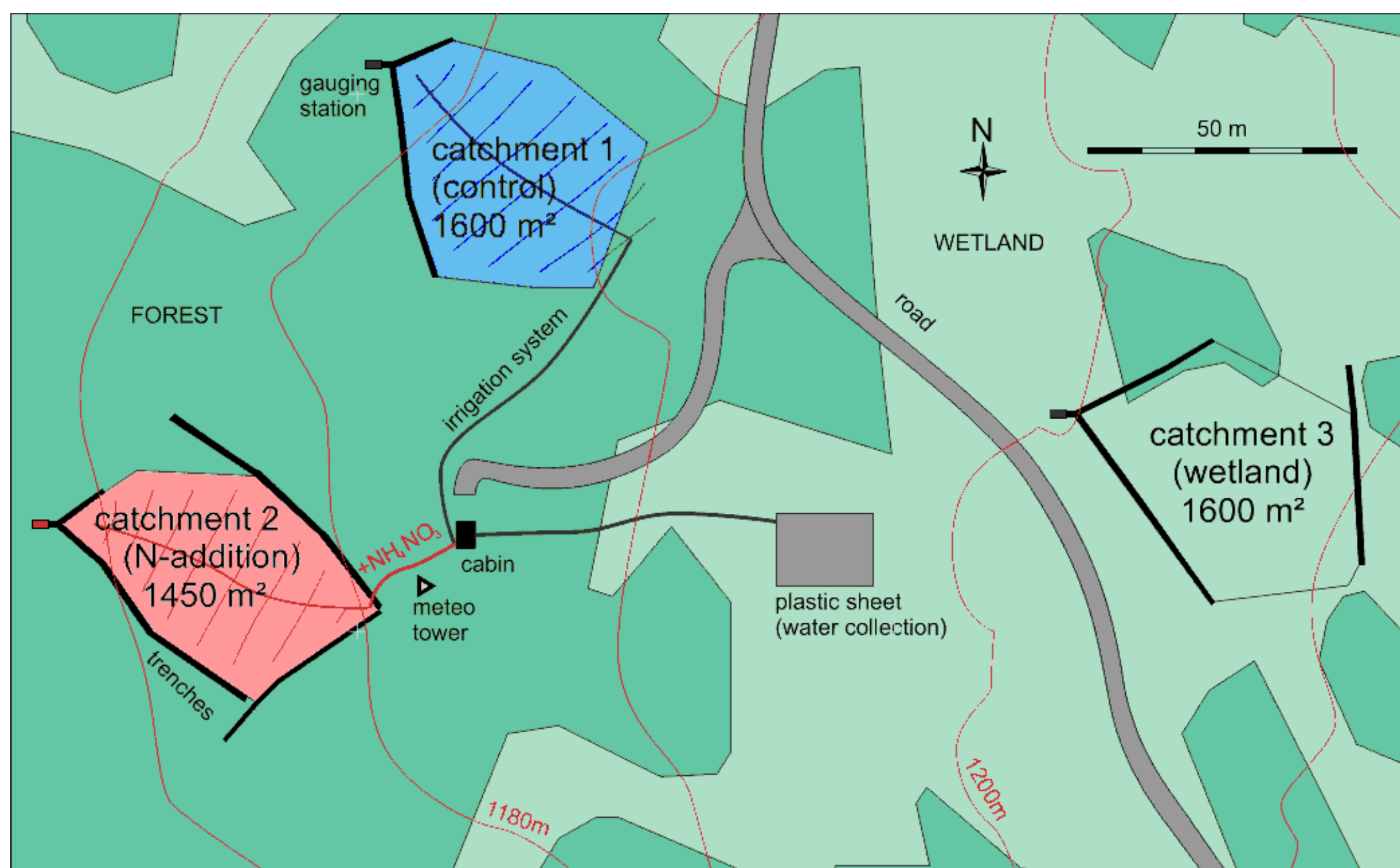


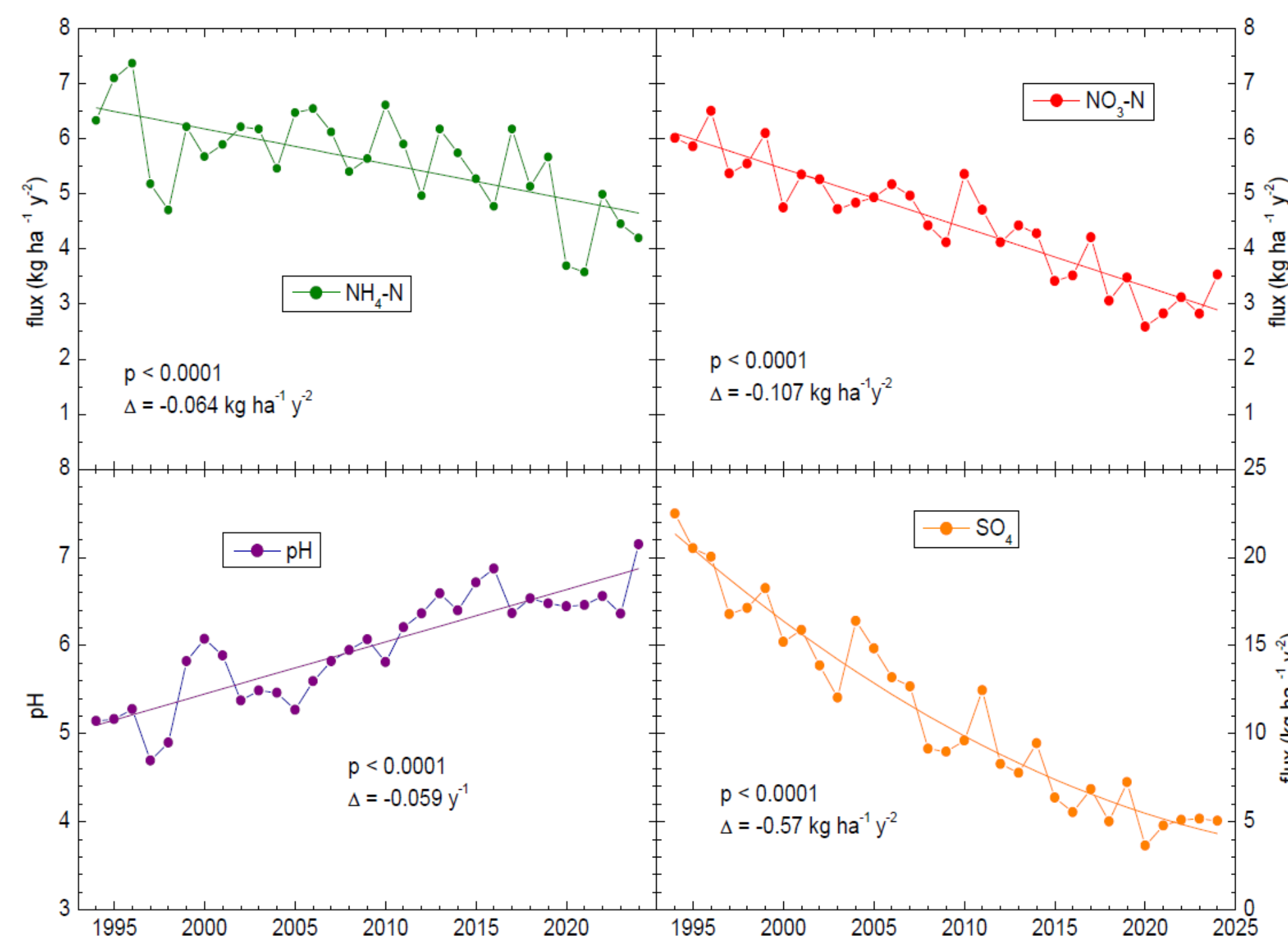
Background & Motivation

- Deposition of inorganic nitrogen (N) to forest ecosystems has increased over the second half of the 20th century due to emissions from human activities. Inputs of ammonium (NH_4^+) and nitrate (NO_3^-) can induce an eutrophication of previously N-limited systems.
- Since 1995, a simulation of a higher N deposition rate is being conducted as a paired-catchment experiment in a spruce forest at Alptal in Switzerland. Here we show the most recent results for bulk deposition, N leaching and partitioning, and from a multi-tracer experiment.
- Within our SNSF project UNICAN, closely related to the EU COST Action CLEANFOREST, we envision to upscale the observed N dynamics at Alptal to European forests. In a first attempt, we aim to constrain the isotopic composition of N sources (NH_4^+ , NO_3^-) in bulk deposition and throughfall samples from a community-based sampling effort.

Experimental Design and Bulk deposition trends

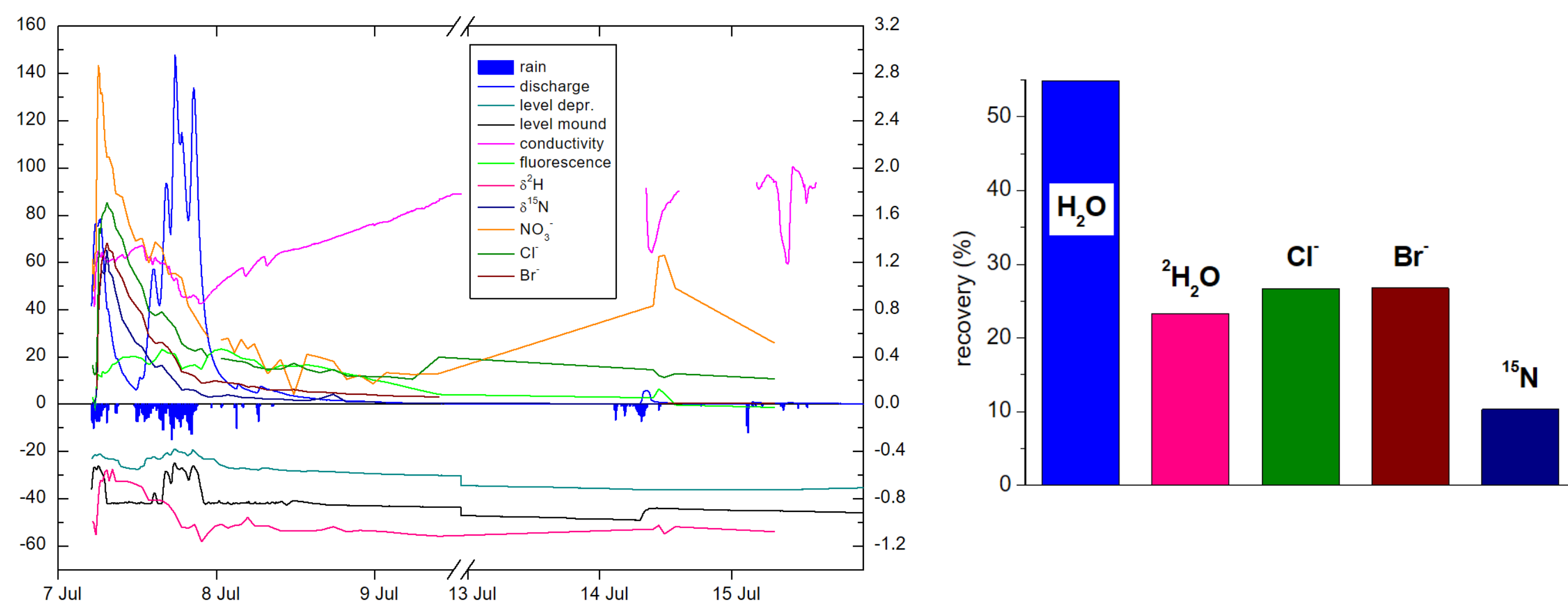


Experimental setup of the Alptal site in the Swiss Prealps close to Einsiedeln at 1200 m elevation (MAP = 2300 mm, MAT = 6 °C) is dominated by Norway spruce (*Picea abies*). Starting 1995, two experimental forested catchments (~1500 m²) have been delimited by trenches within the Erlenbach catchment. Nitrogen is added as NH_4NO_3 (22 kg N / ha / y) to rainwater and applied by sprinklers to catchment # 2. Catchment # 1 is the control and receives only unaltered rainwater. A ¹⁵N tracer (~1400‰ in first year) was added in the beginning of the experiment to both catchments (Schleppei *et al.* 2017).



Recent trend in bulk deposition at the experimental Alptal site. The bulk deposition of nitrate (NO_3^-) and ammonium (NH_4^+) amounted to each 6 kg / ha / y in the 1990's and is slightly decreased since then. The deposition of sulfate (SO_4^{2-}) strongly decreased following abatement measures. This let the pH of precipitation increase by one unit (Baer *et al.* 2023).

Multi-tracer experiment

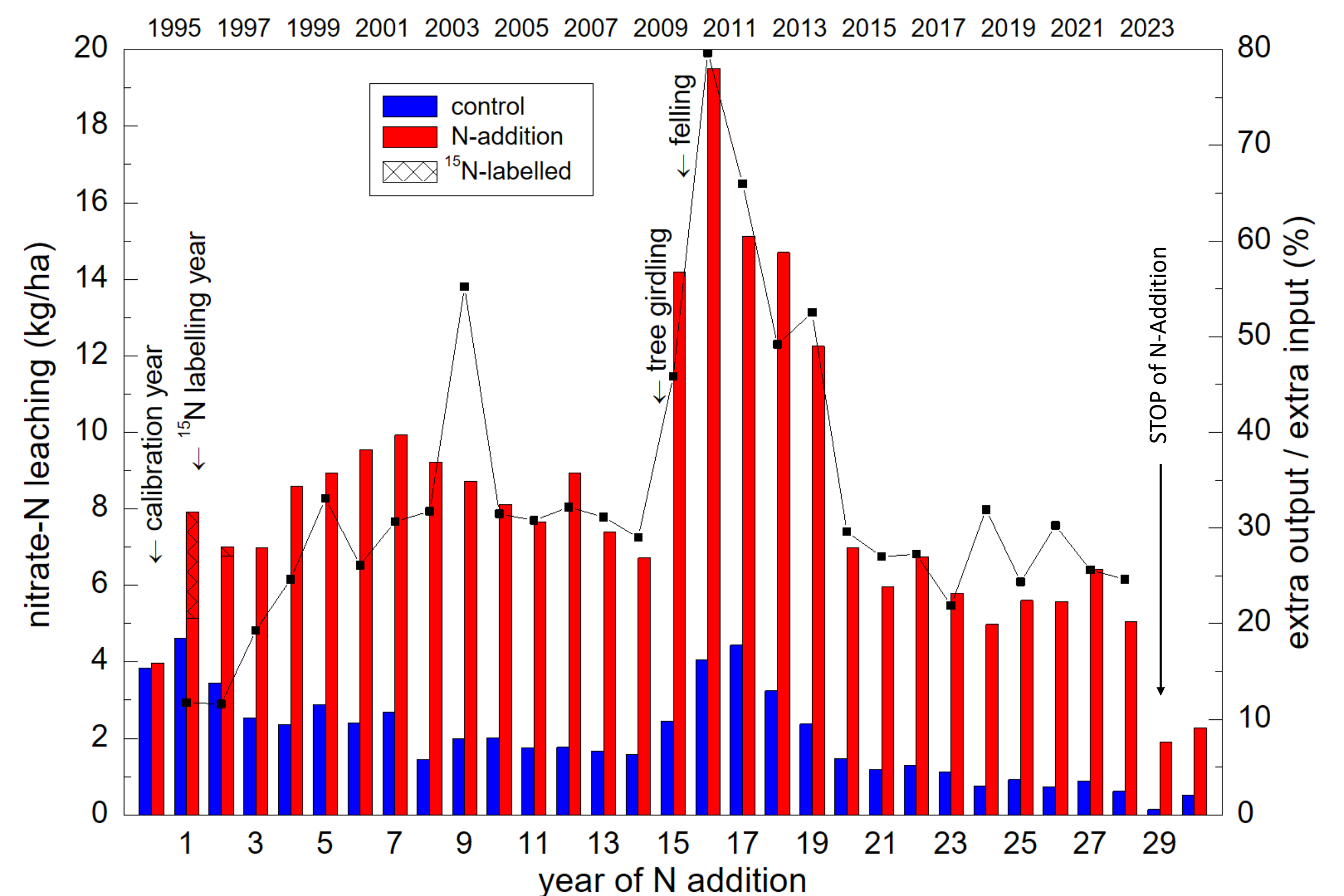


Multi-tracer application in the Alptal in 2025 during a summer rain event at the treatment catchment after stopping the N addition. The water was labelled with ²H, while the biologically inert tracers Cl^- and Br^- were added together with ¹⁵N-labelled nitrate ($^{15}\text{NO}_3^-$). All four tracers reached the catchment outlet with similar dynamics (left panel). Although the event runoff coefficient was 55% (runoff / precipitation, blue bar), only about 25% of the inert tracers were recovered, indicating that much of the runoff consisted of older water (right panel). In contrast, only ~10% of the $^{15}\text{NO}_3^-$ was leached, demonstrating that nitrate loss was governed by both hydrological transport and biological retention.

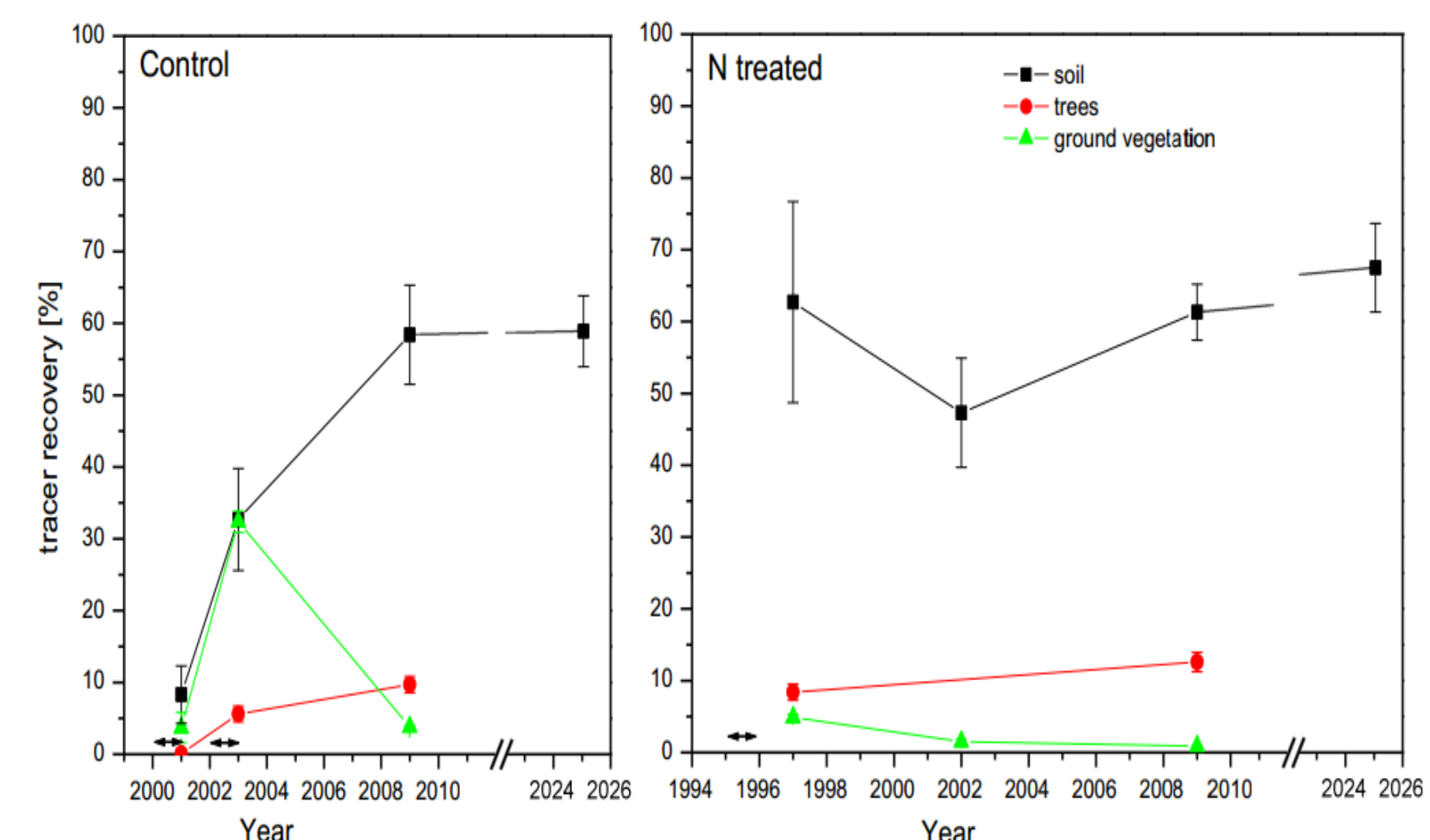
Take home messages

- The Alptal experiment demonstrates how sustained nitrogen inputs can shift a forested catchment from efficient nitrogen retention toward nitrogen saturation and elevated nitrate leaching.
- After N-addition stopped in 2024, nitrate losses remained higher than in the control, revealing persistent legacy effects from accumulated soil N pools and ongoing soil N saturation.
- The 2025 multi-tracer event showed that N leaching is governed by an interaction between hydrological transport and biological retention.
- Improved characterization of the spatial and temporal variability in N source isotope signatures is needed to parameterize and apply isotope-enabled ecosystem models, such as TRACE, across European forest sites.

N leaching and partitioning

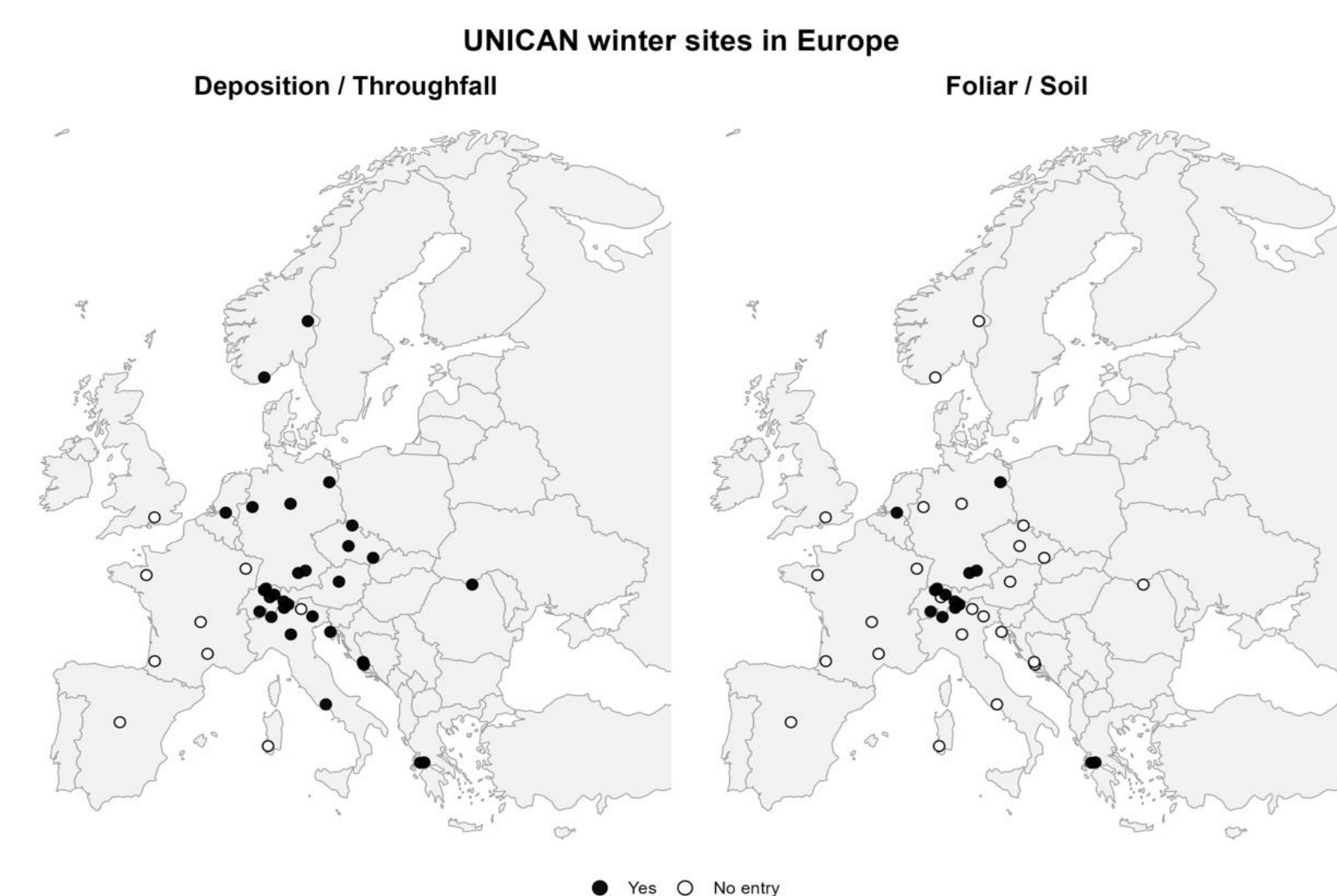


Nitrate leaching in the Alptal N-addition experiment since 1995 (after Schleppei *et al.* 2017) increased rapidly during the first treatment year, mainly through preferential and lateral flow, with limited plant and microbial uptake. **Girdling and felling** half the trees (>20 cm diameter) in 2009/2010 further increased leaching, especially in the N-treated catchment, due to reduced root N demand. After **N-addition stop** in 2024, leaching declined but remained above the control, indicating a legacy effect from persistent soil N saturation and accumulated N pools.



¹⁵N partitioning in the Alptal N-addition experiment. Most of the added ¹⁵N was retained in the soil and litter layer. Trees and ground vegetation each accounted for less than 10% of the tracer. Over time, ¹⁵N recovery increased slightly in trees but declined in ground vegetation. In the control catchment, ammonium-¹⁵N was initially retained mainly by mosses, but within a few years its distribution resembled that of the nitrogen-treated catchment.

Outlook: Characterizing N source isotope signatures across Europe



Ongoing seasonal sampling to study the isotopic composition of ammonium and nitrate in bulk deposition/throughfall across European forests. Additional foliar and topsoil samples are taken. Sampling follows harmonized ICPForests protocols.

References

- Schleppei *et al.* 2017. Nitrate leaching from a sub-alpine coniferous forest subjected to experimentally increased N deposition for 20 years, and effects of tree girdling and felling. *Biogeochemistry*, 134, 319-335
- Baer *et al.* 2023. Long-term additions of ammonium nitrate to montane forest ecosystems may cause limited soil acidification, even in the presence of soil carbonate. *Biogeosciences* 20, 4577-4589