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P and K additions enhance canopy N retention and accelerate the associated leaching

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Abstract

This study evaluated the interactive effects of combined phosphorus (P) and potassium (K) additions on canopy nitrogen (N) retention (CNR) and subsequent canopy leaching at a long-term N manipulation site on Whim bog in south Scotland. Ambient deposition is 8 kg N ha^{-1} yr^{-1} and an additional 8, 24, and 56 kg N ha^{-1} yr^{-1} of either ammonium (NH_4^+) or nitrate (NO_3^-) with or without P and K has been applied over 11 years. Throughfall N deposition below *Calluna vulgaris* and foliar N and P concentrations were assessed. Results showed that 60 % for low dose and 53 % for high dose of NO_3^- and 80 % for low dose and 38 % for high dose of NH_4^+ onto *Calluna* was retained by *Calluna* canopy. The CNR was enhanced by P and K addition in which 84 % of NO_3^- and 83 % of NH_4^+ for high dose were retained. CNR for NO_3^- increased the canopy leaching of dissolved organic N (DON) and associated organic anions. NH_4^+ retention increased canopy leaching of magnesium and calcium through ion exchange. Even over 11-years N exposure without P and K, foliage N:P ratio of *Calluna* did not increase, suggesting that N exposure did not lead to N saturation of *Calluna* at this study site. Our study concluded that increases in P and K availability enhance CNR of *Calluna* but accelerate the associated canopy leaching of DON and base cations, depending on foliar N status.

Keywords: Manipulation experiment; peatland; *Calluna vulgaris*; dissolved organic nitrogen; base cations; long-term study

Introduction

Atmospheric nitrogen (N) deposition has been increasing on a global scale (Galloway et al. 2008) and may affect peatland ecosystems which are sensitive to increased N deposition (Bobbink et et al. 1998). *Calluna vulgaris*, one of the dominant canopy-forming species on many peatlands, can modify throughfall deposition (Bobbink et al., 1992). Understanding of canopy nitrogen (N) retention (CNR) and which factors affect retention is essential to quantifying total atmospheric N deposition and to evaluate its ecological effects. CNR has been widely observed in throughfall measurements (Lovett and Lindberg 1993; Lovett et al., 1996; Staelens et al. 2008; Aguillaume et al., 2017; Avila et al., 2017; Pinkalski et al., 2018). In N manipulation experiments, the application of aliquots of N directly to the canopy (Cape et al. 2001; Chiwa et al. 2004; Gaige et al. 2007), has shown that CNR can lead to underestimation of total atmospheric N deposition. CNR often exceeded 75% of total N deposition to coniferous forests during the growing season in the Niwot Forest with low (3 kg N ha^{-1} during the growing season) atmospheric N deposition (Tomaszewski et al. 2003; Sievering et al. 2007). Even at a site with moderate or high (17–96 kg N ha^{-1} $year^{-1}$) atmospheric N deposition, the canopy may retain up to 40% (Lovett and Lindberg 1993; Chiwa et al. 2004) and 70% of total N deposition (Gaige et al. 2007), respectively. CNR is an important factor affecting the impact of elevated atmospheric N deposition on forest C sequestration (Tomaszewski and Sievering, 2007; Dezi et al., 2010; Chiwa et al., 2012), suggesting the likelihood of an important link with C sequestration in *Calluna*, a key component of peatland canopies.

Several researchers have explored factors affecting CNR including tree species (Brumme et al., 1992; Eilers et al., 1992), canopy leaf area (Lovett et al., 1996; Wuyts et al., 2008), leaf phenology (Houle et al., 1999; Hagen-Thorn et al., 2006), and leaf surface condition (Boyce et al., 1991; Sase et al., 2008; Adriaenssens et al., 2011). However, little information exists concerning the interactive effect of the availability of other nutrients such as phosphorus (P) and potassium (K). Our first hypothesis is that increases in P and K availability enhance the CNR, because P and K are also limiting in wetlands in addition to N (Venterink et al., 2002).

The process of CNR remains elusive, especially for NO_3^-. Chiwa et al. (2016) showed that NO_3^- retention by *Sphagnum* moss caused the leaching of DON and organic anions from *Sphagnum*. However, it remains to be shown whether this process can be applied to vascular plants. Canopy retention of NH_4^+ is usually accompanied by base cation leaching (Bobbink et al., 1992; Krupa, 2003; Li et al., 2013; Staelens et al., 2008; Stevens et al., 2011) and hydrogen ion (H^+) leaching (Krupa, 2003; Liu et al., 2013; Manninen et al., 2011; Paulissen et al., 2004; Stevens et al., 2011; Tomassen et al., 2003). Our second hypothesis is that the enhanced CNR by P and K addition accelerates canopy leaching including DON and base cations.

To test these two hypotheses, this study aimed to 1) quantify CNR of *Calluna* exposed with/without P and K addition and 2) explore the leaching from the canopy when NO_3^- and NH_4^+ are taken up by a *Calluna* canopy with/without P and K. These objectives were addressed using the N manipulation experiment on Whim bog in SE Scotland where the theoretical input to the *Calluna* canopy can be calculated using known concentrations and volumes of N treatments, giving us information about the input-output balances of ions through a canopy and the possibility of exploring the processing of nitrogen retention in the *Calluna* canopy.

Materials and Methods

Study site

This study was conducted at an N manipulation experiment on 3-6 m of deep peatland (282m a.s.l., 3°16'W, 55° 46'N) at Whim bog located *c.* 30 km south of Edinburgh in Scotland. No active management has been conducted for at least 70 years. The vegetation is dominated by *Calluna vulgaris, Eriophorum vaginatum*, *Sphagnum capillifolium*, *Hypnum jutlandicum*, *Pleurozium schreberi* and *Cladonia portentosa* which occur widely on similar habitats through the northern hemisphere (Gore, 1983). Ambient N deposition is 8 kg N ha^{-1} yr^{-1}, consisting of wet deposition for NH_4^+ (*ca.* 3 kg N ha^{-1} yr^{-1}) and NO_3^- (*ca.* 3 kg N ha^{-1} yr^{-1}), and dry deposition for NH_3 (2 kg N ha^{-1} yr^{-1}) (Leith et al., 2004; Sheppard et al., 2004; Sheppard et al., 2014). Mean annual values (and corresponding ranges) of temperature and precipitation between 2003 and 2013 were 7.9 (5.9 – 9.0) °C and 1,124 (734 – 1,486) mm, respectively.

Treatments

The experimental peatland area was divided into four replicated blocks each containing eleven 12.8 m^2 circular plots. To avoid contamination from adjacent plots, plots are 3 m apart. The eleven different N treatments (Table 1), replicated in four plots, have been supplied to each plot from a central spinning disc generating fine rain droplets all year round since June 2002 (Sheppard *et al.*, 2004). The wet N treatments are in addition to the estimated ambient deposition of *ca.* 8 kg N ha^{-1} yr^{-1} and supply 10 % additional rainwater (Sheppard *et al.*, 2014). Potassium hydrogen phosphate (K_2HPO_4) adjusted in a 1:14 molar ratio (1:14 and 1:7 for P and K, respectively) to N was used as the P and K treatments. Treatments are applied automatically when weather conditions meet the following criteria: sufficient rainfall in the holding tanks, air temperature > 0 °C and wind speed < 5 m s^{-1} simulating a much more realistic frequency scenario *ca.* 120 applications yr^{-1} (Sheppard *et al.*, 2014).

Sampling and chemical analysis

Six samplings were conducted for throughfall under *Calluna vulgaris* between July and October 2013 (Table 2). During the sampling period, 35 individual rainfall events, defined as > 1 mm of continuous precipitation over 6 hours, occurred, of which, 63%, 22 rainfall events were collected in this study (Table 2). The six samplings were also typical events in terms of rainfall intensity (Table 2).

Before the sampling occurred the *Calluna* which is mostly in the mature/degenerate phase (Sheppard et al., 2011; Carfrae et al., 2007) had already received 11 years of N treatment. Throughfall collectors for *Calluna* were made of a silicone tube cut lengthwise (width 2.8-3.2 mm × length 150 – 200 mm: *c.* 50 cm^2) draining into a 150 ml square polyethylene bottle. Prior to sampling, the sample bottles (100 mL HDPE) and tubes were placed into a 1% Decon solution (Decon 90, Decon Laboratories Limited, East Sussex, UK) for at least 24 h and then washed with distilled water. After drying, the tube was connected to the polyethylene bottle using duct tape. The projected area of the tube was measured with a ruler.

One throughfall collector was randomly placed under green *Calluna vulgaris* shrubs (height 30-50 cm) in control and N treated plots prior to a rain event. Precipitation was also collected in the open area at the study site using three collectors, each with a 20 cm diameter polyethylene funnel mounted 1.5 m above ground, draining to a 2 litre polyethylene bottle.

Collected water samples were immediately transported back to the nearby laboratory where aliquots were filtered through a 0.45 µm membrane filter (Puradisc^{TM}, Whatman Inc., NJ, USA), and stored in the dark at 4°C. The following chemical determinations were carried out on the filtered pore water samples: pH by glass electrode (MP220, Mettler Toledo, Leicester, UK), major ions (Cl^-, NO_3^-, SO_4^{2-}, Na^+, K^+, Ca^{2+}, and Mg^{2+}) by ion chromatography (CH-9101, Metrohm, Herisau, Swizerland), NH_4^+ by AMmonia Flow Injection Analyser (AMFIA, ECN; Wyers *et al.* 1993), and dissolved total nitrogen by HPLC with a nitrogen specific detector (Model 8060, Antek Instruments, Houston, USA). Dissolved inorganic N (DIN) concentrations were calculated as the sum of NO_3^- and NH_4^+. The concentrations of dissolved organic nitrogen (DON) were calculated by subtracting DIN from the total N concentrations. Anion deficits were calculated by subtracting total anion ($Cl^- + NO_3^- + SO_4^{2-}$) concentration from total cation ($H^+ + Na^+ + NH_4^+ + K^+ + Mg^{2+} + Ca^{2+}$) concentration.

Foliage sampling

To evaluate the nutrient status of *Calluna* in control and N treated plots, *Calluna* foliage (current year) was collected at the beginning of December 2013. One sample of foliage was collected in each plot from similar green *Calluna* shoots. Collected foliage samples were transported to the laboratory, then dried at 70 °C for 72 h, and ball milled. Total N in foliage was determined by the combustion method (CN Corder MT-700; Yanaco Co., Ltd., Tokyo, Japan). For P, the dried samples were heated at 550 °C for 2 h, then digested using potassium peroxodisulfate ($K_2S_2O_8$), and the P content was measured using the molybdenum blue (ascorbic acid) spectrophotometric method (UV mini-1240; Shimadzu, Kyoto, Japan). Standard reference material (NIST Apple Leaves 1515; National Institute of Standards and Technology, Gaithersburg, MD, USA) was analyzed along with leaf samples to ensure accuracy within 5% of known N and P concentrations.

Calculation and statistical analysis

CNR of NO_3^- and NH_4^+ by *Calluna* was calculated using the following equations:

$$NO_3^-\ uptake_{plot\ x} = (Na^+_{plot\ x} - Na^+_{control}) - NO^-_{3\ plot\ x}$$

$$NH_4^+\ uptake_{plot\ y} = (Cl^-_{plot\ y} - Cl^-_{control}) - NH^+_{4\ plot\ y}$$

where the unit is µmol m^{-2} for the ions in throughfall. $Na^+_{control}$ and $Cl^-_{control}$ concentrations were averaged over the 4 control plots.

In calculating the retention of N from the treatments in each plot, it was assumed that the counter ions (ions of opposite charge in a solution) of oxidized and reduced N treatments (*i.e.* Na^+ for NO_3^- and Cl^- for NH_4^+) were not retained by *Calluna*, but acted as conservative tracers, allowing the total amount of applied N to be estimated from the throughfall of the counter ions. This assumption is based on the premise that Na^+ and Cl^- in pore water are derived only from atmospheric deposition, such as rainfall, and the treatment supplied in this study. Conservative tracer behaviour has been shown for both Na^+ (Eppinga *et al*., 2008; Staelens *et al*., 2008) and Cl^- (Appelo and Postma, 1994; Bragazza *et al*., 2005).

Spearman's rank correlation coefficient (*r*) was used to examine the relationships between CNR of NO_3^- or NH_4^+ and DON and the sum of Mg^{2+} and Ca^{2+}deposition. Statistical differences in deposition of DON, Mg^{2+} and Ca^{2+}, and anion deficit among the plot were determined using Tukey's honest significant difference test followed by analysis of variance. Statistical analyses were carried out using SPSS 22.0J (SPSS Japan Inc., Tokyo, Japan).

Results

Throughfall deposition of NO_3^- and NH_4^+ below the *Calluna* canopy was 3.5 and 5.5 times respectively lower than bulk precipitation to the canopy (Figure 1). Figure 2 shows the relationship between throughfall NO_3^- and counter ions of Na^+ (conservative tracer) (Figure 2a) and NH_4^+ and counter ions of Cl^- (conservative tracer) (Figure 2b). There were linear relationships with slope value of 0.40 and 0.47 for NO_3^- of lower (8-32 kg N ha^{-1} yr^{-1}) and higher (16-64 kg N ha^{-1} yr^{-1}) dose respectively (Figure 2a) and I still don't understand why low is designated 8-32 and high 16=64 what do these values represent why not 16 1nd 64 ?????0.20 and 0.62 and for NH_4^+ of lower (8-32 kg N ha^{-1} yr^{-1}) and higher (16-64 kg N ha^{-1} yr^{-1}) dose respectively (Figure 2b). Calculating from the slope values, 60 % for low dose and 53 % for high dose and 80 % for low dose of NO_3^- and 38 % for high dose of NH_4^+ total (ambient deposition plus fertilization) inputs onto *Calluna* were retained by *Calluna*.

Slope values with P and K addition were lower for NO_3^- (0.16, Figure 2a) and NH_4^+ (0.17, Figure 2b) for the higher N doses (16-64 kg N ha^{-1} yr^{-1}) than those without P and K, indicating the positive effects of P and K additions on CNR. Based on the slope values, 84 % of NO_3^- and 83 % of NH_4^+ total (ambient deposition plus fertilization) inputs onto the *Calluna* canopy were retained. Therefore, PK addition increased CNR by 31% (53 → 84%) and 45% (38 % → 83%) for NO_3^- and NH_4^+, respectively. There were significant differences in water depth, amount of deposition collected, of throughfall among treatments (Figure 3).

There was a significant positive relationship between NO_3^- retention by the *Calluna* canopy and the concentration of DON in throughfall (Figure 4a), but there was no increase in throughfall DON with retention of NH_4^+ by the *Calluna* canopy (Figure 4b). There was a significant positive relationship, with slope value of 0.49, between NH_4^+ retention by the *Calluna* canopy and the sum of magnesium (Mg^{2+}) and calcium (Ca^{2+}) in throughfall (Figure 4d). There was a significant positive relationship between anion deficit and DON concentration (Figure 5a). DON deposition (Figure 6a) and deposition of anion deficits (Figure 6c) were significantly higher for Nox 56PK and Mg^{2+} and Ca^{2+} deposition (Figure 6b) was significantly higher for Nred 56PK, indicating significance of P and K addition. Figure 7 illustrates the total amount of N deposition collected under the canopy exposed to N with and without P and K addition. P and K addition substantially increased CNR for both Nox and Nred and DON leaching for Nox affecting the total N deposition under the *Calluna* canopy.

Foliar N:P ratio in *Calluna* exposed to different levels of N addition did not increase even after 11-years exposure without P and K (Figure 8a) and with P and K (Figure 8b). Foliar N (Figure 8cd) and P (Figure 8ef) concentrations of *Calluna* increased with increasing N deposition.

Discussion

Calluna *CNR*

The presence of a *Calluna* canopy in peatlands will modify throughfall N deposition (Figure 1), as suggested by Bobbink et al. (1992). Lower throughfall deposition of NO_3^- and NH_4^+ than bulk precipitation indicates CNR by the *Calluna* canopy. In contrast, higher throughfall deposition of DON could be due to canopy leaching of dissolved organic matter (DOM) and canopy processing of wet or dry-deposited inorganic nitrogen (Cape et al., 2010). Quantifying CNR is of great importance for precise quantification of atmospheric deposition of pollutants using throughfall collection. CNR has been widely observed in throughfall measurements (Lovett and Lindberg 1993; Staelens et al. 2008; Aguillaume et al., 2017; Avila et al., 2017; Pinkalski et al., 2018) and in N manipulation experiments applied directly to the tree canopy (Cape et al. 2001; Chiwa et al. 2004; Gaige et al. 2007). However, these studies mostly focused on trees in upland forests, althoughCNR has also been observed in heathland (Bobbink et al., 1992; Limpens et al., 2004). Bobbink et al (1992) recorded N retention of between 40-90% of net throughfall. Here we discriminated between the N forms and against a background of 11 years of known deposition and measured similar amounts of retention. Our results for retention, even after 11 years' N applications (Figure 2) were 60 % for low dose and 53 % for high dose of NO_3^- and 80 % for low dose and 38% for the high dose of NH_4^+ total (ambient deposition plus fertilization). Different slope values between high and low doses of NH_4^+ (Figure 2b) indicate that the capacity for canopy NH_4^+ retention varies with the dose of atmospheric NH_4^+ deposition.

Increased CNR by P and K addition

Lower slope values with P and K addition than those without P and K (Figure 2) suggest that P and K additions enhance CNR of *Calluna*, supporting the first hypothesis. 84 % of NO_3^- and 83 % of NH_4^+ total (ambient plus fertilization) inputs onto *Calluna* was retained by *Calluna* canopy, exceeding the 53 and 38 % of retention for NO_3^- and NH_4^+ by the *Calluna* canopy without P and K addition.

The reason for the increased CNR by P and K addition cannot be established from this study, but it may have to do with enhanced N demand of *Calluna* exposed to P and K treatment. Enhanced CNR could be caused by increased canopy area resulting from increased biomass production and/or increased physiological activity per unit of surface area. Canopy area is an important contributor to CNR (Lovett 1996 et al., 1996). However, we have no evidence that the *Calluna* canopy area increased in response to P and K addition. Although the morphology of the *Calluna* canopies exposed to various treatments was not estimated in this study, water depth of throughfall (Figure 3) indicates that the canopy area of *Calluna* exposed to N treatment with P and K addition does not exceed the control or those without P and K addition, because throughfall volume is inversely proportional to canopy area under the same meteorological condition, reflecting canopy interception loss (Levia et al., 2006). It is possible that physiological activity per unit of canopy area increased in response to P and K addition. The increased physiological activity of the canopy may be the result of increased physiological activity of the shoots, but also of any epiphytes living on the leaves which may be responsible for some of the canopy exchange reactions observed. Measurements of photosynthesis made around the same time, LICOR in the field, did not reveal significant treatment differences (Owen S. pers comm). P and K addition did have positive effects on N assimilation of *Sphagnum* moss, non-vascular plant (Limpens et al., 2004). However, to our knowledge, this is the first study showing that increases in P and K availability enhance canopy N retention by vascular plants.

Increased DON and cation leaching with NO_3^- and NH_4^+ canopy retention by P and K addition

The significant positive relationship between NO_3^- retention by the *Calluna* canopy and DON deposition in throughfall (Figure 4a) but no increase in DON deposition with NH_4^+ retention by the *Calluna* canopy (Figure 4b) indicates the link between DON leaching and *Calluna* canopy NO_3^- retention, as found for *Sphagnum* moss (Chiwa et al. 2016). DON leaching appears to be associated with the leaching of organic N anions to retain the charge balance when NO_3^- is taken up, as suggested by the significant positive relationship between anion deficit and DON concentration (Figure 5a).

The significant positive relationship with a slope value of 0.49 between NH_4^+ retention by *Calluna* canopy and the sum of Mg^{2+} and Ca^{2+} deposition of throughfall (Figure 4d) indicates that NH_4^+ retention by *Calluna* canopy can be partly explained by the leaching of Mg^{2+} and Ca^{2+} through ion exchange. We did not include potassium (K^+) and hydrogen ion (H^+) to evaluate canopy leaching because K_2HPO_4 mist solution was used for P and K addition. Canopy retention of NH_4^+ is usually accompanied by cation leaching (Bobbink et al., 1992; Krupa, 2003; Li et al., 2013; Staelens et al., 2008; Stevens et al., 2011) and hydrogen ion (H^+) leaching (Krupa, 2003; Liu et al., 2013; Manninen et al., 2011; Paulissen et al., 2004; Stevens et al., 2011; Tomassen et al., 2003). Our result was consistent with those of Bobbink et al (1992) for *Calluna*.

Significantly higher DON deposition for Nox 56PK (Figure 6a), higher Mg^{2+} and Ca^{2+} deposition for Nred 56PK (Figure 6b), and higher deposition of anion deficits for Nox 56PK (Figure 6c) indicate that P and K addition increased the DON and cations leaching from the canopy associated with the increased canopy retention of NO_3^- and NH_4^+. Therefore, it is suggested that P and K additions accelerate the nutrient cycling of substances leaching from the canopy. These results demonstrate that PK availability can influence the cycling of N by the *Calluna* canopy (Figure 7).

Effects of N status of Calluna *on enhanced CNR and the associated canopy leaching with P and K addition*

Foliar N concentrations of *Calluna* increased with increasing N deposition (Figure 8cd), which is consistent with the study of Pitcairn et al. (1995) which found significant increases in tissue N concentration of *Calluna* along a N deposition range from 15 to 30 kg N ha^{-1} yr^{-1} throughout Europe. Although there were not significant differences for foliar P concentrations among the treatments, the stable N:P ratio (Figure 8a) must be caused by increases in the foliar P concentration (Figure 8e). One plausible explanation for the increases in P concentration is that *Calluna* may upregulate its P aquisition in order to utilise the N, incorporate it into amino acids, rather than allow it to accumulate in toxic forms, in response to increased N deposition. It is known that terrestrial plants allocate excess N to proteins for enzyme production enabling increased enzyme activity, e.g. the phosphatase enzymes, to enhance P availability , thus delaying the onset of P limitation (Marklein and Houlton 2012; Maistry et al. 2015). If a higher leaf N:P ratio is indicative of N saturation diagnosed from the leaf stoichiometry in wetlands (Koerselman and Meuleman 1996; Gü̈ewell 2004; Chiwa et al., 2018), then the small increases in foliar N:P ratio of *Calluna* exposed to different levels of N addition without P and K even after 11-years exposure (Figure 8a) and decreases in the N:P ratio with P and K (Figure 8b), suggest that N exposure at this site does not cause N saturation in *Calluna* even for the high N dose without P and K addition.

Chiwa et al. (2018) showed that *Sphagnum* tissue N concentration at this same site also increased, whereas tissue P concentrations did not, in response to N dose. Subsequently, *Sphagnum* N:P ratio did increase and *Sphagnum* exposed to NH_4^+ addition of 56 kg N ha^{-1} yr^{-1} for 11 years became N-saturated. Therefore, it is suggested that *Calluna* could have lower sensitivity than *Sphagnum* to elevated N deposition because *Calluna* could enhance P acquisition via increased enzyme activity.

Conclusions

This study has provided the first results of enhanced canopy N retention by increases in P and K availability. This study has advanced our understanding of canopy N retention and the factors controlling its variation, improving our ability to evaluate atmospheric N deposition and its ecological effects. It was found that DON and base cation leaching are accelerated by the enhancement of canopy N retention, in which canopy retention of NO_3^- and NH_4^+ was accompanied by leaching of DON and base cations, respectively. Importantly this study has distinguished between the effects of reduced versus oxidised N. More intensive measurements will be required to investigate the seasonal effects of P and K addition on the CNR and the associated leaching.

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Figure Captions

Figure 1 Effect of *Calluna* canopy on nitrate (NO_3^-), ammonium (NH_4^+), and dissolved organic nitrogen (DON) deposition. Bars represent standard deviation (n = 3 for rainfall and n = 4 for throughfall).

Figure 2 Relationship between a) throughfall sodium (Na^+) deposition and throughfall nitrate (NO_3^-) deposition and between b) throughfall chloride (Cl^-) deposition and throughfall ammonium (NH_4^+) deposition.

Figure 3 Rainfall and throughfall depth (mm). Bars represent standard deviation (n = 3 for rainfall and n = 4 for throughfall).

Figure 4 Relationship between throughfall deposition of dissolved organic nitrogen (DON) and retention of a) NO_3^- and b) NH_4^+. Relationship between throughfall deposition of magnesium (Mg^{2+}) and calcium (Ca^{2+}) and retention of c) NO_3^- and d) NH_4^+.

Figure 5 Relationship between throughfall deposition of anion deficits and dissolved organic nitrogen (DON) for a) Nox and b) Nred.

Figure 6 Throughfall deposition of a) dissolved organic nitrogen (DON), b) magnesium (Mg^{2+}) + calcium (Ca^{2+}), and c) anion deficit. Bars represent standard deviation ($n = 4$).

Figure 7 Effect of P and K addition on throughfall deposition of nitrate (NO_3^-), ammonium (NH_4^+), and dissolved organic nitrogen (DON) deposition. Bars represent standard deviation ($n = 4$).

Figure 8 Relationship of nitrogen (N) deposition (the sum of ambient N deposition and applied N) with *Calluna* foliage of N:P ratio, N concentration, and phosphorus (P) concentration. Background N deposition is *ca.* 8 kg N ha^{-1} yr^{-1} (Leith *et al.*, 2004; Sheppard *et al.*, 2004).

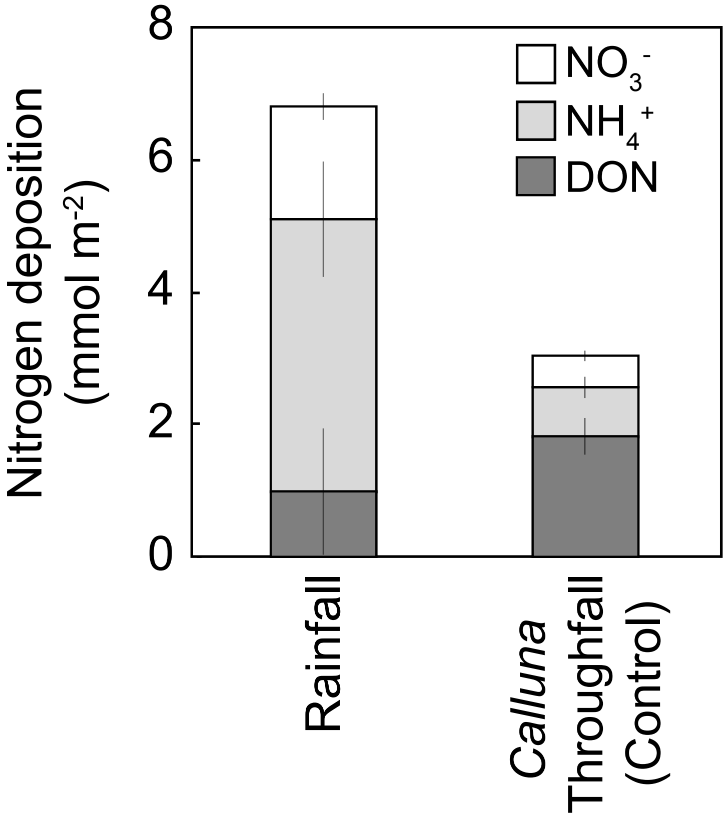

Figure 1
Chiwa et al.

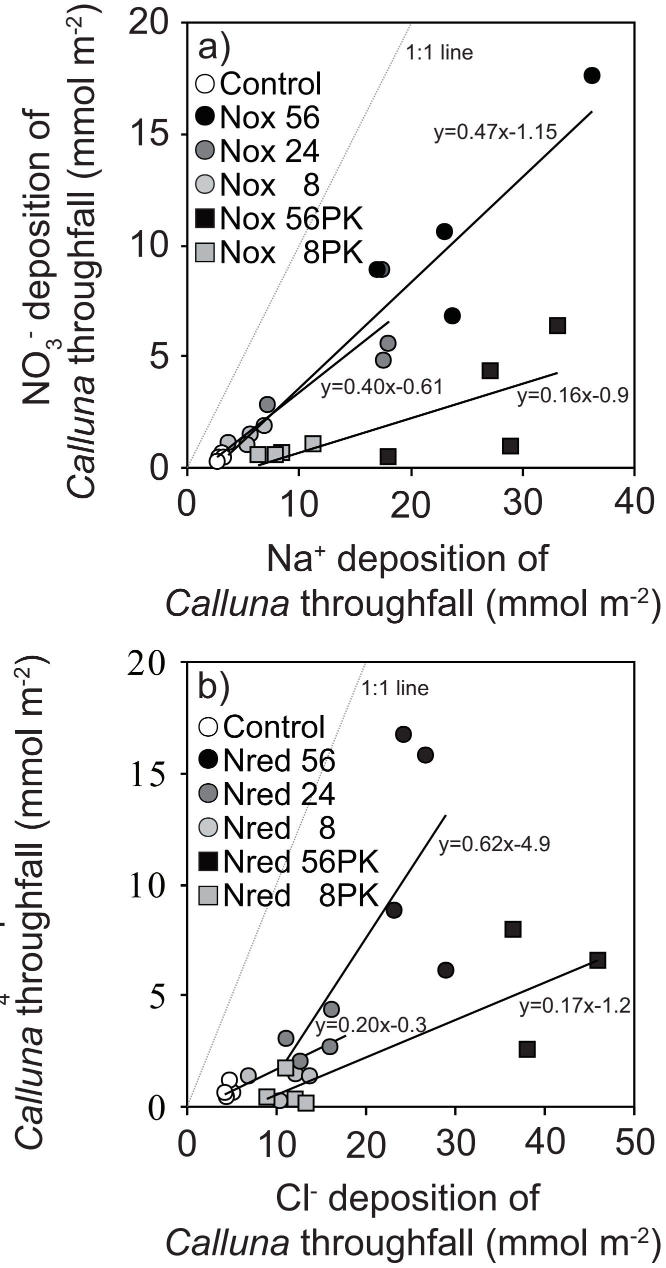

Figure 2
Chiwa et al.

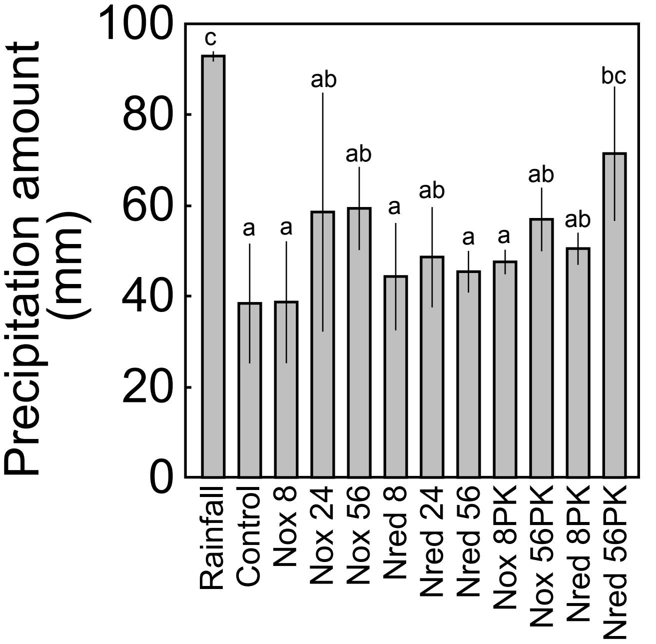

Figure 3
Chiwa et al.

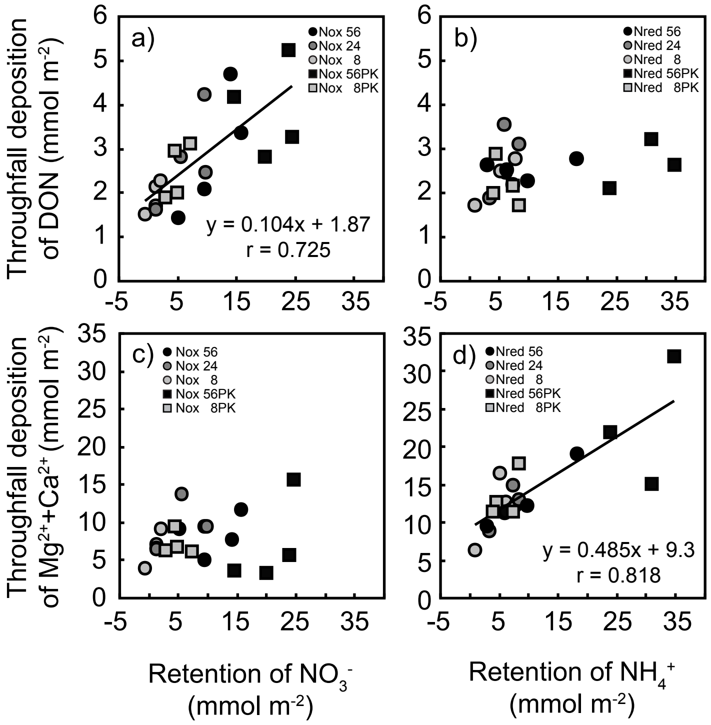

Figure 4
Chiwa et al.

Figure 5

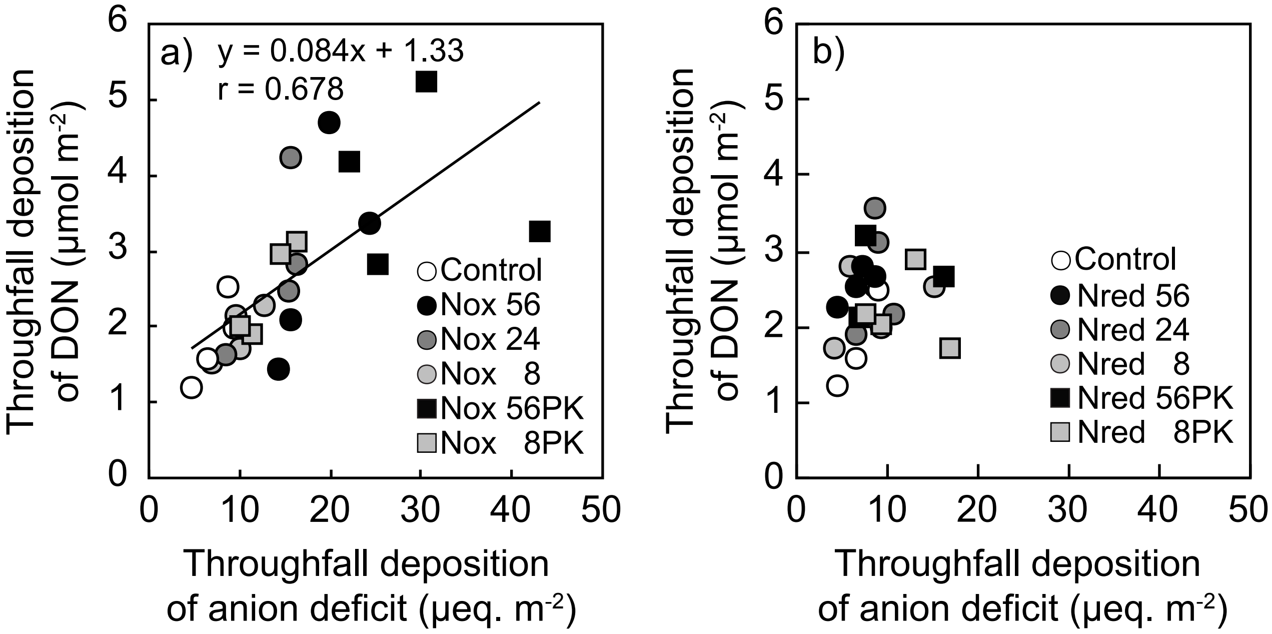

Figure 5

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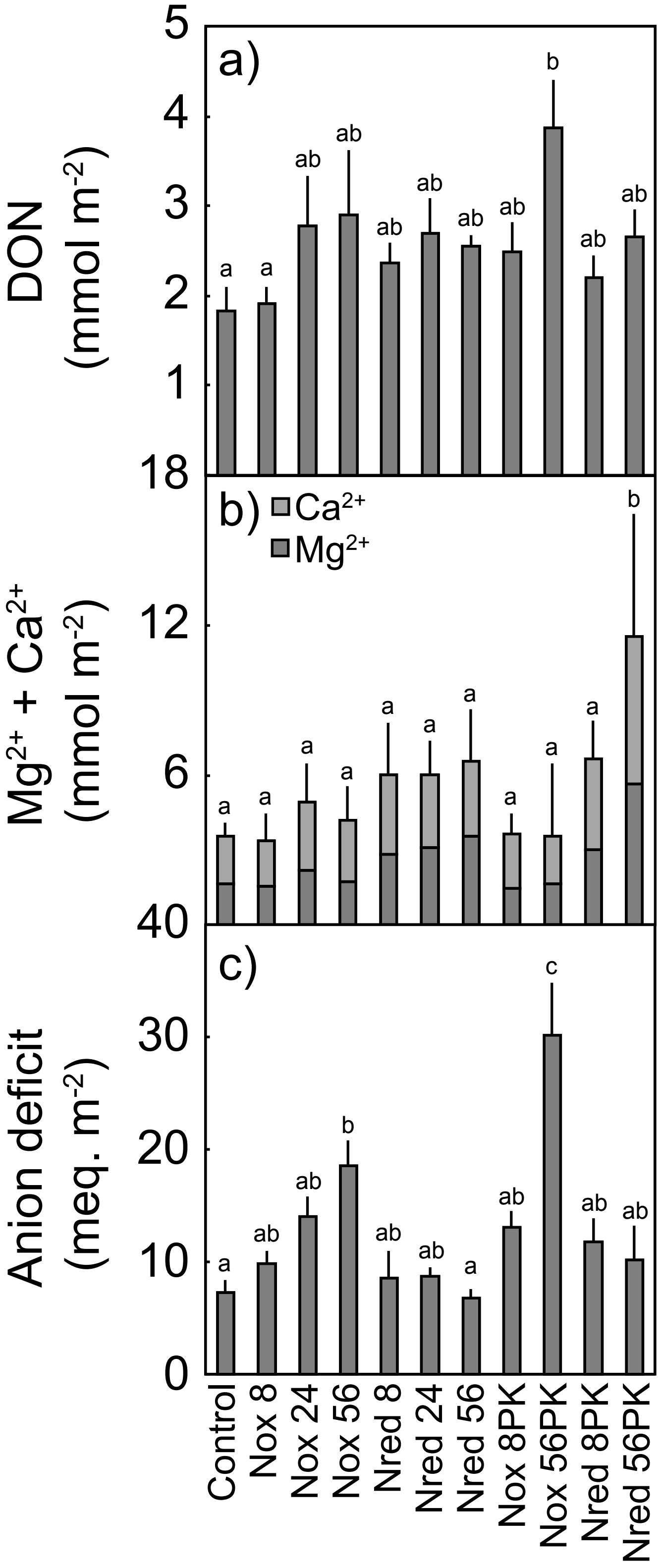

Figure 6
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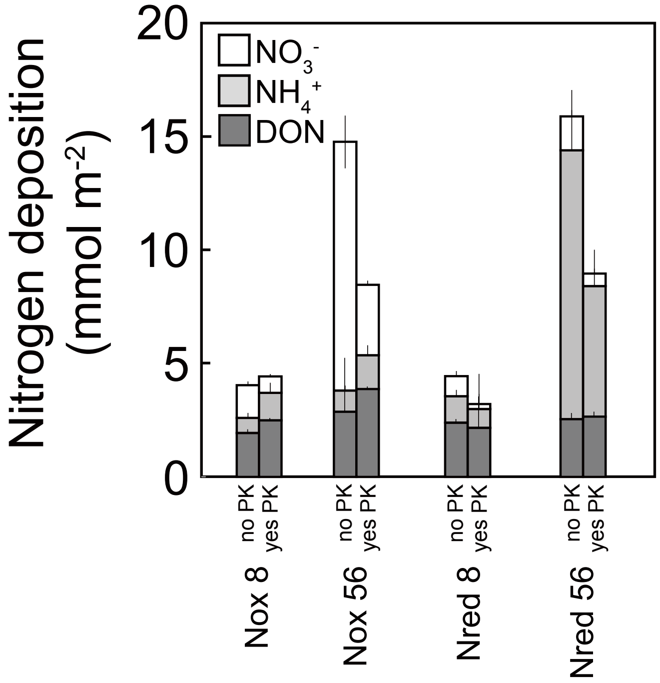

Figure 7
Chiwa et al.

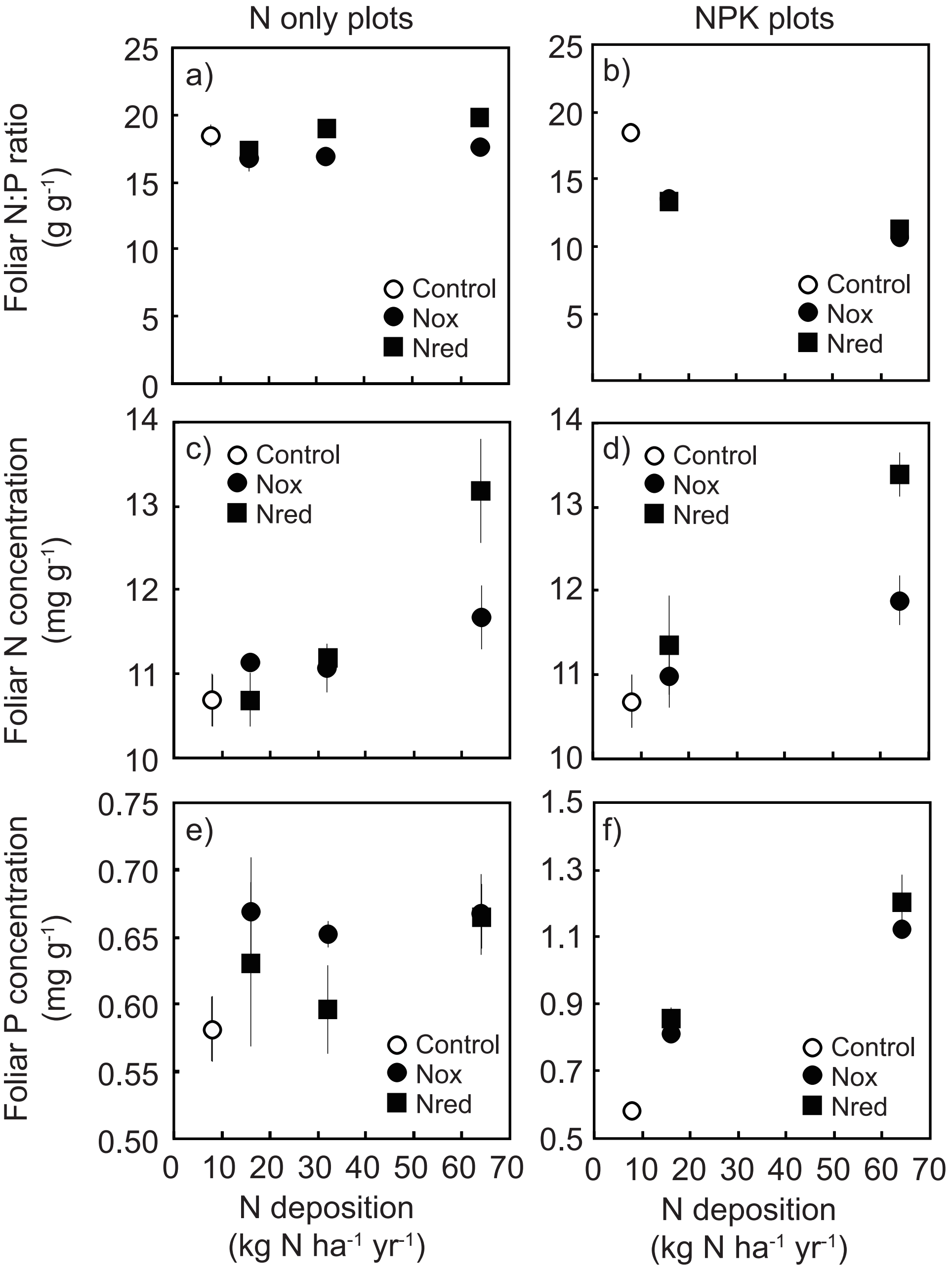

Figure 8
Chiwa et al

Table 1 Composition of the artificial mist treatments applied to the Whim bog peatland in each of the 11 different treatment plots. The total annual input is the cumulative application from *ca.* 120 treatments.

Treatment	Components	Concentration (mmol L^{-1})	Total annual input (kg ha^{-1} yr^{-1})
Control			8 kg N ha^{-1} yr^{-1}
Nox 8	$NaNO_3$	0.57	16 kg N ha^{-1} yr^{-1}
Nox 24	$NaNO_3$	1.71	32 kg N ha^{-1} yr^{-1}
Nox 56	$NaNO_3$	4.0	64 kg N ha^{-1} yr^{-1}
Nred 8	NH_4Cl	0.57	16 kg N ha^{-1} yr^{-1}
Nred 24	NH_4Cl	1.71	32 kg N ha^{-1} yr^{-1}
Nred 56	NH_4Cl	4.0	64 kg N ha^{-1} yr^{-1}
Nox 8PK	$NaNO_3$	0.57	8 kg N ha^{-1} yr^{-1}
	K_2HPO_4	0.018	0.57 kg P ha^{-1} yr^{-1}
			1.4 kg K ha^{-1} yr^{-1}
Nox 56PK	$NaNO_3$	4.0	64 kg N ha^{-1} yr^{-1}
	K_2HPO_4	0.13	4 kg P ha^{-1} yr^{-1}
			10 kg K ha^{-1} yr^{-1}
Nred 8PK	NH_4Cl	0.57	16 kg N ha^{-1} yr^{-1}
	K_2HPO_4	0.018	0.57 kg P ha^{-1} yr^{-1}
			1.4 kg K ha^{-1} yr^{-1}
Nred 56PK	NH_4Cl	4.0	64 kg N ha^{-1} yr^{-1}
	K_2HPO_4	0.13	4 kg P ha^{-1} yr^{-1}
			10 kg K ha^{-1} yr^{-1}

Table 2 Meteorological condition at each event for throughfall (TF) collection

Sampling	Setup	Collection	Number of rainfall events	Rainfall depth (mm)	Rainfall duration (h)	Rainfall intensity (mm/h)	Air Temp (°C)	TF control volume (mm)
1	1 Jul	4 Jul	2	18.0	20	1.0	11.7	8.4
2	22 Jul	25 Jul	2	25.0	8	4.3	16.5	12.2
3	5 Aug	13 Aug	4	14.8	25	1.5	12.5	5.6
4	19 Aug	2 Sep	5	15.2	60	1.3	13.4	4.7
5	10 Sep	17 Sep	4	24.8	34	0.7	9.6	9.9
6	24 Sep	8 Oct	5	21.6	52	0.5	11.5	10.1
Collected period			22	114	199	1.6	12.2	38.6
All period (1 Jul - 8 Oct)			35	250	351	1.5	13.1	NA