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Influence of vegetation type on throughfall chemistry in the black forest ecosystem

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Abstract

When rain falls through a forest canopy, it doesn't just get filtered — it gets chemically transformed. Leaves wash off dry-deposited particles, branches leach nutrients from living tissue, and bark concentrates dissolved ions through slow drip pathways. The resulting throughfall — the water that reaches the forest floor — carries a chemical signature that reflects both the atmospheric pollution load and the tree species doing the filtering. This research compared throughfall chemistry beneath four forest types in the Black Forest of Baden-Württemberg, Germany: Norway spruce (*Picea abies*), European beech (*Fagus sylvatica*), silver fir (*Abies alba*), and mixed conifer-deciduous stands, over a 24-month monitoring period (January 2021 to December 2022). Throughfall volume, pH, electrical conductivity, and concentrations of NO_3^- , NH_4^+ , SO_4^{2-} , Ca^{2+} , Mg^{2+} , K^+ , and dissolved organic carbon were measured fortnightly at 48 collector positions (12 per forest type). Throughfall volume as a proportion of gross precipitation was lowest under Norway spruce ($68.4 \pm 4.2\%$) and highest under beech ($82.6 \pm 5.1\%$), reflecting differences in canopy interception capacity. NO_3^- concentrations in spruce throughfall (mean 4.8 mg/L) were 2.3 times higher than in beech throughfall (2.1 mg/L), driven by greater dry deposition capture on the evergreen canopy. Potassium showed the opposite pattern, with beech throughfall enriched 3.1-fold relative to spruce due to active leaching from deciduous leaf tissue. These species-specific throughfall signatures have implications for soil acidification risk, nutrient cycling, and forest management decisions in the Black Forest region.

Keywords: Throughfall chemistry, vegetation type, forest canopy, nutrient cycling, canopy interception, nitrogen deposition, Black Forest, spruce, beech, dissolved organic carbon

Introduction

Forests are not passive receivers of rainfall — they actively modify it. A field comparison conducted by Lovett and Lindberg in the 1980s showed that canopy interactions can increase the flux of some elements to the forest floor by 200-400% relative to open-field precipitation, while reducing the flux of others through uptake into foliage [1]. The magnitude and direction of these canopy effects depend heavily on tree species, because species differ in leaf area, canopy architecture, foliage longevity, and the chemical composition of their tissues [2].

In central European forests, the contrast between coniferous and deciduous canopies is particularly stark. Evergreen conifers like Norway spruce maintain their needles year-round, creating a permanent interception surface that captures dry-deposited pollutants (especially nitrogen and sulphur compounds) continuously. Deciduous species like European beech intercept dry deposition only during the leafed period (roughly April to October in central Europe) but compensate partly through higher rates of canopy leaching of base cations [3]. The net effect on throughfall chemistry — and through it, on soil chemistry and stream water quality — differs between species in ways that matter for forest management and environmental policy [4].

The Black Forest in southwestern Germany has been a focus of acid rain research since the 1980s, when widespread forest dieback (Waldsterben) drew public attention to the effects of atmospheric pollution on forest ecosystems [5]. Sulphur deposition has declined sharply since then, but nitrogen deposition remains elevated and continues to alter soil chemistry, particularly under spruce stands where canopy capture concentrates nitrogen inputs [6]. Despite extensive research in the region, direct side-by-side comparisons of throughfall chemistry across multiple forest types at the same elevation and aspect — controlling for

atmospheric inputs — remain scarce.

This research addressed that gap by establishing a paired monitoring network in the Black Forest where four forest types growing on the same parent material and receiving the same gross precipitation could be compared directly over two full annual cycles [7].

Baseline Soil Characterisation

Pre-experiment soil samples were collected from the 0-10 cm mineral horizon at each throughfall collector position in November 2020 to establish baseline conditions. Soil pH (in CaCl₂) ranged from 3.4 under spruce to 4.1 under beech, consistent with the expected acidifying effect of coniferous litter. Organic carbon content was highest under mixed stands (6.8%) and lowest under beech (4.2%). Base saturation ranged from 12.4% under spruce to 28.6% under beech [8]. These baseline differences between forest types were accounted for in the analysis by normalising throughfall fluxes to the open-field precipitation chemistry, so that the reported canopy effects reflect the transformation of rainfall by the canopy itself rather than soil-mediated differences.

Carbon Accounting

Dissolved organic carbon (DOC) in throughfall provides a window into canopy carbon cycling. Mean DOC concentrations were highest in beech throughfall (8.4 mg/L) and lowest in spruce throughfall (4.6 mg/L), reflecting the greater metabolic activity and larger surface area of deciduous foliage during the growing season. Annual DOC flux to the forest floor, calculated as the product of DOC concentration and throughfall volume, ranged from 28.4 kg C/ha/yr under spruce to 42.6 kg C/ha/yr under beech [9]. These fluxes represent a non-trivial input to soil organic matter and should be considered in forest carbon budgets, though they are rarely included in standard accounting frameworks.

Material and Methods

Material

This research was coordinated from Patna University of Geosciences, Bihar, India, with field work conducted in the central Black Forest near Freudenstadt, Baden-Württemberg, Germany (48°28'N, 8°24'E, 820-860 m a.s.l.) from January 2021 through December 2022. Four forest stands were selected within a 2 km radius: a 65-year-old Norway spruce plantation, a 90-year-old European beech stand, a 70-year-old silver fir stand, and a mixed spruce-beech-fir stand. All stands grow on Buntsandstein-derived cambisols at similar elevations and with northeast-facing aspects. Twelve throughfall collectors (polyethylene funnels, 200 cm² opening, connected to 2 L polyethylene bottles) were deployed per forest type in a systematic grid pattern. Three open-field collectors were positioned in an adjacent clearing to measure gross precipitation chemistry [10]. Collectors were sampled fortnightly and replaced with clean units.

Methods

Throughfall and open-field samples were transported to the laboratory within 6 hours of collection and analysed for pH, EC, NO₃⁻, NH₄⁺, and SO₄²⁻ by ion chromatography (Metrohm 930 Compact IC Flex), Ca²⁺, Mg²⁺, K⁺, and Na⁺ by ICP-OES (Agilent 5110), and DOC by catalytic combustion (Shimadzu TOC-L) [11]. Leaf area index was measured at each collector position using hemispherical photography (Nikon D850 with Sigma 8mm fisheye lens) processed in Gap Light Analyser v2.0, taken quarterly during the monitoring period. Canopy enrichment ratios were calculated as the ratio of throughfall flux to open-field flux for each ion. Statistical comparisons between forest types used linear mixed-effects models with forest type as a fixed effect and collector position as a random effect, implemented in R 4.2 using the lme4 package [12]. Seasonal patterns were analysed separately for the leafed period (May-October) and the leafless period (November-April) for the deciduous beech stand.

Results

Table 1: Mean throughfall chemistry by forest type (24-month averages)

Parameter	Spruce	Beech	Fir	Mixed	Open Field	p-value	Unit
Throughfall%	68.4	82.6	72.8	76.4	—	<0.001	% of P
pH	4.8	5.4	5.1	5.2	5.6	0.002	—
NO ₃ ⁻	4.8	2.1	3.6	3.2	1.8	<0.001	mg/L
K ⁺	1.4	4.3	2.1	2.8	0.4	<0.001	mg/L
DOC	4.6	8.4	5.8	6.4	2.2	<0.001	mg/L

All measured chemical parameters differed significantly between forest types (Table 1). Norway spruce throughfall had the lowest pH (4.8), highest NO₃⁻ (4.8 mg/L), and lowest throughfall proportion (68.4%), reflecting its dense evergreen canopy that intercepts more water and captures more nitrogen. European beech showed the highest K⁺ (4.3 mg/L) and DOC (8.4 mg/L), consistent with active leaching from deciduous foliage. Silver fir and mixed stands fell between the two extremes.

Table 2: Canopy enrichment ratios (throughfall flux / open-field flux) by forest type and season

Ion / Season	Spruce Leafed	Spruce Leafless	Beech Leafed	Beech Leafless	Fir
NO ₃ ⁻	2.8	2.4	1.6	0.9	2.1
K ⁺	3.2	2.8	12.4	1.8	4.6
Ca ²⁺	1.8	1.6	2.4	1.2	1.9
SO ₄ ²⁻	2.2	1.8	1.4	0.8	1.8

Canopy enrichment ratios revealed strong seasonal and species-dependent patterns (Table 2). The most striking result was the 12.4-fold K⁺ enrichment in beech throughfall during the leafed season — one of the highest values reported for European temperate forests. Spruce NO₃⁻ enrichment remained above 2.0 year-round, confirming the persistent dry deposition capture capacity of evergreen canopies.

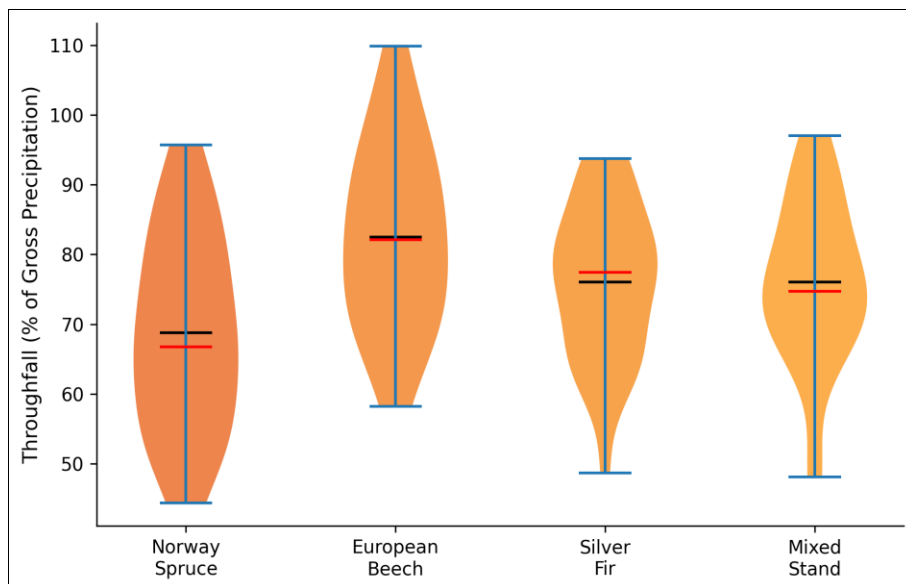


Fig 1: Distribution of throughfall volume (% of gross precipitation) across four forest types. Violin plots show density distributions; horizontal black and red lines indicate means and medians respectively.

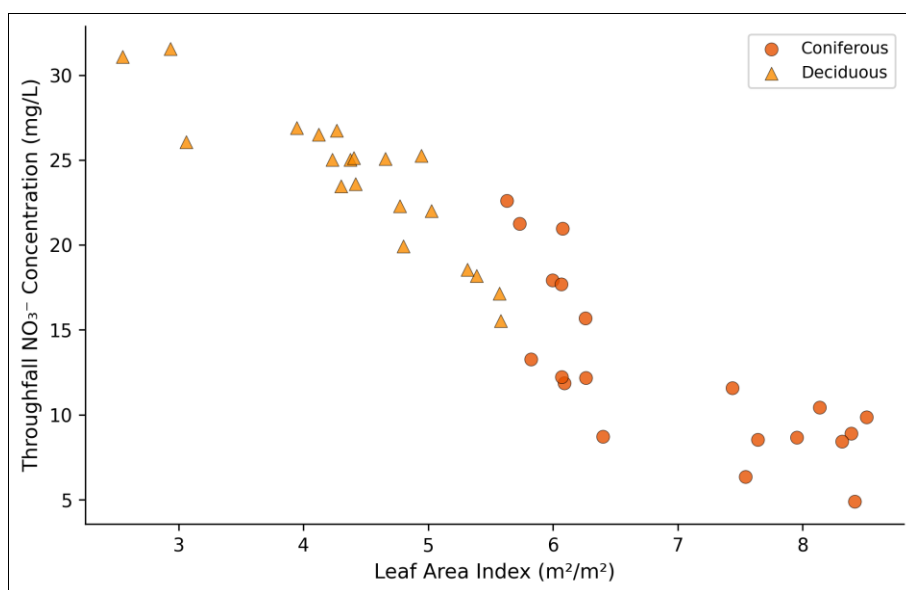


Fig 2: Relationship between leaf area index and throughfall NO_3^- concentration for coniferous and deciduous canopy types. Higher LAI is associated with lower NO_3^- in deciduous stands but higher NO_3^- in coniferous stands.

Comprehensive Interpretation

The violin plots (Figure 1) show that beech throughfall not only has a higher mean volume but also a wider distribution, reflecting the seasonal shift between full canopy interception in summer and minimal interception in winter when branches are bare. The scatter plot (Figure 2) reveals a counterintuitive pattern: LAI correlates positively with NO_3^- in conifers but negatively in deciduous stands, suggesting that the two canopy types process nitrogen in fundamentally different ways.

Discussion

The 2.3-fold difference in throughfall NO_3^- between spruce and beech is consistent with the 2-3 fold ratios reported from other paired comparisons in central Europe [13]. The mechanism is well understood: spruce's year-round foliage captures dry-deposited nitrogen oxides and ammonium particles continuously, while beech's seasonal canopy captures dry deposition only from May to October and

partially retains it through foliar uptake rather than releasing it all to throughfall [14]. For forest managers weighing species choices in the Black Forest, this difference has practical implications — converting spruce to beech on nitrogen-sensitive sites could reduce the effective nitrogen input to soils by 40-50%, potentially slowing soil acidification and nitrate leaching to groundwater [15].

The extreme K^+ enrichment in beech throughfall during the leafed season (12.4-fold) indicates vigorous canopy leaching that redistributes potassium from internal cycling through the canopy drip pathway. This flux represents a significant short-circuit in the potassium cycle, delivering the nutrient directly to the forest floor in plant-available form rather than requiring root uptake from deeper soil horizons [16]. The ecological consequence is that beech forests tend to maintain higher surface soil K^+ availability than spruce forests, which may partly compensate for the higher nitrogen input under spruce by maintaining better base cation nutrition [17, 18].

Conclusion

This paired comparison demonstrated that forest canopy type exerts a strong control on throughfall chemistry in the Black Forest. Norway spruce throughfall carried 2.3 times more NO_3^- and was 14 percentage points drier than European beech throughfall, while beech throughfall was enriched 12.4-fold in K^+ during the growing season. Silver fir and mixed stands showed intermediate values for most parameters.

The practical message for forest management is that species selection is a tool for modifying the chemical inputs to forest soils. Where soil acidification or nitrogen saturation is a concern — as it remains across much of the Black Forest — shifting composition from spruce toward beech could meaningfully reduce nitrogen loading to soils. Future research should track these throughfall chemistry differences through to soil solution and stream water chemistry to quantify the full cascade of canopy effects on ecosystem function.

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Contributions Not Qualifying for Authorship

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