuse pollution, can in extreme cases result in eutrophication of receiving waters, where algal growth can deplete oxygen levels and eventually lead to death of fish and other aquatic life. More commonly, a relatively small rise in phosphate concentrations causes unwelcome ecological changes that disturb the ecosystem balance, especially within oligotrophic (nutrient-poor) standing waters such as lochs and reservoirs. Many of our forests are planted in upland catchments that drain to oligotrophic waters supporting sensitive Priority Species such as the freshwater pearl mussel. Therefore, careful land-use management is required to ensure that water quality remains high.

Forest phosphate fertilisation has been an issue of concern in the UK since the late 1970's (Harriman, 1978). Fertiliser losses have been shown to be greatest during the first six months after an application but can continue for up to five years or longer (Swift, 1987). The method of application is an important factor, with greater losses from aerial compared to hand fertiliser treatments. Improvements to fertiliser practice following the introduction of the Forests & Water Guidelines in 1988, including better helicopter targeting systems and the use of buffer areas, succeeded in reducing phosphate losses to water (Binkley et al., 1999; Nisbet, 2001; Nisbet et al., 2002), although some concerns remain, particularly involving fertiliser applications to deep peat. Deep peat is less able to absorb and retain applied P leading to a greater risk of nutrient runoff to local streams.

Although hand fertiliser applications pose less risk, in some areas aerial treatments are necessary due to issues of accessibility, scale and cost, particularly on second and third rotation restocking sites. A number of these sites occur in Forest Enterprise Scotland's (now Forestry and Land Scotland) North Highland Forest District (now North Region), who consulted the Scottish Environmental Protection Agency (SEPA) about potential impacts. SEPA expressed concern over planned aerial and hand fertiliser applications within catchments draining to highly sensitive waters such as Loch Shin. Whilst past evidence suggests that the applications could be undertaken without impairing water quality, SEPA, FES and FCS agreed that it would be prudent to undertake water quality monitoring in a few selected sub-catchments around Loch Shin, the River Oykel and the River Peffery to check that this was the case. The results would inform FES' ongoing fertiliser application programme and test the efficacy of the UKFS water guidelines and General Binding Rules related to fertiliser applications (GBR 18). Any lessons learned would be incorporated into future revisions of good practice guidance.

This report presents the results of over 3.5 years of monitoring by the partnership project, where FES provided field-based support and funding, SEPA analysed the water samples in their laboratory and Forest Research managed the project, including processing and interpreting the data and producing reports.

3. Methods

3.1 The sites

Five sites were selected for water quality monitoring from N. Highland Forest District's fertiliser application programme. Three were to receive aerial fertiliser applications, two in the River Oykel catchment and one in the Peffery Burn catchment, while another two were to be fertilised by hand within the Loch Shin catchment (Figure 1).

The Oykel is a famous salmon fishing river and designated a Special Area of Conservation (SAC) for both Atlantic salmon and freshwater pearl mussel. Loch Shin is also an SAC and a Special Protection Area (SPA); in 2013 the waterbody was classified overall as bad for ecological status and poor for water quality (moderate for total phosphorus). Phosphorus is a long-standing issue in the loch, leading to concerns about any land use activities in the catchment that could contribute additional nutrients, hence SEPA's interest in monitoring the effects of the planned hand fertiliser applications.

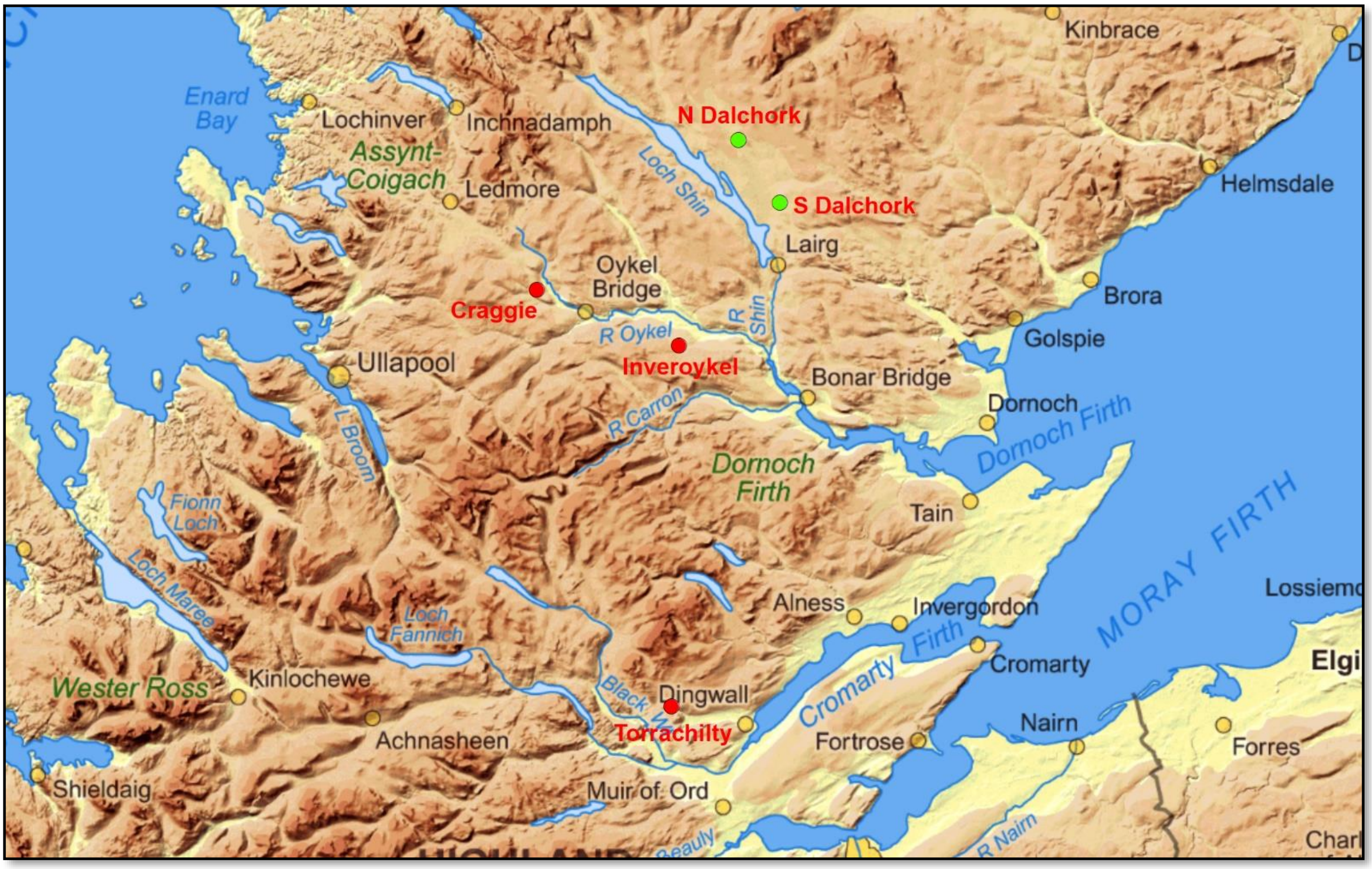

Figure 1 Location of the five study sites with red circles indicating the aerial fertiliser application sites and green circles the hand application sites.

Craggie, Inveroykel and Torrachilty – aerial fertiliser applications

The Craggie and Inveroykel sites are located within the River Oykel catchment, and the Torrachilty site is in the River Peffery catchment. Soils at all three sites belong to the Arkaig soil association and comprise peaty gleys with dystrophic blanket peat and peaty gleyed podzols; the parent material consists of drifts derived from schists, gneisses, granulites and quartzites, principally of the Moine Series (Soil Survey of Scotland Staff, 1981).

The Craggie site was ploughed and planted in 1972/73, mainly with Lodgepole pine but also Sitka spruce. The site was fertilised with phosphorus around the time of planting and most likely received a second application to achieve establishment. The site was felled in 2009 and lay fallow until 2014 when it was mounded, restocked with a Lodgepole pine/Sitka spruce mix and fertilised with an aerial PK (phosphorus-potassium) application in 2014. A second aerial fertiliser application was made in 2015 to an area north of the 2014 treatment (Figure 2). Three sites were identified for water sampling following the 2014 application: the Craggie Road Drain (CRD), which drains the north-eastern part of the fertilised area; the Allt Ruchain, which captures runoff from the north-western treated section; and the River Chonachair, which receives the Allt Ruchain and waters draining the south-east part of the fertilised area, before flowing for some 3.5 km directly into the River Oykel. These three sampling points also collect much of the water draining from the area that received the 2015 fertiliser application.

The Inveroykel site was ploughed and planted in 1970 with mostly Lodgepole pine but also a mixture of Sitka spruce/Scots pine/Japanese larch. The site was fertilised with phosphorus around the time of planting and probably received a second application thereafter; it was felled in 2009/10. A fallow period was followed by mounding in 2013/14, restocking with mixtures of Lodgepole pine/Sitka spruce and Japanese larch/Sitka spruce, and an aerial PK fertiliser application in 2014. Two sites were identified for sampling (Figure 3): the Allt a Charraigh burn that captures most of the drainage from the fertilised area, and the Kilmachalmack Burn, which drains a strip running the full length of the southern end of the fertilised area; the Kilmachalmack Burn meets the River Oykel around 2.5 km downstream of the sampling point.

The Torrachilty site was ploughed and planted between 1972-74, most likely 1972, and would have been fertilised around the time of planting. The site was felled in 2002 and after a fallow period, was replanted in 2005/06 with a Lodgepole pine/Sitka spruce mix; an aerial NPK fertiliser application was made in 2016. Three sites were identified for sampling (Figure 4): the Allt Dearg which captures most of the drainage from the western part of the fertilised area; an unnamed burn that we named the Peffery Tributary, which captures drainage from the eastern side of the fertilised area; and a site further downstream on the Peffery Burn that both afore-mentioned burns drain to. The Peffery Burn becomes the River Peffery around 2.8 km downstream of the sampling point.

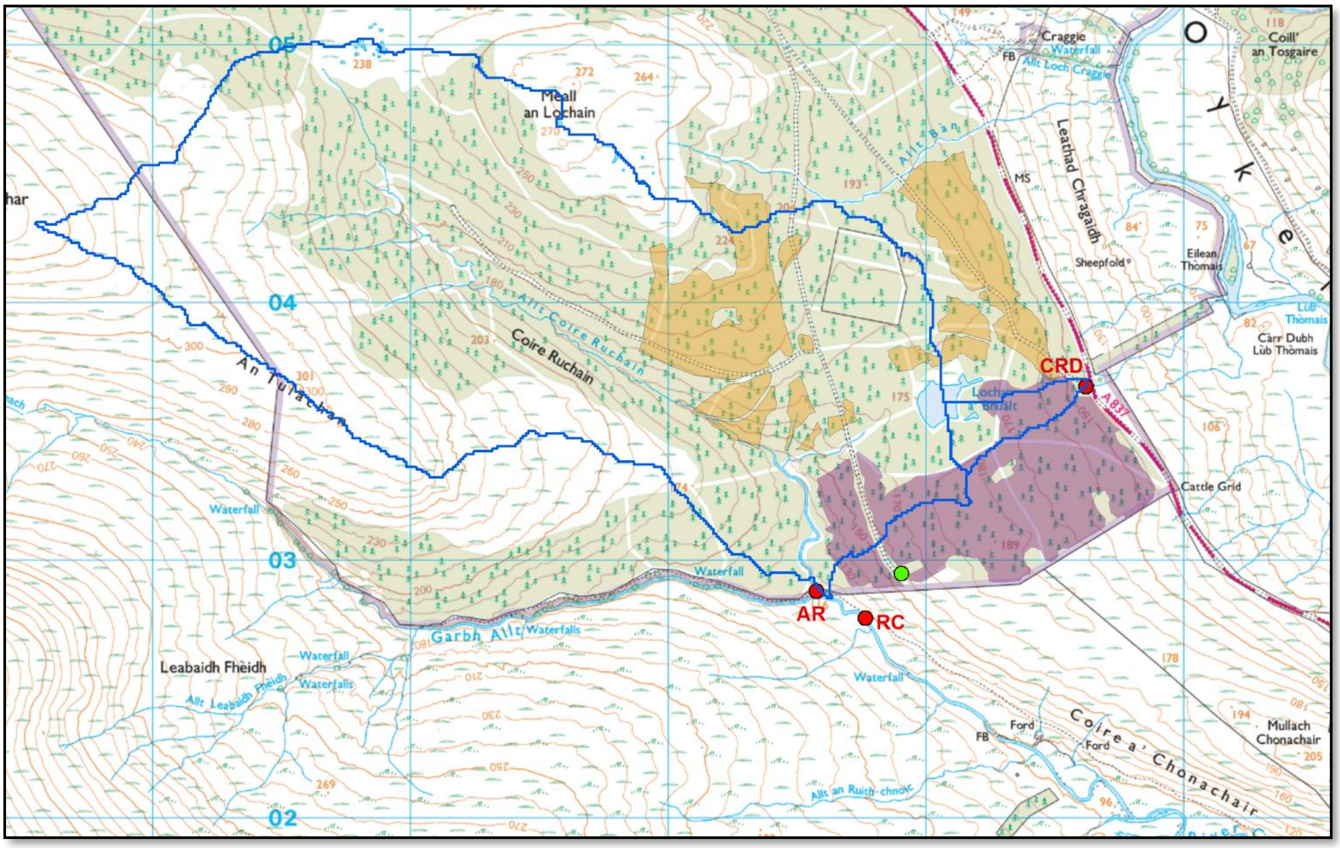

Figure 2 The Craggie site with the Craggie Road Drain (CRD), Allt Ruchain (AR) and River Chonachair (RC) sampling points indicated by red circles, the fertiliser storage area by the green circle, the 2014 fertilised area by purple shading and the 2015 fertilised area by orange shading. Catchment boundaries for the AR and CRD are indicated by the blue outline; the River Oykel can be seen to the east.

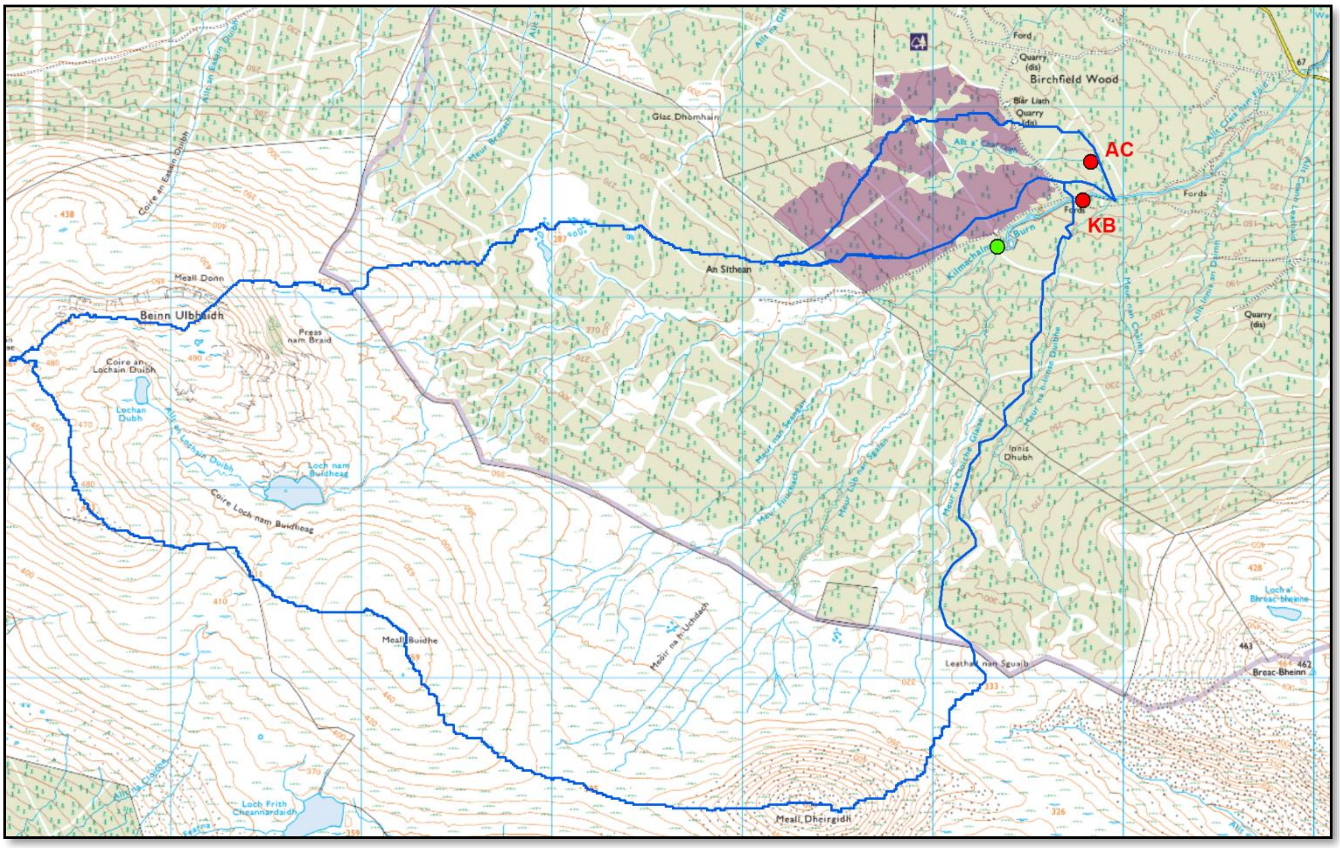

Figure 3 The Inveroykel site with the Allt a Charraigh (AC) and Kilmachalmack Burn (KB) sampling points indicated by red circles, the fertiliser storage area by the green circle and the fertilised area by purple shading. Catchment boundaries are indicated by the blue outline.

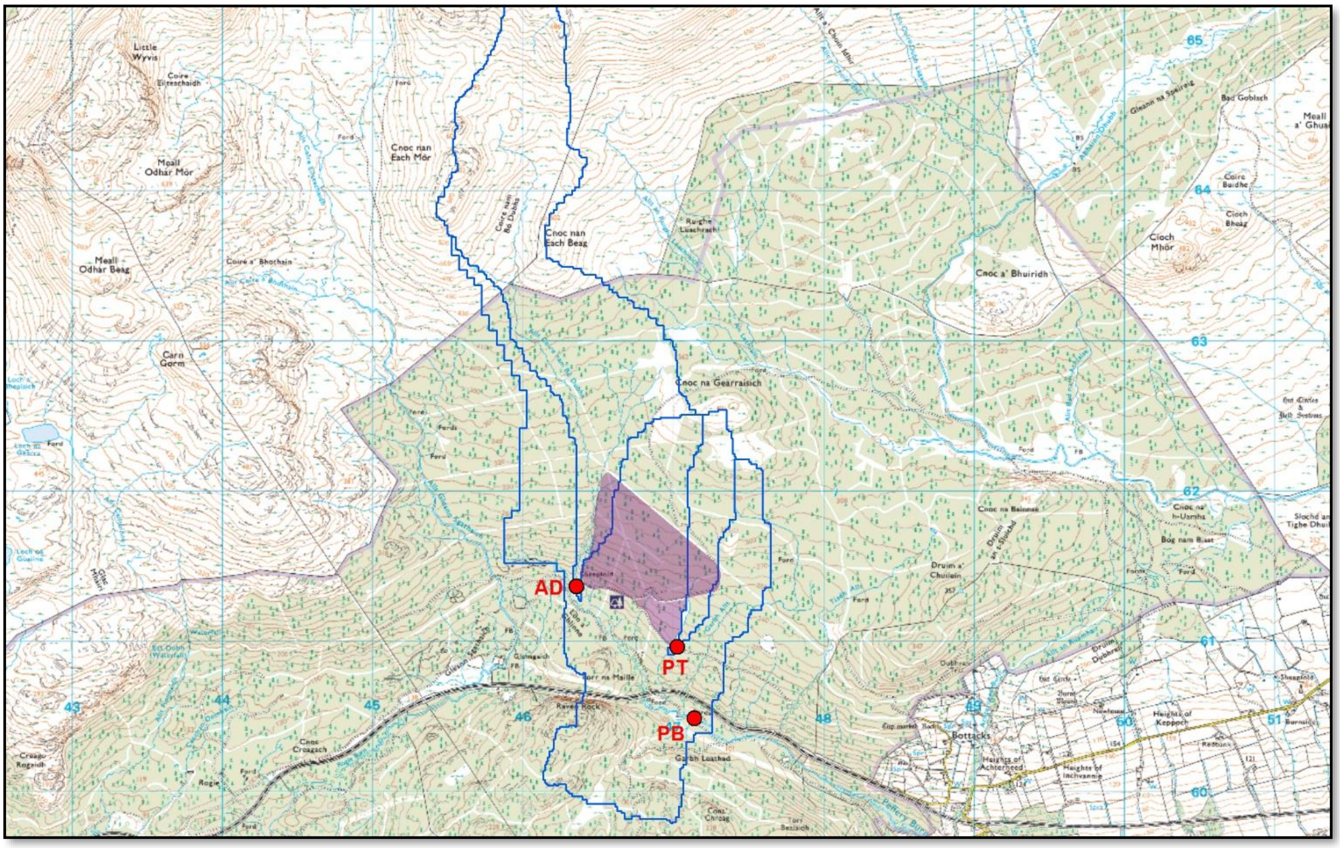

Figure 4 The Torrachilty site with the Allt Dearg (AD), Peffery Tributary (PT) and Peffery Burn (PB) sampling points indicated by red circles and the fertilised area by purple shading. Catchment boundaries are indicated by the blue outline.

South and North Dalchork – hand fertiliser applications

The Dalchork sites are located within the Loch Shin catchment. The soils belong to the Arkaig soil association and comprise peaty gleyed podzols with dystrophic, semi-confined peat and peaty gleys on higher ground; the parent material consists of drifts derived from schists, gneisses, granulites and quartzites, principally of the Moine Series (Soil Survey of Scotland Staff, 1981).

The S. Dalchork site was ploughed and planted in 1964, mostly with Lodgepole pine but also Sitka spruce and Scots pine. The site was fertilised with phosphorus around the time of planting and probably received a second application to achieve establishement; the crop was felled in 2009. Following a fallow period the site was mounded and planted in 2014 with a Japanese larch/Sitka spruce mix in the mid-Dalchork catchment and Lodgepole pine/Sitka spruce and Japanese larch/Sitka spruce mixes in the Allt Bhreac Lethaid catchment; native broadleaves were planted adjacent to watercourses and both catchments were hand fertilised with PK in August 2014. Three sampling points were identified for monitoring (Figure 5): two downstream of fertilised areas, the Allt Bhreac Lethaid and a burn that we named mid-Dalchork, and one point on the River Tirry that essentially acts as a control; the Tirry flows into Loch Shin about 4 km downstream of the sampling point.

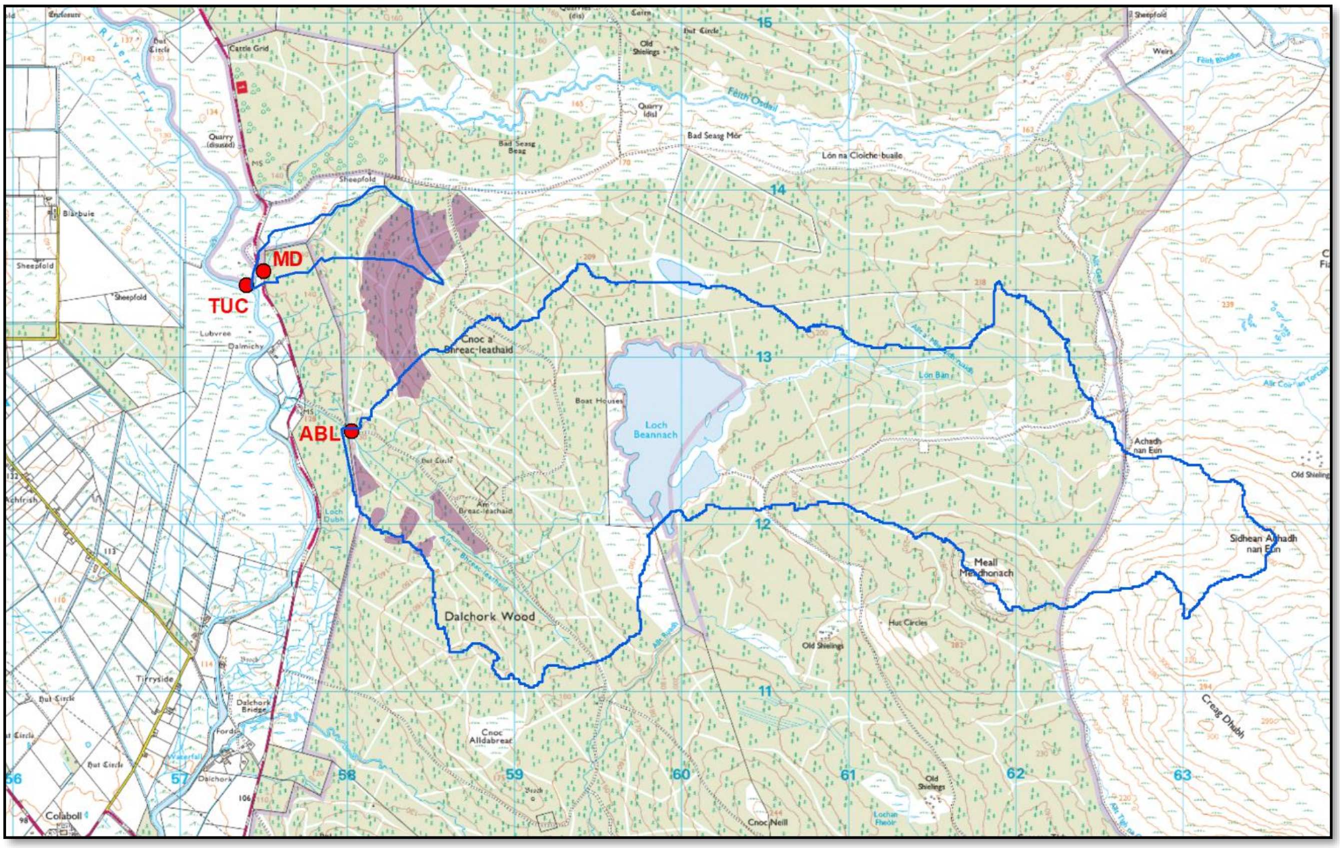

Figure 5 The South Dalchork site with the three sampling points indicated by red circles and the hand fertilised area by purple shading. The control site is furthest west on the River Tirry, which flows south into Loch Shin. Catchment boundaries for MD and the ABL are indicated by the blue outline.

The N. Dalchork site was planted in 1970 with Lodgepole pine and Sitka spruce, and fertilised with phosphorus around the time planting. The trees were clearfelled in 2012 and following a fallow period, the site was mounded and planted in 2017 with an intimate mix of Sitka spruce and Lodgepole pine. The site was fertilised by hand with PK in September-October 2018. Two sampling points were identified for monitoring on unnamed burns draining the fertilised area (Figure 6); we named them Tirry tributary north and Tirry tributary south and both drain directly into the River Tirry.

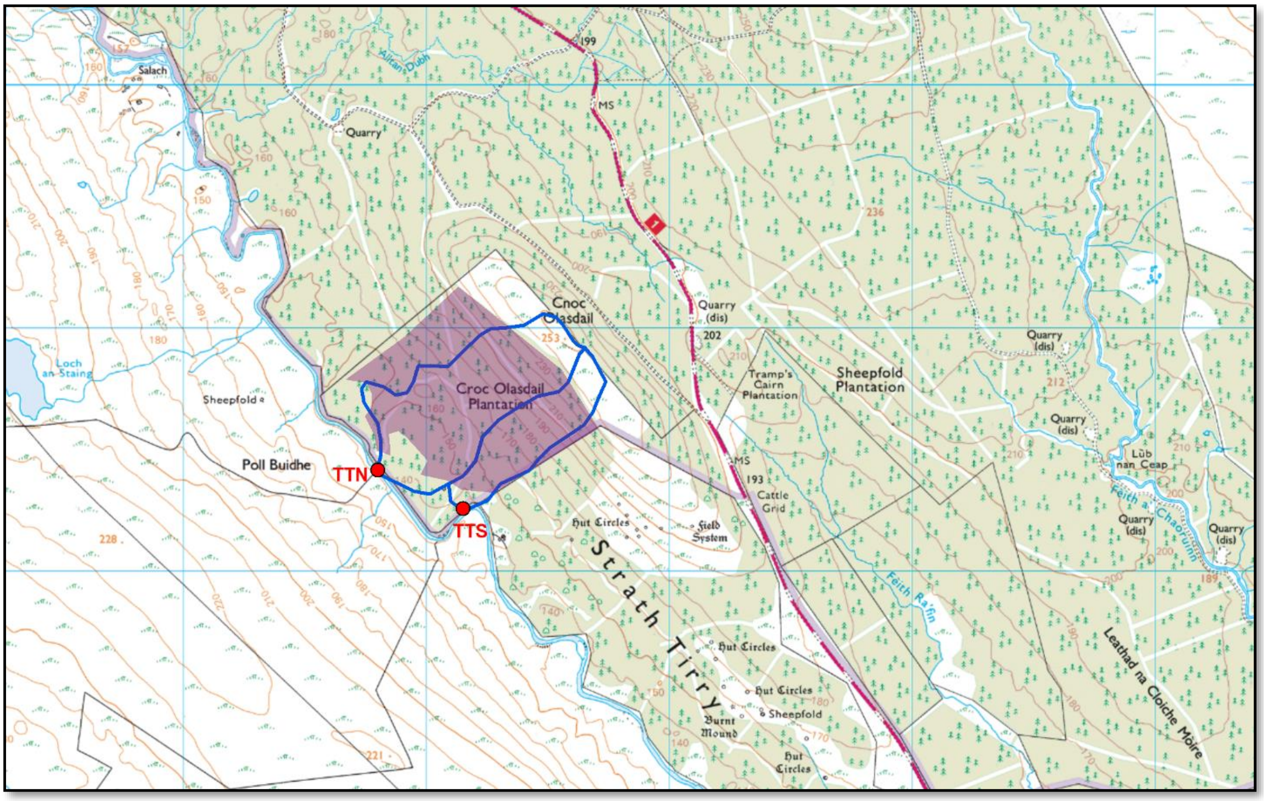

Figure 6 The North Dalchork site with the Tirry Tributary North (TTN) and Tirry Tributary South (TTS) sampling points indicated by red circles and the hand fertilised area by purple shading. The River Tirry flows along the western edge of the forest. The catchment boundaries are indicated by the blue outline.

3.2 Details of fertiliser applications

The Craggie and Inveroykel sites received an aerial fertiliser application of granular PK (18:20) at 650 kg ha^{-1}, the former on the 31st May 2014 and the latter on the 30th May 2014. In terms of the weather, it was dry on both application days with a slight breeze; 0.2 mm of rain was recorded at the SEPA rainguage at Loch Ailsh on the 31st May, with heavier rain in the 10 days following the applications. The Craggie site received another aerial application on 12th May 2015, to the north of the 2014 application; again with granular PK (18:20) at 650 kg ha^{-1} (Figure 2).

The Torrachilty site was fertilised with NPK (16:12:12) granules at 1000 kg ha^{-1} on the 22nd May 2016; on the day of application the wind speed was low and there was a light shower in the afternoon.

Figures 7 to 9 show the fertiliser spread patterns recorded by the helicopter guidance system.

The S. Dalchork site was fertilised by hand with standard non-granular PK (19:20) at 500 kg ha^{-1}, with the application beginning on the 1st August 2014 and ending on the 8th September 2014. The N. Dalchork site was hand fertilised with PK (19:20) at 400 kg ha^{-1} from 19th September 2018 to 4th October 2018.

For the aerial applications, the helicopter pilot was instructed to leave 50 m untreated buffer areas from all watercourses. These were generally respected but some breaches were noted on the helicopter spread patterns, including treatment of parts of the Allt a Charraigh stream at Inveroykel and the mid-section of the Peffery Tributary at Torrachility. For the hand applications 10 m untreated buffers were left alongside all watercourses.

Catchment areas for the monitoring sites and the proportion of the catchment fertilised are shown in Table 1.

Table 1 Catchment areas upstream of the monitoring points, the fertilised area and the percentage of the catchment fertilised.

Site	Catchment Area (ha)	Fertilised area (ha)	% catchment fertilised
Craggie			
Allt Ruchain (AR)	394.7	42.5	10.8
River Conachair (RC)	797.1	11.1	1.4
Craggie Road Drain (CRD)	8.8	4.9	55.7
Inveroykel			
Allt a' Charraigh (AC)	67.1	42.3	63.0
Kilmachalmack Burn (KB)	1120.6	10.2	0.9
Torrachilty			
Allt Dearg (AD)	239	5.4	2.3
Peffery Tributary (PT)	33.4	5.6	16.8
Peffery Burn (PB)	552.6	51.7	9.4
S. Dalchork			
Allt Bhreac Lethaid (ABL)	735.2	11.3	1.5
Mid-Dalchork (MD)	32.1	8.2	25.5
Tirry Upstream Control (TUC)	12541.2	17.6	0.1
N. Dalchork			
Tirry Tributary North (TTN)	32.9	25.3	76.9
Tirry Tributary South (TTS)	14.6	11.2	76.7

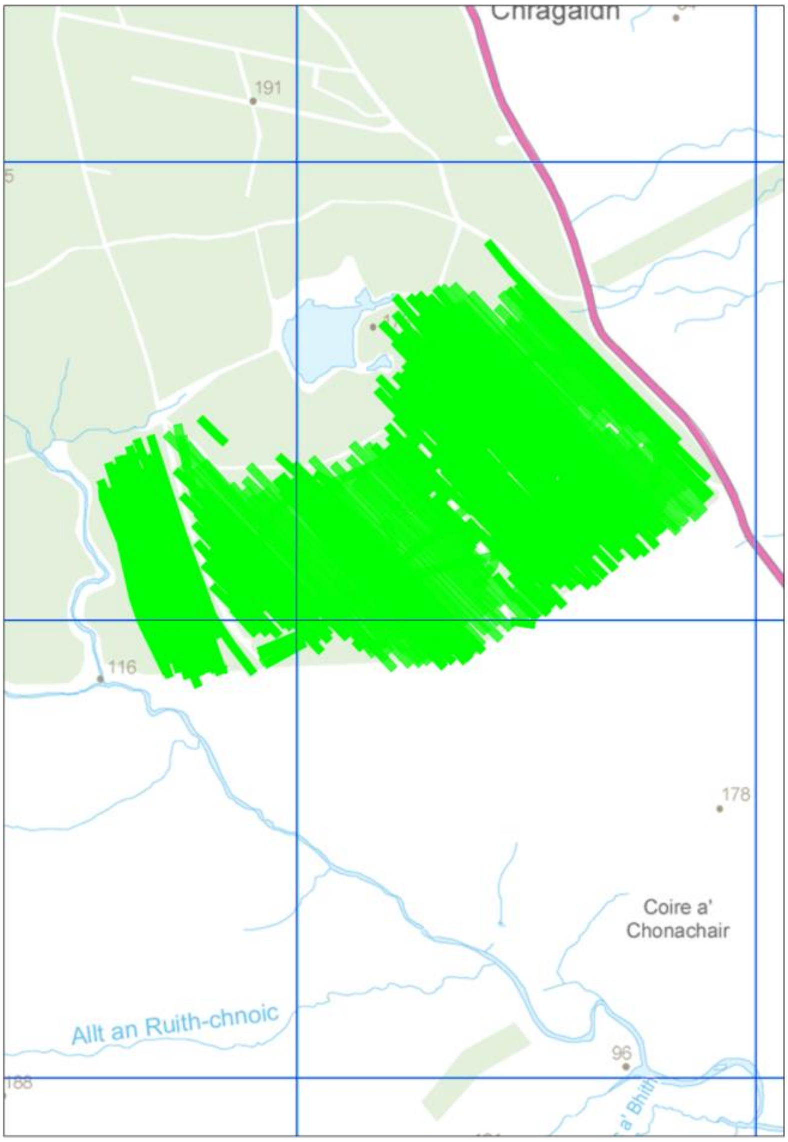

Figure 7 Spread pattern (brighter green) recorded by helicopter guidance system showing the area that received an aerial fertiliser application at Craggie in May 2014 (map courtesy of PDG helicopters).

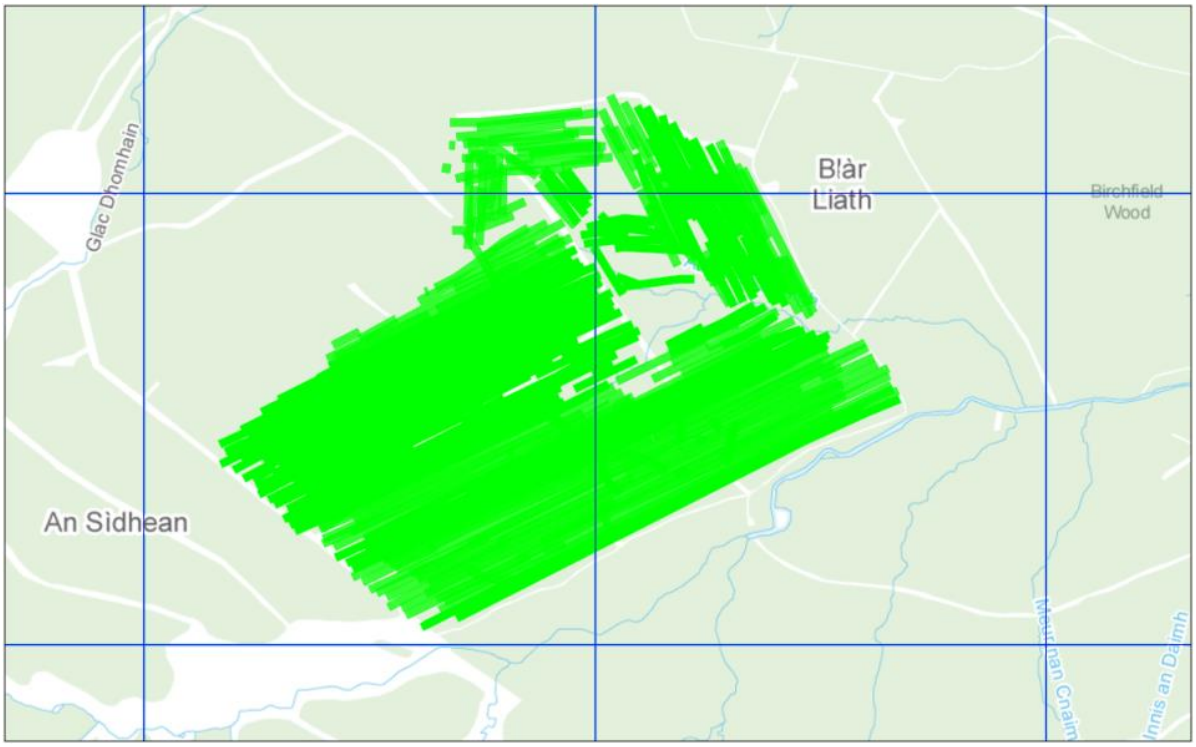

Figure 8 Spread pattern (brighter green) recorded by helicopter guidance system showing the area that received an aerial fertiliser application at Inveroykel in May 2014 (map courtesy of PDG helicopters).

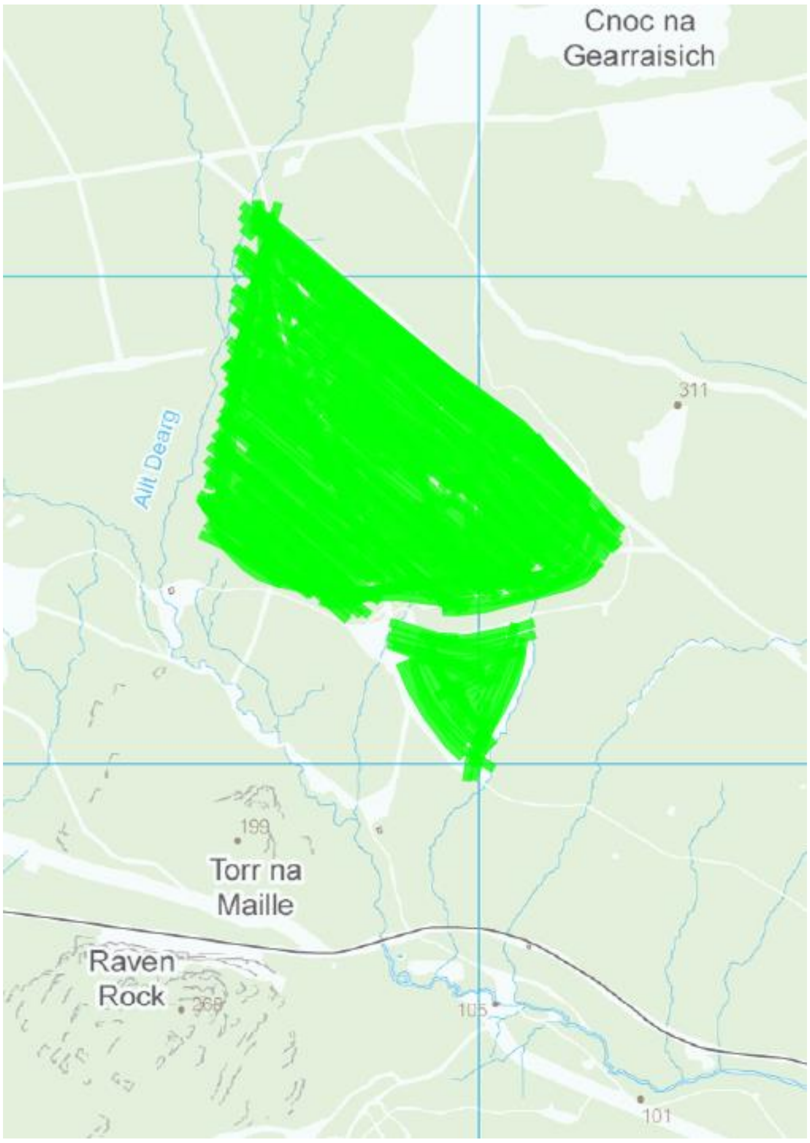

Figure 9 Spread pattern (brighter green) recorded by helicopter guidance system showing the area that received an aerial fertiliser application at Torrachilty in May 2016 (map courtesy of PDG helicopters).

3.3 Sampling and chemical analysis

Water samples were collected fortnightly from planned sampling locations and posted on the day of sampling to SEPA's Angus Smith Building laboratory. Nutrient analysis was undertaken using standard colorimetric techniques. In general this involved the addition of reagents to the samples resulting in the development of a colour, the intensity of which is dependent on the concentration of the analyte.

The storage, handling and analysis of samples at the SEPA laboratory was carried out in accordance with the laboratory's ISO 17025 (UKAS accredited) quality assurance procedures. There were a small number of occasions where the time between sampling and receipt exceeded SEPA's in-house targets requiring the removal of the UKAS accreditation from the test result. However the impact on data quality is regarded as minimal and is not expected to have affected the results.

The laboratory analysis returned many values below the limit of detection (LOD), also known as censored values. In order to facilitate data analysis, particularly the calculation of means, we assigned a value of half the LOD to all censored values (Cohen and Ryan, 1989). Like other methods dealing with censored data, this technique is not without errors but is the one adopted by SEPA; moreover, an analysis of the data using censored data versus half the LOD showed that the latter better represented the results.

Analysis at the Craggie, Oykel and Dalchork sites

Samples were analysed for trace levels of total and reactive phosphorus using a manual technique, with a 2µg/l limit of detection. To facilitate this samples were collected in iodised polycarbonate bottles, pre-washed in the laboratory with deionised water. The analytical technique involves reacting orthophosphate ions with acidic molybdate reagents to form a reduced phosphomolybdenum blue complex. The intensity of the blue complex colour formed is proportional to the concentration of orthophosphate present, the absorbance of which is measured on a spectrophotometer at 882 nm. In the determination of total phosphorus, which includes all inorganic and organic forms of phosphorus, an initial sulphuric acid-persulphate digestion was carried out to convert all forms of phosphorus to the orthophosphate form.

Analysis at the Torrachilty sites

For the Torrachilty samples nutrient-N and P were measured using a discrete colorimetric analyser (Thermo Scientific Aquakem 600 Prime). Samples were collected in clear, 500ml plastic (PET) bottles.

Reactive phosphorus analysis used the same underlying methodologies as above, however the addition of reagents and measurement of colour were automated. The reporting LOD for this test was 8 µg l^{-1} (9 µg l^{-1} to 19/09/2016).

Ammoniacal nitrogen determination was based on the following colour chemistry - ammonia-N reacts with hypochlorite ions (generated from the alkaline hydrolysis of sodium dichloroisocyanurate) to form monochloramine. This then reacts with salicylate in the presence of sodium nitroprusside (catalyst), to produce a blue indophenol compound that is measured spectrophotometrically at 660 nm. The reporting LOD for this technique was 24 µg l^{-1} (17 µg l^{-1} to 19/09/2016).

Nitrate concentrations were obtained by calculation. Nitrite present in the sample is first measured by the addition of sulphanilamide to form a diazonium compound which, in dilute phosphoric acid, couples with N-1 naphthylethylene diamine dihydrochloride to form a reddish-purple azo dye which is measured spectrophotometrically at 540 nm. In parallel analysis, nitrate in the sample is reduced to nitrite by hydrazine under alkaline conditions, using cupric ion as a catalyst. This reduced nitrate (in the form of nitrite), along with any nitrite already present, is tested as above and expressed as total oxidisable nitrogen (TON). The nitrate concentration is then calculated by subtracting the nitrite value from the TON value. The LOD for this technique was 148 µg l^{-1} (200 µg l^{-1} to 19/09/2016).

Total phosphorus was determined using similar methodologies to the other sites (low-level technique) outlined above, but at a slightly higher limit of detection (5 µg l^{-1}).

4. Results and Discussion

4.1 Aerial fertiliser applications

Craggie

Following the aerial fertiliser application at Craggie in May 2014, total P and orthophosphate concentrations increased at the Allt Ruchain, the Craggie Road Drain (CRD) and, to a lesser extent, the River Chonachair (Figure 10). At the Allt Ruchain, concentrations peaked some five weeks after the fertiliser application at 31.6 µg P $l^{-1}$and 10.8 µg P l^{-1} for total P and orthophosphate, respectively. At the CRD concentrations peaked around 7 weeks after the application at 62.2 µg P l^{-1} and 14.8 µg P l^{-1} for total P and orthophosphate, respectively, whilst at the River Chonachair concentrations peaked at 12.7 µg P l^{-1} and 7.5 µg P l^{-1}, respectively. The variation in response of the concentrations between the three watercourses may reflect the scale of the fertiliser application in each catchment; the CRD is the smallest watercourse with the highest percentage of the catchment area treated (~ 55.7 %), followed by the Allt Ruchain with around 10.8 % of the catchment fertilised and the River Chonachair with 1.4 % of the catchment treated. Research shows that the impact of fertiliser applications is often directly related to the proportion of a catchment treated (Nisbet, 2001). The proximity of the sampling points to the fertilised area may also have had a bearing on the concentrations recorded.

After peaking, total P and orthophosphate concentrations decreased at all sites to < 9µg P l^{-1} and < 4 µg P l^{-1}, respectively, by January 2015. A period of baseline, pre-fertilisation monitoring was not possible, but samples taken at the CRD and the River Chonachair one week before the fertiliser application show that total P concentrations were higher than those recorded in May in subsequent years, suggesting that they may have been elevated due to meteorological conditions at the time. It is notable that in the period leading up to the May 2014 fertiliser applications, precipitation in the River Oykel area was high in the preceding February (~ 200 mm), March (~ 160 mm) and April (~ 140 mm) when compared with the 1910-2014 North of Scotland long-term averages for these months of 125 mm, 119 mm and 99 mm, respectively (Met Office, 2015). Total phosphorus is known to increase in watercourses during and after rainfall events (Hutton et al., 2008; Swift, 1987), being carried in surface runoff or in subsurface drainage due to sediment washout and leaching from soil horizons that are enriched naturally or by historic phosphate fertiliser applications (Sims et al., 1998; Domagalski and Johnson, 2011).

Total P and orthophosphate concentrations increased again following the second fertiliser application in May 2015, with concentrations reaching their highest levels in July and August 2015 (Figure 10); simultaneous increases at the Inveroykel and Loch Shin sites in summer 2015 indicate that a significant portion of the rise reflects increases in background phosphorus levels. As with the 2014 application the increase is not immediate with the first sign of increase in early June, almost 4 weeks after the application. The delayed release seen after both applications may be due to the granular nature of the fertiliser, which takes time to break down and release phosphorous into the soil and water. It is worth noting that after rainfall the total P concentration increases more relative to orthophosphate, which could be due to physical wash-off of the granular fertiliser, indicating that the particulate P fraction is more responsive compared to dissolved P, something we would expect in erosion-prone soils following heavy rainfall. Summer increases in P may also be related to increased mineralisation of soil, vegetation and forest residues such as brash, with P being transported to watercourses when rainfall follows dry periods or drought conditions.

Importantly, after the May 2014 fertiliser application, the concentration of orthophosphate at both the Allt Ruchain and River Chonachair never exceeded 13 µg P l^{-1}, with annual means always < 4 µg P l^{-1} (Figure 10 and Table 2), well below the 13 µgl^{-1} high ecological status Water Framework Directive (WFD) standard concentration for annual mean reactive phosphorus in upland, low alkalinity waters (UKTAG, 2013). Concentrations would be further diluted as the River Chonachair flows downstream into the Oykel. At the CRD, the maximum recorded orthophosphate concentration was 44.8 µg l^{-1} (in September 2015), with annual means < 7 µg P l^{-1} (Figure 10 and Table 2), again below the high ecological status standard. The CRD drains into a field below the road where it flows for a distance of at least 600 m to the River Oykel; this may provide some processing and buffering of phosphorus within the stream channel, potentially reducing phosphorus transfer to the River Oykel.

In the River Chonachair and Allt Ruchain, the highest total P and orthophosphate concentrations were recorded on the 2nd October 2017 when peaks were also seen at other monitoring sites, notably in the Loch Shin sub-catchments, including the Tirry control. This suggests that whilst some of the P contribution may have been due to the fertiliser applications, especially in the case of the smaller CRD catchment, there is a significant contribution from background sources, identification of which requires further investigation.

The results show that total P and to a lesser extent orthophosphate concentrations peak in summer/autumn in each year of monitoring, indicating seasonal effects. Similar trends can be seen at the Tirry control site at Loch Shin (see below), further indicating the significant role of background climatic and related processes. Only the CRD exhibits a clear, above background response of both total P and orthophosphate to the fertiliser application, reflecting the larger scale application (Table 1) of fertiliser to the upstream catchment.

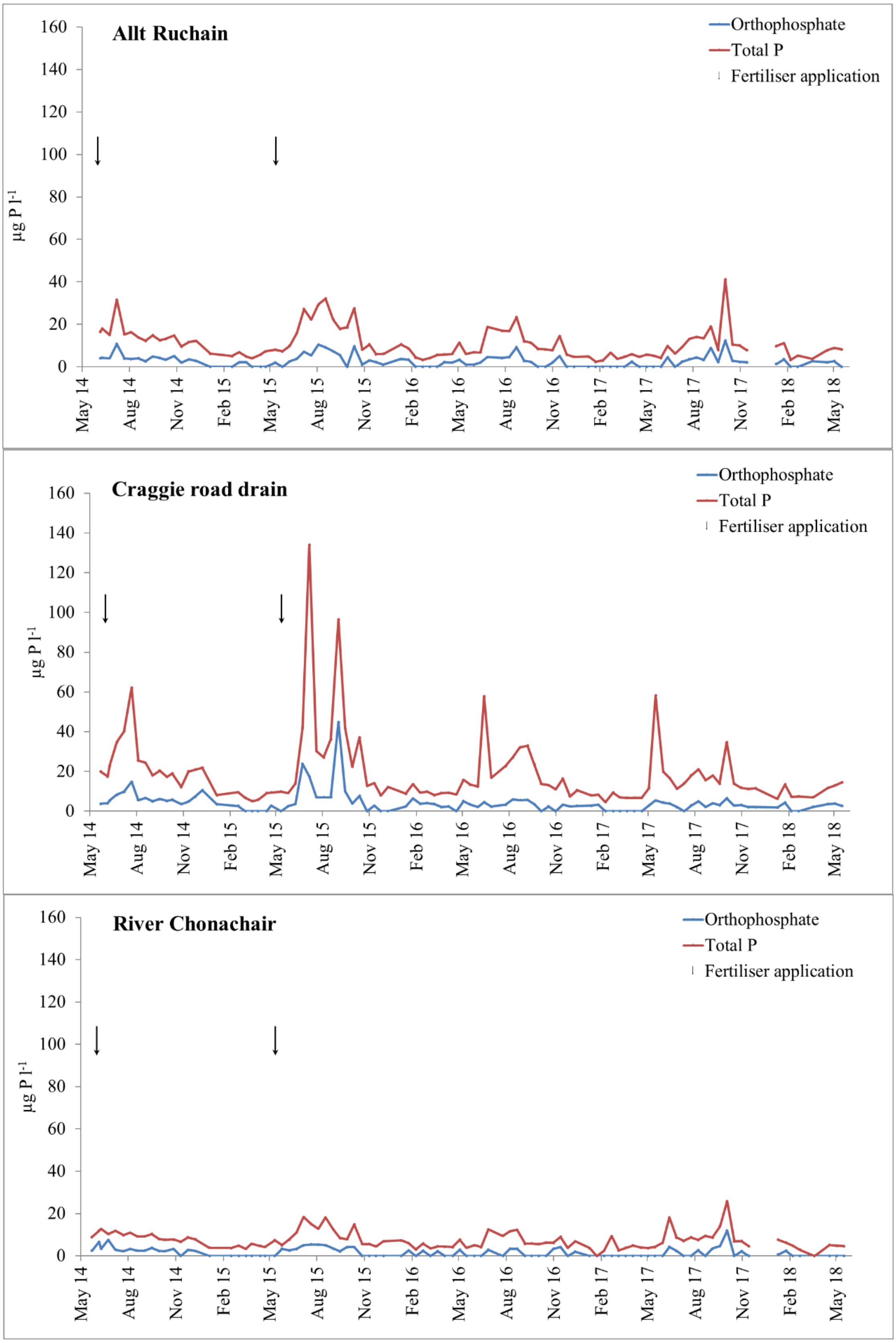

Figure 10 Total P and orthophosphate concentrations at Craggie; the arrow indicates the timing of the fertiliser applications.

Inveroykel

Very little if any increase in orthophosphate was seen in the Allt a Charraigh following the aerial fertiliser application, despite breaches in the buffer area as noted on the helicopter spread pattern, while the total P concentration increased only slightly to 48.1 µg P l^{-1} in the months after the application (Figure 11). Concentrations were lower at the Kilmachalmack Burn (maximum of 16.2 µg P l^{-1} for orthophosphate and 27.8 µg P l^{-1} for total P), perhaps reflecting the larger catchment and size of the burn, and both orthophosphate and total P again increased only slightly after the fertiliser application. The period following the application was characterised by a series of peaks and troughs but concentrations did not display any sustained rise; orthophosphate and total P concentrations never exceeded 23 µg P l^{-1} and 65 µg P l^{-1}, respectively, in either of the burns until after a year when, as with the Craggie site, both orthophosphate and total P increased during summer 2015, beginning in early June. It is possible that this represented a lag effect from the 2014 fertiliser application, although the absence of baseline data or an adjacent control catchment makes it difficult to confirm. There appears to be a strong link with rainfall as the June increases were preceded by heavy rainfall in May 2015, which continued into June; orthophosphate and total P concentrations reached 52.5µg P $l^{-1}$and 97.3 µg P l^{-1}, respectively, at the Allt a Charraigh in early July. Another peak in total P in September 2015 was also preceded by rainfall. The most likely reason that peaks were seen at the Allt a Charraigh but not the Kilmachalmack Burn is because a larger proportion of the former catchment received the fertiliser application, i.e. 63.1% versus 0.9%.

Again, the important point is that with the exception of the July and September 2015 peaks at the Allt a Charraigh, concentrations remained overall low with annual means of 11.2 µg P l^{-1} for the Allt a Charriagh and 6.5 µg P l^{-1} for the Kilmachalmack Burn (Table 2), below the 13 µg l^{-1} high ecological status standard for annual mean reactive phosphorus in upland, low alkalinity waters (UKTAG, 2013).

The presence of a natural vegetated buffer (wetland flush) at the eastern end of the fertilised area, before the Allt a Charraigh burn flows under the forest road, may have intercepted some of the fertiliser runoff and thus helped to reduce phosphorus loading to the Allt a Charraigh burn.

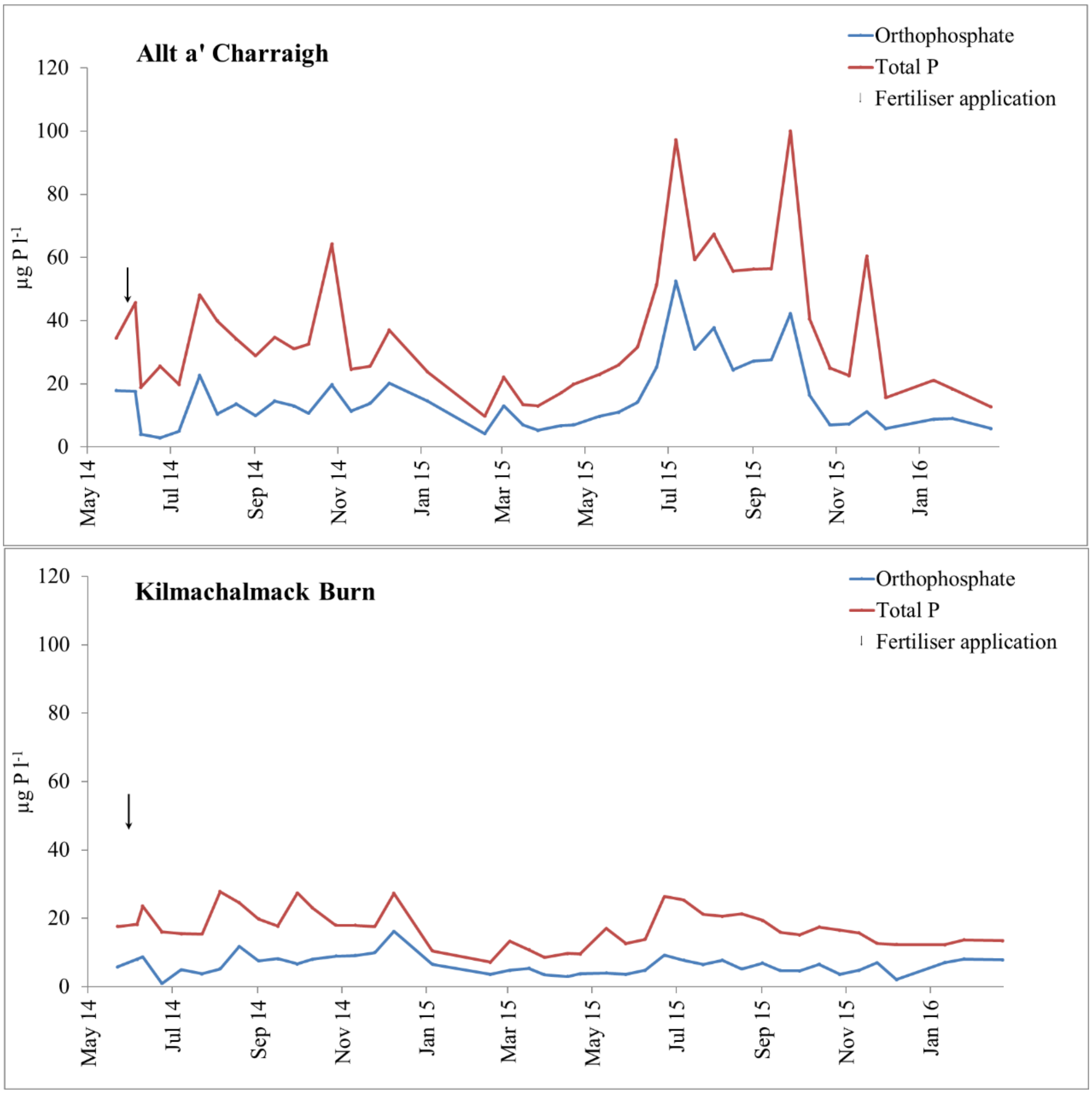

Figure 11 Total P and orthophosphate concentrations at Inveroykel; the arrow indicates the date of the fertiliser application

Torrachilty

Total P concentrations were steadily increasing at the Allt Dearg and in the Peffery Burn in the period preceding the fertiliser application (Figure 12), most likely following the trend of summer/autumn peaks seen at the other monitoring sites, e.g. Tirry control (Figure 14). Following the aerial fertiliser application, orthophosphate concentrations increased in the Peffery Tributary and the Peffery Burn from below the limit of detection (LOD) of 8 µg P l^{-1} to highs of 14 µg P l^{-1} and 16 µg P l^{-1}, respectively, before dropping back to below the LOD by winter 2016. In the absence of baseline data, it is difficult to say whether the increase is related to the fertiliser application or due to background sources. Orthophosphate concentrations were higher at the Allt Dearg increasing from below the LOD in the week before the fertiliser application to a peak of 28 µg P l^{-1} in July 2016; an unexpected result given the low percentage of the catchment fertilised, suggesting that there may be other sources of phosphorus in the catchments. Otherwise concentrations followed the trend of summer peaks and winter troughs. Again, the lack of baseline monitoring makes it impossible to apportion the phosphorus concentrations between the fertiliser applications and background sources. The Allt Dearg continued to be monitored as part of another research project and the results show that orthophosphate concentrations returned to below the LOD in line with the trends seen in previous winters (Figure 12).

In the year after fertilisation, annual means for the Peffery Tributary were 5.8 µg P l^{-1} and 25.3 µg P l^{-1} for orthophosphate and total P, respectively, compared to 6.1 µg P l^{-1} and 23.3 µg P l^{-1} for the Peffery Burn (Table 2). Orthophosphate concentrations at both sites remained below the 13 µg l^{-1} high ecological status WFD standard. Annual means were slightly higher in the Allt Dearg at 12.3 µg P l^{-1} and 30.7 µg P l^{-1}, for orthophosphate and total P, respectively, even though the percentage of the catchment treated at the Allt Dearg was lower than at the Peffery Burn and Peffery Tributary. The higher concentrations are perhaps due to the proximity of the sampling point to the fertilised area; nevertheless, orthophosphate was still below the 13 µg l^{-1} standard.

To summarise, in the Peffery Burn and the Peffery Tributary, orthophosphate concentrations increased following the aerial fertiliser application from levels below the LOD to < 13 µg P l^{-1}, representing a low-level increase that was difficult to separate from background seasonal effects. Another low-level increase in orthophosphate occurred in summer 2017 at these two sites but without a control catchment and baseline data it is not clear whether this increase is wholly, or even partly, due to the fertiliser application in 2016. At the Allt Dearg, we recorded a low-level increase in orthophosphate in the first year after fertilisation but concentrations returned to below the LOD in winter 2017.

In contrast to the other sites, Torrachilty received an NPK application. The results for NH_3-N and NO_3-N are presented in Figure 13 and show NH_3-N to increase at all three sites after the fertiliser application. At the Allt Dearg the NH_3-N concentration peaked at 0.25 mg l^{-1} two days after fertilisation, dropping to 0.07 mg l^{-1} a week later and below the LOD after a further two weeks. At the Peffery Tributary, NH_3-N increased to 0.88 mg l^{-1} two days after fertilisation, had decreased to 0.12 mg l^{-1} one week later and below the LOD a further 3 weeks later. At the Peffery Burn, NH_3-N increased to 0.33 mg l^{-1} two days after the application, decreased to 0.04 mg l^{-1} a week later and below the LOD a further two weeks later. In the year after fertilisation annual means were 0.02 mg l^{-1} for the Allt Dearg, 0.05 mg l^{-1} for the Peffery Tributary and 0.02 mg l^{-1} for the Peffery Burn, with the higher concentration at the Peffery Tributary possibly reflecting the higher percentage of fertilisation in the catchment (Table 1).

The Scotland River Basin District standards (Scottish Government, 2014) for ammonia in rivers vary according to typology (altitude and alkalinity) and are given as both 90th percentile and 99th percentile values, with the latter addressing short-term and intermittent changes in ammonia concentration. After fertilisation the 90th percentile value was 0.03 mg l^{-1} for the Allt Dearg and 0.01 mg l^{-1} at both the Peffery Tributary and Peffery Burn, well below the 0.2 mg l^{-1} NH_3-N standard for high status for Type 1 or Type 2 rivers (> 80m above mean sea level and alkalinity ≤ 50 mg l^{-1} as $CaCO_3$).

The recorded 99th percentile values for total NH_3 were 0.3 mg l^{-1} for the Allt Dearg, 0.4 mg l^{-1} for the Peffery Tributary and 1.1 mg l^{-1} for the Peffery Burn. Therefore, both the Allt Dearg and Peffery Burn results remained below the 0.5 mg l^{-1} high status threshold for total NH_3, while that for the Peffery Tributary fell between the limits for good (0.7 mg l^{-1}) and moderate (1.8 mg l^{-}1) status. The latter represents a very short-lived and localised deterioration in water quality that is unlikely to have a significant biological impact; there was no deterioration downstream in the receiving Peffery Burn. The higher concentrations at the Peffery Tributary reflect the larger scale of the fertiliser application in this sub-catchment, 16.8% versus 9.4% and 2.3% in the Peffery Burn and Allt Dearg, respectively (Table 1). The results are in accordance with the findings of Nisbet and Stonard (1995) who found that urea applications to more than 15% of a catchment could cause ammonium concentrations to exceed water quality standards; they suggested that fertiliser wash-off was the main mechanism by which ammonium entered the watercourse with the risk greatest on saturated ground. No buffer areas were used in their study and it is possible that the breaches to the buffer area in the Peffery Tributary, as seen on the helicopter spread pattern, was responsible for the spike in ammonia concentration. A light shower was noted at Torrachilty on the day of the fertiliser application (7 mm of rain recorded at Dingwall (MetOffice, 2017)) and on the day after, which may also have had a bearing on the NH_3-N increase recorded two days after the application.

Nitrate-N concentrations remained below the LOD before and after fertilisation in the Allt Dearg (Figure 13). A small nitrate peak occurred in the Peffery Burn on 9th May 2016 but it was around 2 weeks before fertilisation and there was no increase at the other two sites, indicating another cause or background effect. NO_3-N increased to 0.32 mg l^{-1} on 8th June 2016 in the Peffery Tributary around 3 weeks after fertilisation and returned to below the LOD by the end of June. This is possibly a delayed release of nitrate following fertilisation but the concentration is very low. Nitrate-N increased again in the Peffery Tributary and Peffery Burn in January 2017, peaking at 0.25 mg l^{-1} in the former and 0.51 mg l^{-1} at the latter. Concentrations returned to below the LOD in the Peffery Tributary by 21st February 2017, whilst intermittent releases continued in the Peffery Burn until 18th April 2017.

Whilst it is possible that the fertiliser application is the source of the NO_3-N released, we cannot say for sure due to the absence of a control site and the lack of baseline data. Moreover, the NO_3-N release at the Peffery Burn before fertilisation suggests that there are background sources of NO_3-N within the catchment. From the point of view of this study, the important point is that NO_3-N concentrations remained very low, never exceeding 0.51 mg l^{-1}.

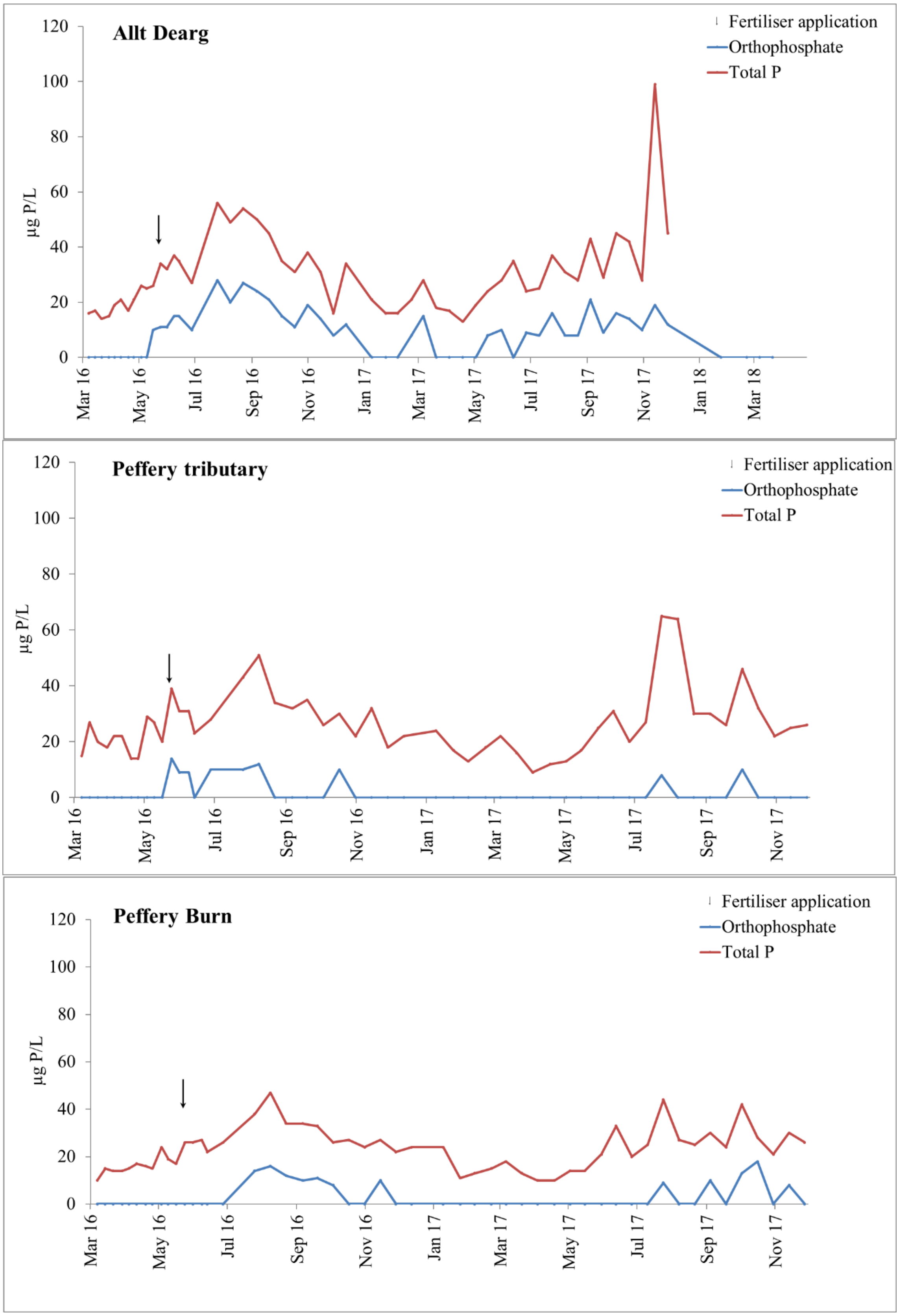

Figure 12 Total P and orthophosphate concentrations at Torrachilty; the arrow indicates the date of the fertiliser application

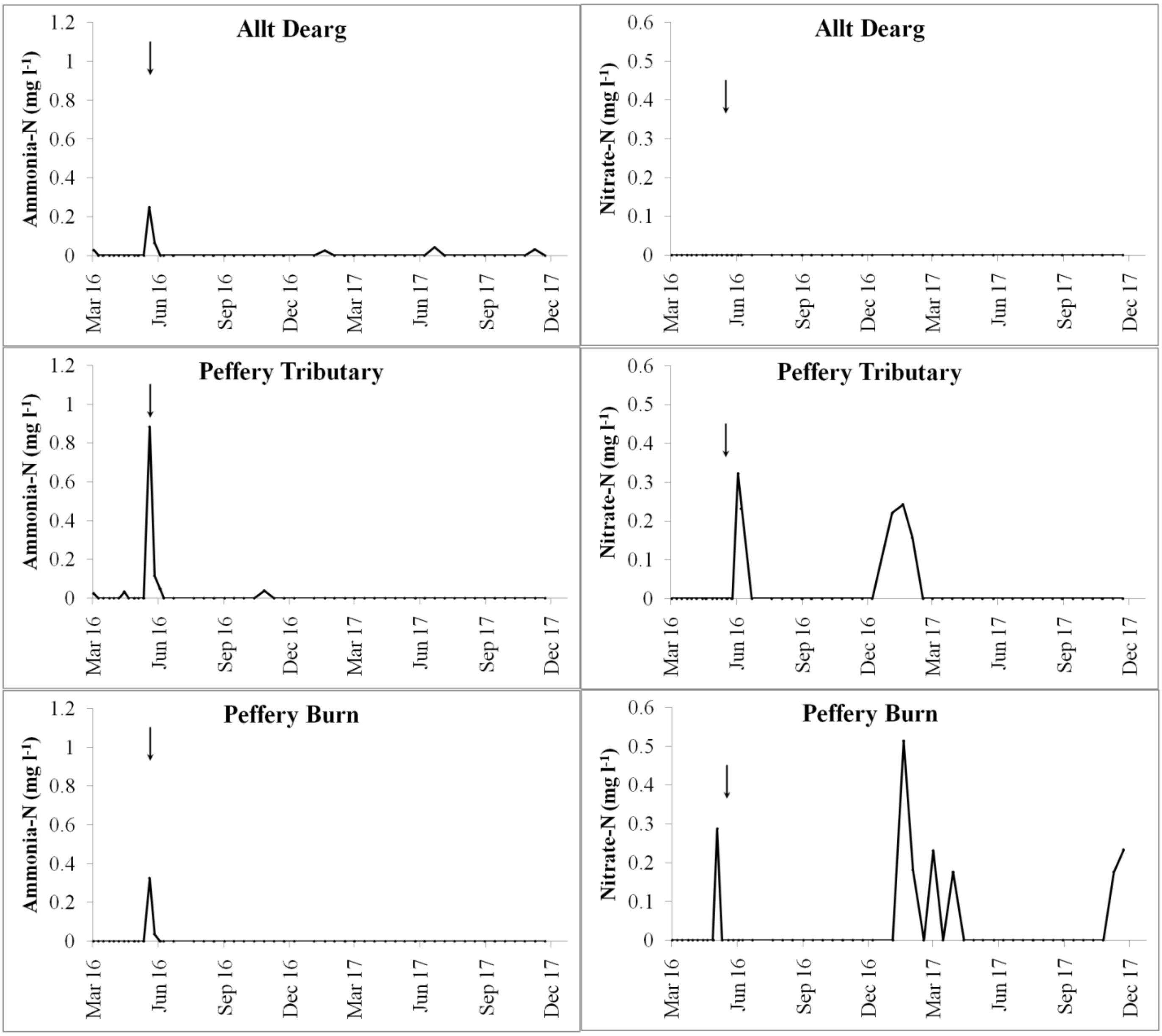

Figure 13 Ammonia-N and Nitrate-N concentrations at Torrachilty; the arrow indicates the date of the fertiliser application

4.2 Hand fertiliser applications

S. Dalchork (Loch Shin)

Both total P and orthophosphate showed a small increase during the hand fertiliser application period at the Mid-Dalchork site (Figure 14), but it was within the background range recorded in the monitored catchments, including the Tirry control, indicating that the rise was not due to the hand fertiliser application. The cause is thought to be a natural response to the period of heavy rainfall that occurred in the week before the measured peak, when the highest daily rainfall total (41 mm) of 2014 was recorded. Orthophosphate levels proceeded to decline during the following months after the fertiliser application, as with the Oykel sites, reaching minimum values in early 2015. Two baseline samples were taken at the S. Dalchork sites prior to the hand fertiliser application and the results indicate that total P and orthophosphate concentrations were elevated prior to the fertiliser application and returned to what appear to be natural winter background levels by January 2015, similar to the trend at the Craggie and Inveroykel sites (Figures 10 and 11).

Both total P and orthophosphate increased in summer 2015 at the two fertilised sites and in the River Tirry control, suggesting a natural seasonal response. The increase at mid-Dalchork in September 2015 is larger than at the River Tirry control and could be related to felling that took place in the catchment at the end of August and early September. Peaks in summer 2016 and 2017 are seen at all three sites, again suggesting a natural seasonal trend. The peak at mid-Dalchork in August 2017 was most likely a result of heavy rainfall following a dry period. It is not clear why the peak was only seen at this site but could be due to an isolated convective thunderstorm; in any case, the concentration of orthophosphate was still relatively low at 16.1 $\mu g\ P\ l^{-1}$.

After fertilisation, annual means for orthophosphate are below the 13 $\mu g\ l^{-1}$ high ecological status WFD standard at all sites (Table 2); the annual means are lower within the fertilised catchments compared to the River Tirry control indicating that there was very little if any water quality deterioration after the hand application.

Except for a few points during the baseline period in the Tirry Tributary North, orthophosphate concentrations remained below the LOD before, during and after the hand fertiliser application at N. Dalchork (Figure 15); this is despite fertilisation of 77% of these sub-catchments, further emphasising the absence of any adverse water quality impact following hand fertiliser applications. As with other sites, phosphorus concentrations appeared to be decreasing from summer highs to winter lows. There was no trace of any orthophosphate or total P release from the time of the fertiliser application until monitoring ceased in January 2019.

Hand fertiliser applications, which are targeted to the base of individual trees, have generally been shown to result in little or no fertiliser loss to runoff (Roberts et al., 1986 in Nisbet, 2001); our results support this conclusion and indicate that the 10 m buffers and other aspects of good practice were effective in protecting water quality at both North and South Dalchork. The source of the rise in TP concentrations recorded in the summer/autumn of 2015, 2016 and 2017 at all three sites at S. Dalchork could be seasonal/climatic effects, including rainfall-runoff induced soil or bank erosion, generating particulate P, as well as increased phosphorus leaching from soil horizons. This could involve both natural P (weathering), losses from previous fertiliser treatments, as well as forest felling activity. Further investigation of the soils and past land use activities in the Loch Shin catchment would be required to try and separate these contributions.

Table 2 Pre-fertiliser levels and annual means[1] (μg P l^{-1}) for orthophosphate and total phosphorus (latter given in parentheses); maximum and minimum recorded values are also shown.

Time in relation to fertilisation	**Craggie**			**Inveroykel**		**Torrachilty**			**S. Dalchork**		
	Ruchain	**CRD**	**Chonachair**	**Charraigh**	**Kilmachalmach**	**Dearg**	**Trib**	**Peffery**	**Lethaid**	**Dalchork**	**Tirry**
Pre-fertiliser[2]	n/a	3.8 (20)	2.4 (8.9)	17.9 (34.4)	5.8 (17.6)	5 (19.7)	<LOD (20.7)	<LOD (16)	9.6 (29.4)	4.5 (12.8)	5 (19.9)
Post fertiliser											
1st year after application	3.1 (11.8)	5 (18.8)	2.5 (7.7)	11.2 (28.3)	6.5 (17.1)	12.3 (30.7)	5.9 (25.3)	6.1 (23.3)	4 (15.1)	4.1 (10.9)	5.9 (15.9)
2nd year after application	3.6 (13.1)	7 (25.9)	2.5 (8.2)						3.6 (13.7)	3.7 (11)	5.6 (15.2)
3rd year after application	2.2 (8.6)	2.8 (18.0)	1.5 (6)						3.1 (11.8)	3.3 (10.8)	4.6 (12.3)
4th year after application	3.3 (11.0)	2.9 (13.9)	2.3 (8.2)								
Maximum	12.4 (41.2)	44.8 (134)	11.9 (25.8)	52.5 (100)	16.2 (27.8)	28 (56)	14 (65)	16 (47)	14.2 (34.2)	18.2 (37.7)	10.8 (28.4)
Minimum	< 2 (2.4)	< 2 (4.6)	< 2 (2.5)	2.9 (9.8)	1 (7.2)	8 (13)	8 (9)	8 (10)	1 (7.4)	1 (3.6)	2.3 (6.8)

[1] Annual means are calculated on 12-month periods post-fertiliser application.

[2] Pre-fertiliser periods vary between sites as shown on the graphs above but were very short.

LOD – limit of detection

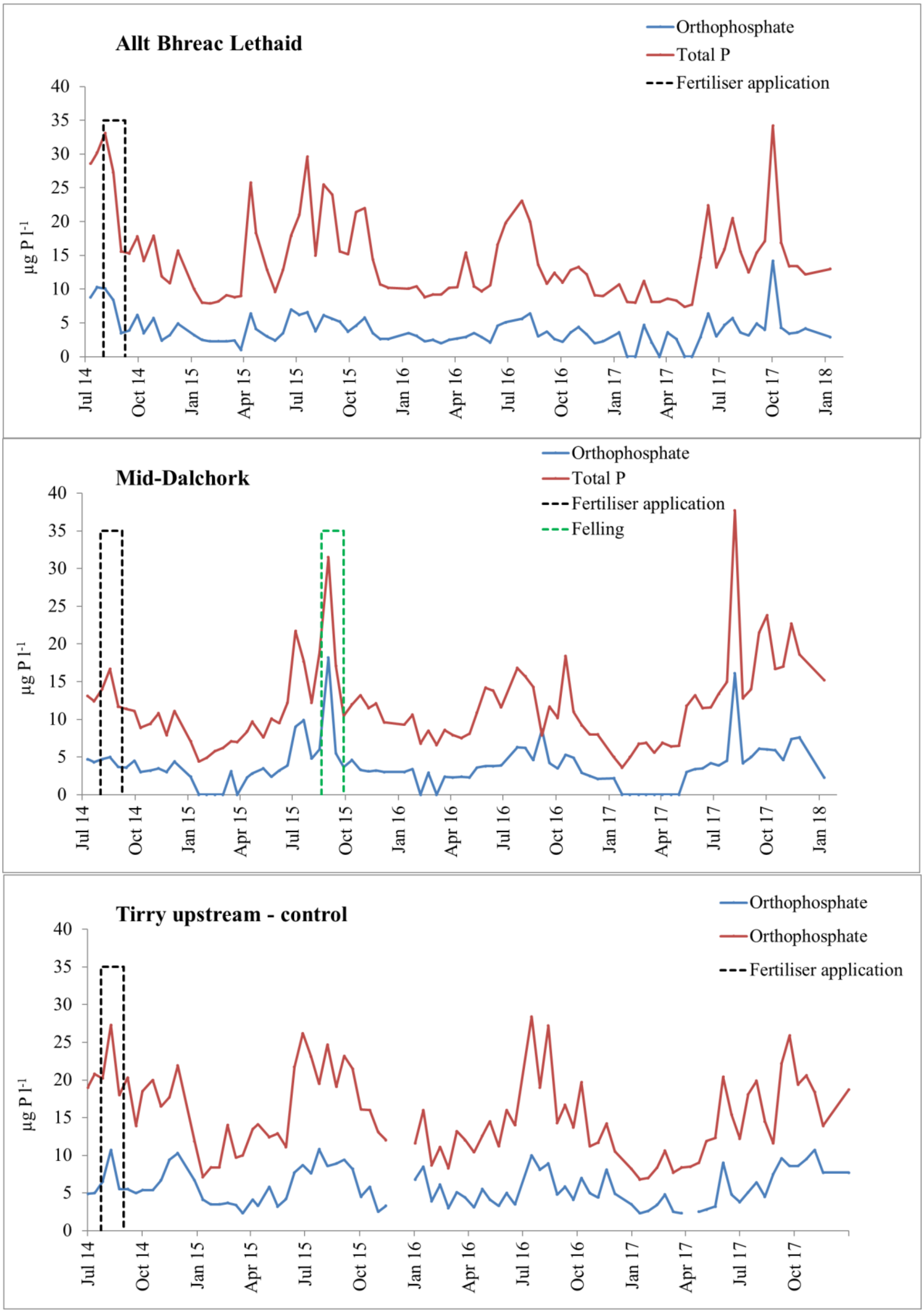

Figure 14 Total P and orthophosphate concentrations at S. Dalchork; the black, dashed rectangle demarcates the fertiliser application period; the green, dashed rectangle indicates the felling period in the mid-Dalchork catchment.

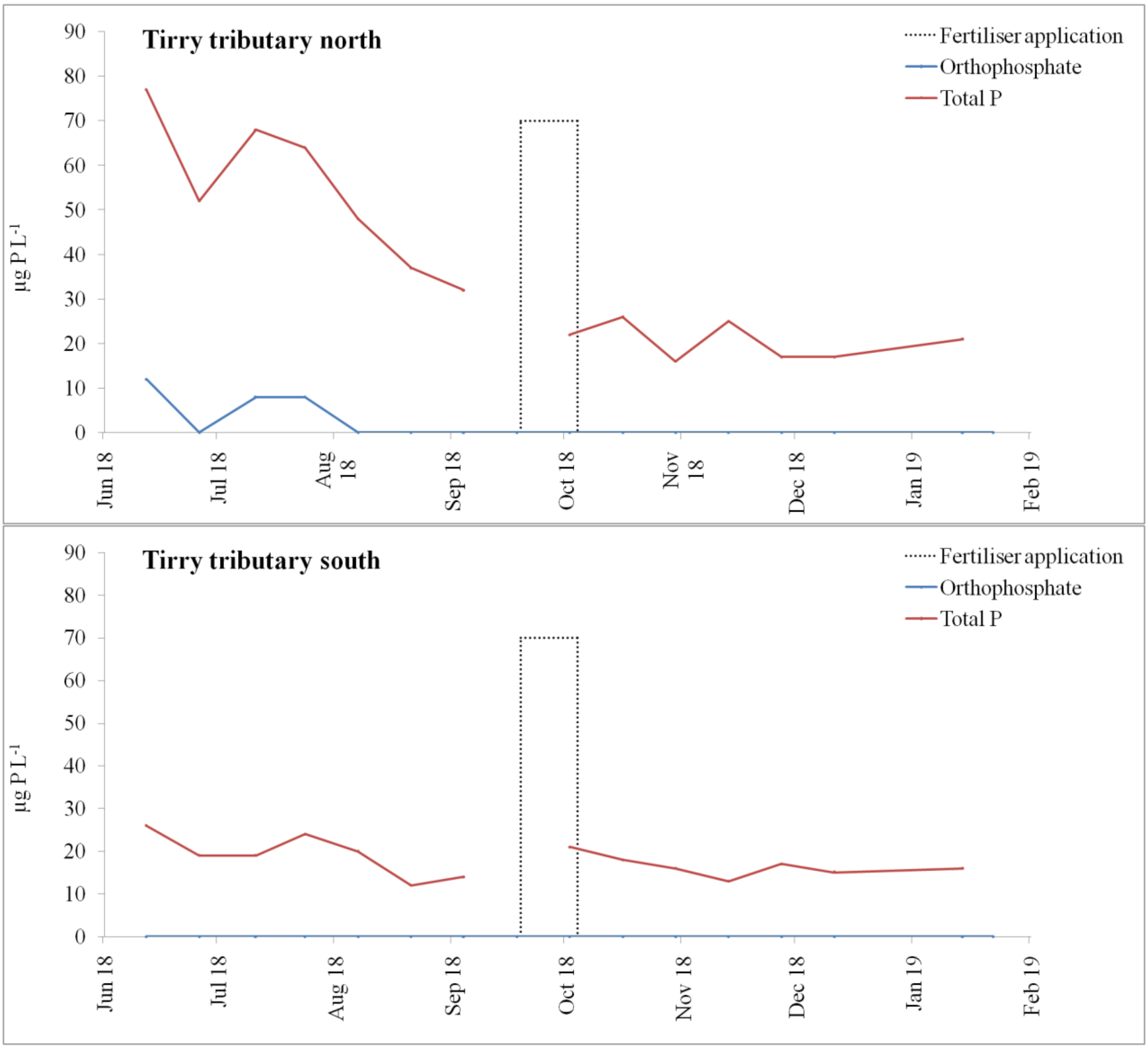

Figure 15 Total P and orthophosphate concentrations at N. Dalchork; the black, dashed rectangle demarcates the fertiliser application period.

5. Findings

- Aerial fertiliser applications were generally followed by increases in both orthophosphate (the reactive form) and total P concentrations in waters draining the fertilised areas, although these were often difficult to separate from background seasonal variation. Apart from a few isolated peaks, stream water orthophosphate concentrations remained overall low with annual means of < 7 µg P l^{-1} for the Craggie streams, < 11.3 µg P l^{-1} for the Inveroykel streams and < 12.4 µg P l^{-1} for the Torrachilty streams, all of which are below the 13 µg l^{-1} high ecological status standard for annual mean reactive phosphorus that applies to these upland, low alkalinity rivers (UKTAG, 2013).

- The results indicate that by following the UKFS Water Guidelines (Forestry Commission, 2017; Forestry Commission, 2019) and employing good practice measures, e.g. the use of 50 m buffers, there should be no adverse impacts of aerial phosphorus applications on water quality or ecology, even when up to 63% of the catchment is fertilised.

- Following the aerial application of NPK fertiliser to sub-catchments of the Peffery Burn, an immediate and very short-lived increase in ammonia-N was seen in all three monitored streams. The 90th percentile value for NH_3-N was 0.03 mg l^{-1} for the Allt Dearg and 0.01 mg l^{-1} at both the Peffery Tributary and Peffery Burn, well below the 0.2 mg l^{-1} NH_3-N high status standard for Type 1 or Type 2 rivers (> 80m above mean sea level and alkalinity ≤ 50 mg l^{-1} as $CaCO_3$).

- In terms of short-term and intermittent changes in the total ammonia (99th percentile), concentrations in the Allt Dearg and Peffery Burn were below the 0.5 mg l^{-1} high status threshold while that for the Peffery Tributary (1.1 mg l^{-1} total NH_3) fell between good (0.7 mg l^{-1}) to moderate (1.8 mg l^{-}1) status, indicating a deterioration in water quality in this watercourse, which was thought to be due to breaches of the buffer area. The results are in line with Nisbet and Stonard (1995) who found that aerial applications of nitrogen fertiliser (without buffers) to > 15% of the catchment can lead to a breach of the ammonia water quality standard. However, the brief nature and relative size of response was unlikely to exert a biological impact; the temporary exceedance of the standard was restricted to the tributary catchment and effectively diluted in the receiving Peffery Burn.

- A low-level nitrate-N increase was seen at the Peffery Tributary in the month after fertilisation, but no such increase was seen at the other two streams indicating a localised release that may have been related to the fertiliser application. Further low-level increases were seen in early 2017 at the Peffery Tributary and Peffery Burn, but not at the Allt Dearg, and could be related to meteorological conditions, namely snowfall and subsequent snowmelt. From the point of view of this study, the important point is that NO_3-N concentrations were very low, never exceeding 0.51 mg l^{-1}.

- There was very little or no obvious response in phosphorus concentrations to the hand fertiliser application in the Loch Shin sub-catchments. A peak in TP and orthophosphate concentrations in the mid-Dalchork site in September 2015 could have been related to forest felling within the catchment and a forestry contribution to another peak in August 2017 cannot be ruled out, however these were isolated events atypical of a felling response and had little effect on annual means.

- The lack of baseline data made it difficult to apportion phosphorus concentrations between natural sources and fertiliser treatments. However, results from the few pre-fertilisation samples collected, together with those for the River Tirry control site, suggest that much of the recorded seasonal variation in TP concentrations was due to background contributions, particularly associated with autumn rainfall events and spring and summer low flows. The source of the background phosphorus could be natural (weathering), historic fertiliser applications or forest felling, and further investigation of the soils and past land use activities would be needed to try and separate these.

- This study shows that carefully planned aerial and hand fertiliser applications adhering to UKFS Water Guidelines and supporting guidance do not result in adverse water quality or ecological changes in nutrient sensitive waters.

6. Recommendations

- The results indicate that routine monitoring of fertiliser applications is not required, but it may be prudent to monitor water quality in particularly sensitive areas.

- In terms of nitrogen, overflying of the mid-section of the Peffery Tributary was thought to be responsible for the short-term rise in the total ammonia concentration (99th percentile) breaching good water status. This highlights the need for greater care in identifying and avoiding the treatment of buffer areas, especially where the treated area drains to nutrient-sensitive waters.

- It is recommended to use the results of this monitoring to inform future updates to UKFS Water Guidelines and GBRs related to fertiliser use in forestry (GBR 18).

- One research need is to explore the source of background phosphorus fluctuations within these sensitive catchments; consideration could be given to the use of stable isotope analysis or chemical fingerprinting techniques to help determine the precise sources of phosphorus within the studied catchments.

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