

The Earth System Science Project HILUC

(Hydrological Impact of Historical Land Use and Climate)

Final Report



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1. Project Summary

Project Title:

Hydrological Impact of Historical Land Use and Climate - Interdisciplinary research on flood formation in small Alpine catchments from around 1850 to present by focussing on specific land use practices

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Non-Academic Stakeholder(s):

Regional Tyrolean Government / Forest Department (LFD)

Forest Engineering Service in Torrent and Avalanche Control, Section Tyrol (WLV)

Municipality chroniclers

Forest Campus Austria, Traunkirchen

Municipality forest managers

Other municipality members (Mayor, Rural Youth Association, Fire Brigade, landowners, residents)

Executive Summary

The overarching objective of the project was to quantify the effect of land use change and especially on changes in land use practices within land use types on flood events in small Alpine catchments for the time periods around 1850, 1960 and 2020. We concentrated on secondary forest uses such as litter raking, pollarding and forest grazing, and their possible impact to this day. Over the course of the project, the research questions and methods employed were significantly expanded, resulting in a wide range of individual findings across the three research areas of history, forest ecology and hydrology. The key findings are as follows.

Historical research confirmed that, for some areas, detailed records exist regarding the condition and use of the forests around 1840, which can be analysed in a variety of ways. On this basis, secondary forest uses were comprehensively described for parts of Tyrol for the first time. The results also led to the selection of four test areas in Tyrol in the municipalities of Pfons, Stummerberg/Fügen, Söll and Ellmau (Fig. 01). Through interviews with elderly eyewitnesses, it was possible to reconstruct how and where these practices were carried out, which provided important input for the experiments conducted as authentically as possible within the project.

On the basis of historical sources, detailed conclusions were drawn on the condition and nutrient balance of the forests, as well as material flows from forests into agricultural land around 1840. It became apparent that annually only a small proportion of the total forest area within the study area of Fügen in the Zillertal (Fig. 01) was required to meet the demand for litter. However, there was certainly significant over-exploitation in individual forest areas. Agriculture – and thus the food supply – benefited from this historical practice.

Rainfall simulation experiments showed that forest grazing significantly increases surface runoff, depending on the intensity of grazing. Litter raking has a significantly smaller effect; in some cases, it has even no influence on the formation of surface runoff. Thus, an unexpected finding from our rainfall simulation experiments was that the forest floor may be capable of fully absorbing heavy rainfall even after one time litter raking, depending on the site characteristics. Modelling of surface runoff based on mapping and the modification of input data according to historical land uses revealed different peak runoff values for the time periods 1850, 1920 and 2020. In all four test areas, runoff peaks around 1850 were highest. This is likely to be linked to the widespread practice of forest grazing at that time.

Particularly strong transdisciplinary collaboration took place with colleagues from the forestry sector, ranging from the Forestry department of the federal province of Tyrol and forest rangers to forest owners. Through an ongoing dialogue, the concepts were further developed, the test sites selected, the methods modified and the results discussed. Experts in local history and natural hazards contributed specifically to the project phases relevant to them. A major exhibition on the project results at the Austrian Forest Campus reached a wider public, as well as the numerous trainees at this educational institution. The results of the study are also being distributed to the society (third mission) in various other formats. With regard to natural hazards, they are being incorporated into an existing practical guide for estimating surface runoff. With regard to forests, they are being used in the training of forest rangers. They are utilised in various formats in teaching at the University of Innsbruck and BOKU University Vienna. In addition, they have been communicated and discussed with specialist audiences and the general public through publications and field trips. Within the scientific community numerous paper presentations mainly by the PhD-Students but as well the PIs took place on national as well as international conferences throughout all the project period. Most recently the project’s results had been presented at the Regional Mountain Conference in Obergurgl/Austria.

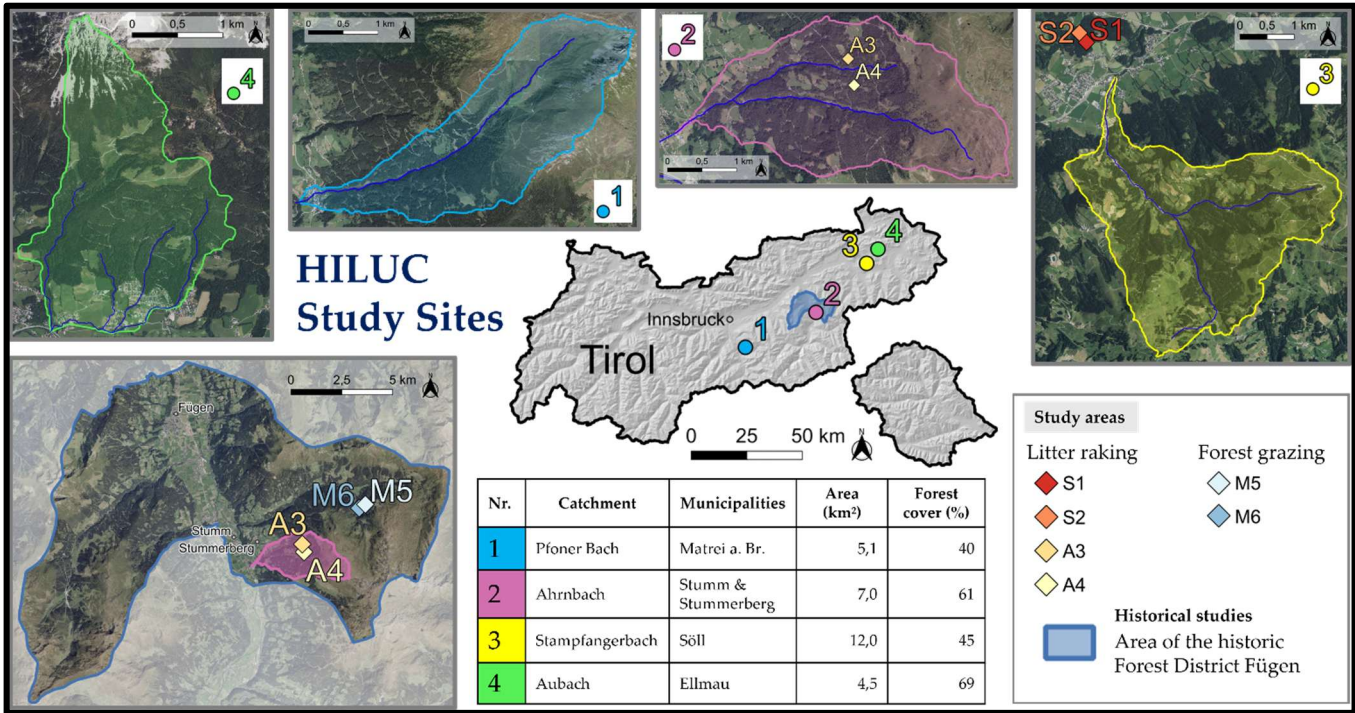


Figure 01: Overview map of the HILUC test catchment areas, rainfall simulation plots and sites for detailed historical analyses.

2. Key Scientific Outcomes

This project was divided into three subprojects, which are closely interlinked. The organisation of the following chapters reflects this structure.

2.1. Initial objectives

The central objective of the project was to quantify the effect of land use change on flood events in small Alpine catchments and to better distinguish it from the effect of climate change for the time periods around 1850, 1960 and 2020. Our focus was not only on changes in land use types per se, but mainly on changes in land use practices within land use types, especially within secondary forest uses. The project should also help to better understand to

what extent past land use practices still have an impact on runoff generation today. This project objectives were to be achieved through the following main project aims:

1. Selection of four small Alpine catchments (< 10 km²) in Tyrol, considering environmental conditions, data on historic land-use types and intensities, and documented extreme flooding events
2. Detailed mapping of recent hydrologically relevant features in these four test catchments
3. Comprehensive survey and evaluation of historic land-use data (around 1850 and 1960) with a special focus on forest utilisation practises
4. Quantification of secondary forest use impacts by experimental and laboratory approaches
5. Modelling of rainfall-runoff-events for the investigated dates (around 1850, 1960 and 2020) and identification of the land use impact on the basis of a developed expert-system to derive run-off classes from historic land-use data
6. Preparing the modelling results and related process understanding and recommended measures in form of educational material and publications

Overall, all the tasks of these aims were completed with only minor adjustments. There were some delays on a few points, but the tasks could be completed at a later date. The following points are summarised and explained below:

- a) Changes to the project schedule in terms of personnel and timing
- b) Completion and modification of content-related tasks
- c) Additional tasks relating to the project content that were carried out

Changes to the project schedule in terms of personnel and timing

The project began on 1 November 2022. The three PhD students started between 1 November 2022 and 1 February 2023. The PhD student in History reduced his work obligation to 10 hours per week as of 1 October 2024, as he had taken up another position. The hours thus freed up were allocated to the other two PhD students, enabling their projects to be extended by two and three months respectively. This extra time meant that tasks that had been postponed could still be completed. Furthermore, they also took on responsibilities of the third doctoral student, particularly with regard to preparing the final project exhibition and other publication tasks.

Completion and modification of content-related tasks

Objectives 1–3 were completed almost in full. Nevertheless, under objective 1, more detailed flood event documentation was planned in the test areas so that modelled events could later be compared with actual discharge rates. However, it became apparent that the search for reliable evidence to quantify past floods proved unsuccessful. Consequently, it was not possible to link the model results to historical information. In terms of the effort required, objective 3 was significantly underestimated. In particular, the time-consuming data preparation (e.g. cadastral records, forest inventories, aerial photographs) took the PhD student and student assistants longer than anticipated.

With regard to objective 4, the litter removal and rainfall simulation experiments required a significant investment of staff and time, but were carried out as planned. Soil investigations on litter removal sites were expanded, particularly with regard to quantifying the water-holding capacity of the organic layers, supplemented by continuous measurements of soil moisture on the experimental plots in comparison with undisturbed areas.

Modelling of rainfall-runoff events for objective 5 was significantly delayed because it required a great deal of preparatory work, in particular the expansion of the expert system – which had been the subject of lengthy and intensive discussion – and the reconstruction of land use for past time slices. The planned integration of precipitation intensity data from the SEHAG project could not be implemented because the test regions of the two projects are, after all, too far apart and new, spatially adapted analyses would have been too labour-intensive. Consequently, it was not possible to incorporate any reliable data on the frequency of heavy rainfall in the earlier time periods into the project.

The numerous tasks under objective 5 were, on the whole, completed, even though some tasks were modified. For instance, the exhibition at the Traunkirchen Forest Campus became the central closing event, reaching a variety of target groups. The carefully designed posters were subsequently also presented at the Regional Mountain conference in Obergurgl and used for teaching purposes at the university of Innsbruck and BOKU University Vienna as well as in the training of forest rangers. Instead of a closing workshop, an entire session comprising four presentations was held during the BFW Hofburg Talks Innsbruck in June 2026, allowing ample time for in-depth discussions. The content of the planned manual will be incorporated into the forthcoming revised edition of the field guide by Markart et al. (2004, 2011). This ensures that it will reach the relevant specialists.

There have been some delays with the journal publications in the field of natural sciences. One reason for this was the very extensive fieldwork and laboratory work, which meant that the data analysis and writing had to be put on hold. Although the project has officially been completed, the PhD students are still working diligently on these publications, so this task will also be completed soon.

Additional tasks relating to the project content that were carried out

The interim report at the halfway point of the project listed ten additional studies that were carried out in addition to the tasks set out in the proposal. These were made possible by the great commitment of the PhD students and their excellent collaboration, as well as the integration of final-year dissertations into the project. Of particular note in this context are the studies

- on the hydrological behaviour of the topsoil (two Master's theses, journal paper in preparation)
- on litterfall, based on recent measurements across all plots
- on stand structure
- on the characterisation of forest floor structure using terrestrial laser scanning (journal article in progress)
- on soil moisture at several sites and profile depths (journal article in review)
- on plant-available nutrients
- on interviews regarding secondary forest use practices.

In two cases, research assistants (postdocs) were employed on a part-time basis to bring in expertise in dendrochronology and the analysis of laser-scan point clouds.

Finally, it should be noted that the assessments of forest condition around 1850, as well as the detailed quantification of material flows from the forest to agricultural land at that time, were carried out on a very large scale, which had not been originally planned. There are as yet very few comparable detailed local studies in this field.

Overall, all project objectives were successfully met. Smaller work packages that could not be implemented – due, for example, to a lack of available data – were more than offset by extensive additional.

2.1.1. Historical subproject

The general objective of the historical research consisted mainly in a detailed reconstruction of forest-use practices, especially litter raking, pollarding, and forest grazing, in Tyrol for the periods around 1850 and 1960. To ascertain the hydrological impacts of past forest-use practices, it was necessary to collate all information that could be extracted from archival sources concerning patterns and intensities of use. Out of which datasets were created to underpin the analyses and modelling carried out over the course of the project. This was achieved through a systematic review and appraisal of largely unprocessed sources from various archives. Building on this evidential base, both suitable test sites for experimental sampling were selected (Aim 1) and – owing to the high level of detail in the historical information – their hydrologically relevant land-use patterns were subsequently reconstructed (Aim 3).

To achieve these objectives as effectively as possible, the evaluation extended beyond the archival sources specified in the proposal. In particular, for the study period around 1960 and with the involvement of our transdisciplinary partners, oral-history interviews with contemporary witnesses were conducted and material evidence (such as tools used for litter raking) was incorporated into the reconstruction of use practices, thereby enhancing the quality of the historical information derived from written sources.

2.1.2. Forest ecology subproject

Historical forest management practices have altered forest ecosystems. The legacy effects of these practices, which have been in place for over a century, may still influence forests and the ecosystem services they provide. Therefore, the objective of the forest ecology part of the project was to improve our understanding of this supposed impact of historical forest use practices on forest soils. We conducted extensive field experiments and laboratory analysis. In addition to the investigations listed in the proposal (Aim 4, Task 4.3), further investigations and measurements were carried out in order to gain a more comprehensive picture of the consequences of historical forest use practices.

2.1.3. Hydrological subproject

The overarching objective of the hydrology subproject was to reconstruct runoff conditions for around 1850, 1960, and 2020 while considering historical forest-use practices, including litter raking, pollarding, and forest grazing, in small Alpine catchments. A key objective was to integrate information across multiple spatial scales. Point-scale findings from rainfall simulation experiments, spatial historical data, and catchment-scale hydrological modelling were linked through an expert system and incorporated into the modelling framework (Aim 5).

The reconstruction was based on the historical surveys and archival analyses, complemented by rainfall simulation experiments that enabled a hydrological assessment of historical forest-use practices using the expert system. Additional long-term soil moisture and temperature monitoring provided insights into the effects of litter removal on soil water dynamics. Furthermore, analyses of undisturbed forest soil samples, including organic layers, supplied valuable information on soil water retention capacity (Aim 2 and 4).

2.1.4. Inter- and transdisciplinary objectives

200 years ago, Tyrol's forests looked very different from today. In addition to the widespread practice of forest grazing with various farm animals, exploitation of non-timber forest products altered stand structure as well as forest soils. Until the middle of the 20th century, litter raking (collecting ground vegetation and organic forest floor material) was practiced by local farmers. Another practice was pollarding, which means gathering branches from living coniferous trees. The branches were lopped off using a billhook. Later, the twigs were chopped up.

The interdisciplinary task was to link the historical information on these usage practices with the measurements, experiments and laboratory analyses. The aim was to link this newly generated understanding of ecological and hydrological processes with historical evidence, in order to better differentiate the relationship between humans and the environment over time.

In the course of the project, it became apparent that the historical data provided was very detailed. When combined with the results of the experiments and analyses, a calculation of historical material stocks and flows from forests to agricultural fields was enabled. As the historical evidence mentioned above for the area of lower Tyrol (Unterland: Stampfangerbach, Aubach and Ahrnbach/Zillertal) appeared to be excellent, the project-team focussed mainly on this area (Fig. 01).

The transdisciplinary task was to integrate all stakeholders into this research process, to discuss the results collectively and to communicate them to a wider public.

2.2. Methods used/developed

2.2.1. Historical subproject

Comprehensive archival research was undertaken to inform the selection of the project's study areas and to reconstruct historical forest conditions and past forest-use practices in these areas. This research primarily drew on the holdings of the Tyrolean Provincial Archives and was progressively expanded over the course of the project to include consultation of records at the Tyrolean Provincial Museum Ferdinandeum, the Bavarian Main State Archives in Munich, the Diocesan Archive of Brixen/Bressanone (Italy), the Archive of the Department of Agricultural Affairs of the Province of Tyrol, and the Archive of the Tyrolean Provincial Forestry Directorate.

In addition, the corpus of written sources was further augmented by digitised materials made available via the Austrian National Library's online platforms. Additionally, a considerable part of the remarkable archival sources (as available in the Tyrolean Provincial Archive) was put into order, as many of the historical maps were – due to older archival storage conditions – no more in a logic connection to its written source, separately stored. Table 01 provides an overview of the methods applied in the source analysis.

Table 01: Summary of the main methods used in the historical subproject, broken down into the relevant aims or tasks.

Aim / Task	Method	Main output
Selection of four test catchments (data base land use)	Archival research, literature study	Compilation of historical datasets as a basis for the selection of test sites and further analyses
Reconstructing former hydrologically relevant land-use pattern (around 1850 and 1960)	Transcription	Preparation of transcripts for subsequent qualitative/quantitative analysis of sources
	Qualitative analysis (text analysis)	Reconstruction of past forest conditions (extent and boundaries of the forests, climate, soil conditions, vegetation/tree species, timber yield, agricultural uses)
	Quantitative analysis (historical statistics)	Quantification of forest-litter removal; validation of litter-use quantities through triangulation with other economic and socio-historical datasets
	GIS analysis	Mapping of past forest use practices; analysis of use patterns
	Comparative historical analysis	Micro-historical comparison of historical forest districts (with regard to forest conditions and use practices, particularly in our test sites)
	Historical discourse analysis	Historical contextualisation of litter-raking practices in Tyrol and their significance within agriculture and forestry
Reconstructing former hydrologically relevant land-use pattern (around 1960)	Oral history	Reconstruction of land-use patterns on the basis of oral-history interviews

2.2.2 Forest ecology subproject

The consequences of historical forest management practices were investigated at four study sites within the Ahrnbach (Stummerberg) and Stampfangerbach (Söll) catchments. Table 02 lists the various methods used. These methods enabled a detailed quantification of the impacts of litter raking on coniferous forest and an investigation of the resulting effects on forest tree stand and soil.

Table 02: Summary of the main methods used in the forest ecology subproject, broken down into the relevant aims or tasks.

Aim / Task	Method	Main output
Soil surveys	Ground vegetation, organic layer and mineral soil sampling and laboratory analysis	Carbon and nutrient pools of the test sites, soil pH
	Litter raking experiments and sampling of the remaining organic layer after litter raking	Quantification of carbon and nutrient extraction by litter raking and of the remaining organic material in the organic layer after litter raking. Determination of forest floor litter properties (bulk density, composition, elemental composition)
	Empirical determination of leaf litter and chopped twigs bulk density	Determination of leaf litter and chopped twigs properties (bulk density)
	Sampling of fresh organic layer and upper mineral soil	Analysis of microbial biomass, pH (three times: before litter raking, one year after and three years after). Comparison of litter raked plots and undisturbed control plots.
	Sand bags analysis	In-growth rates of ectomycorrhizal mycelia, one year after litter raking. Comparison of litter raked plots and undisturbed control plots.
	PRS-probe analysis	Plant available nutrients, one year after litter raking. Comparison litter raked plots and undisturbed control plots.
Tree stands surveys and measurements	Litter fall sampling	Quantification of annual litter fall of the four test sites.
	Dendrometric measurements	Quantification of forest stand biomass stocks of the four test sites.
Dendrochronological surveys	Reconstruction of tree diameter increment of the four test sites.	Reconstruction of tree growth and age, as well as investigations into the immediate effects of the litter raking intervention.
	Comparison of four additional test sites with different historical litter raking intensities according to historical archive data.	Studies on the effect of different forest use intensities on tree growth.

2.2.3 Hydrological subproject

The hydrological subproject combined field experiments, laboratory analyses, historical data reconstruction and hydrological modelling to quantify the effects of historical forest use on rainfall-runoff processes in small Alpine catchments. A summary of the main methods is given in Table 03.

Table 03: Summary of the main methods used in the hydrological subproject, broken down into the relevant aims or tasks.

Aim / Task	Method	Main output
Hydrological field experiments	Litter raking experiment	Effects of historical forest-use practices on runoff, infiltration and soil moisture
	Rainfall simulation experiments	
	Soil moisture monitoring	
Soil hydrological characterization	Soil profile analysis	Soil hydraulic properties and water storage functions
	Hydraulic conductivity and water retention measurements	
Expert-system development	Analysis of a rainfall simulation database	Historical runoff coefficient and roughness maps
	Field mapping	
	Analysis historical land-use information	
Historical land-use reconstruction	GIS analysis	Land-use and land-cover scenarios for 1850, 1960 and 2020
	Aerial photo interpretation	
	Evaluation of forest inventories and archival sources	
Hydrological modelling	Runoff coefficient mapping	Reconstruction of runoff patterns and flood response for 1850, 1960 and 2020
	ZEMOKOST modelling	

A key innovation is the historically authentic implementation of litter raking, implemented on 400 m² plots and evaluated using rainfall simulation experiments (50 m² large mobile rainfall simulation system) and long-term soil moisture monitoring. An existing dataset of rainfall simulation experiments on forest sites (unpublished dataset by Markart and Kohl, 2025), supplemented with additional forest grazing rainfall simulation experiments from the HILUC working group, was statistically analysed to compare surface runoff responses across site and management categories. These experiments provided novel insights into runoff generation and soil moisture dynamics under partially removed organic layers.

Soil hydrological properties were characterised through soil profile descriptions, laboratory measurements of saturated and unsaturated hydraulic conductivity. Highly detailed investigations into the water-holding capacity of large, undisturbed humus monoliths, followed by an analysis of the composition of the organic layer, represented a new approach.

2.2.4 Inter- and transdisciplinary approaches

The interdisciplinary approach centred on linking the three sub-projects. The relevant methods are summarised in Table 04. Methods and structure of the transdisciplinary process are described in detail in chapter 3.

Table 04: Summary of the main methods used at the intersection of historical, ecological and hydrological research.

Aim / Task	Method	Main output
Historical ecology	Archival research, literature study	Compilation of historical datasets as a basis for the selection of test sites and further analyses
	Using archive data for reconstruction of 19th century material fluxes	Quantification of extraction amounts of carbon and nutrients by forest management (harvest of forest bedding material and wood) and the transfer into agricultural fields in the 1840s (forest district Fügen)
	Reconstruction of forest use history of four sites using archive data and dendrochronological surveys.	We have attempted to combine tree-ring widths with records of forest use in order to identify growth pattern linked to historical practice.
Historical hydrology	Using archive data for reconstruction of historical forest management and its consequences for forest hydrology	Developing an expert-system for assessing runoff coefficients for the time period 1850

The accounts of contemporary witnesses, who carried out lopping and litter raking themselves, helped us to better understand the criteria for site selection, as well as the workflow and tools used. This made it possible to create an experimental design that was historically accurate in its recreation of these practices.

By combining archive data from the Tyrolean Regional Archives with the results of our experiments and further literature, it was possible to reconstruct mid-19th-century material flows from forests to agricultural land. Archive data provides detailed information about harvesting amounts of forest bedding material and wood listed as volume. To quantify extraction masses, densities of the material are required. For wood densities from literature were applicable, though not for the various types of forest bedding material. Therefore, bulk densities of forest bedding material were determined empirically.

Elemental composition of wood and forest bedding material was determined using literature and our results of the laboratory analysis. We assume, that forest nutrients were mainly transported into agricultural fields by forest bedding material and fuel wood ash. According to Galler (2009) we assume that 30% of forest bedding material carbon and nitrogen was lost due to volatilization and leaching during storage and application. In addition, we assumed that 60% of fuel wood ash was used for fertilisation. Mid-19th century land use for the Fügen-district was determined using the for the region 1855 elaborated Franciscan Cadastre. To represent the fertilisation practices of the farmers, two scenarios were defined; scenario 1: farmers fertilised crop rotation areas, gardens and meadows; scenario 2: farmers concentrated their available fertiliser on crop rotation areas and gardens. This enabled us to quantify carbon and nutrients extraction from the forests and the transport into agricultural fields for the 19th century Fügen-district.

Historical changes of land-use and land-cover were reconstructed using GIS-based integration of georeferenced forest plans, aerial photographs, cadastral records, and field mapping (channel parameters, runoff coefficient and roughness maps), providing spatially explicit datasets for 1850, 1960 and 2020. These datasets were further refined

using an expert system that links historical land-use intensity to hydrological surface runoff coefficient classes (SCL) according to Markart et al. (2004, 2011).

Our study also aimed to assess whether it would be possible to produce a Tyrol-wide map of previous litter raking impact. This is because other studies have shown that such a map could significantly improve the digital mapping of forest soils. However, two limitations became apparent: firstly, historical data is lacking in some areas; and secondly, reconstructing such a map on the basis of archive material is a very labour-intensive process.

A major methodological advancement is the integration of rainfall simulation data, expert-system classification and historical land-use reconstruction into the hydrological model ZEMOKOST, enabling scenario-based reconstruction of catchment-scale runoff patterns across three time periods.

Conceptually, these methods form a multi-scale framework linking historical land use, soil related processes and catchment hydrology to improve the understanding of both historical material stocks and flows as well as historical flood-related peak discharge responses to changes in surface runoff processes.

Two methodological approaches could be regarded as breakthroughs. Firstly, the combination of litter raking use and rainfall experiments across larger areas. Secondly, the detailed calculation of material and nutrient flows from the forest to agriculture.

2.3. Achievements and new insights

2.3.1. Historical research

A key outcome of the historical work was the first systematic survey and analysis of archival holdings that had hitherto been scarcely examined and that provide information about the condition and uses of Tyrolean forests some 170 years ago. In this way, it was possible to evaluate the documented historical soil conditions, tree species, wood growth, and rights of use of the forested areas and select the catchment areas to be studied. This foundational research enabled the general reconstruction of historical forest use and yielded a series of core findings that offer insights both for assessing hydrologically relevant land-use patterns and for broader contexts in economic, social, and environmental history.

In general, access to forest products and the intensity of certain forest-use practices in nineteenth-century Tyrol were structured by contested property and usufruct regimes, with litter-raking rights confined to particular forests rather than being universally available. Broadly speaking, a distinction must be made between, on the one hand, state forests owned by the sovereign – either encumbered by subjects' usufruct rights or free of servitudes – and, on the other hand, collectively used forests whose use or ownership derived from a grant by the territorial sovereign. Thus, a micro-historical comparison of forest areas necessary was made in order to determine the quantities of forest litter removed in the past. The detailed spatial reconstruction (Fig. 02) brought to light several patterns that are not self-evident from administrative sources alone and must be interpreted in the context of local conditions:

- Depending on the study area, different forest-litter utilisation practices predominated. These, in turn, depended on the local composition of tree species (deciduous versus coniferous), on customary forest uses, and prevailing economic practices.
- With regard to Tyrol's topographic and socio-economic situation of this period, a pattern emerges whereby higher-elevation municipalities tended to make more extensive use of forest areas, which were employed for livestock husbandry and alpine pastoralism. This, in turn, drove up the demand for forest litter. By contrast, in lower-lying areas more arable farming could be practised.
- The sources point to deliberate spatial strategies of extraction: all localities obtained forest litter from both communal and state forests, yet in absolute terms many communities collected the greater share in the latter, plausibly to spare their own communal woodland. When use intensities are considered relative to the size of the forest areas, it becomes apparent that state forests, owing to their size and remoteness, tended not to be subject to excessive use. However, where state and communal forests were comparable in site conditions and distance from farms, the former often showed higher use intensities.
- A municipality-level comparison suggests that settlement patterns and farm-building structures may serve as relevant explanatory variables alongside livestock holdings.

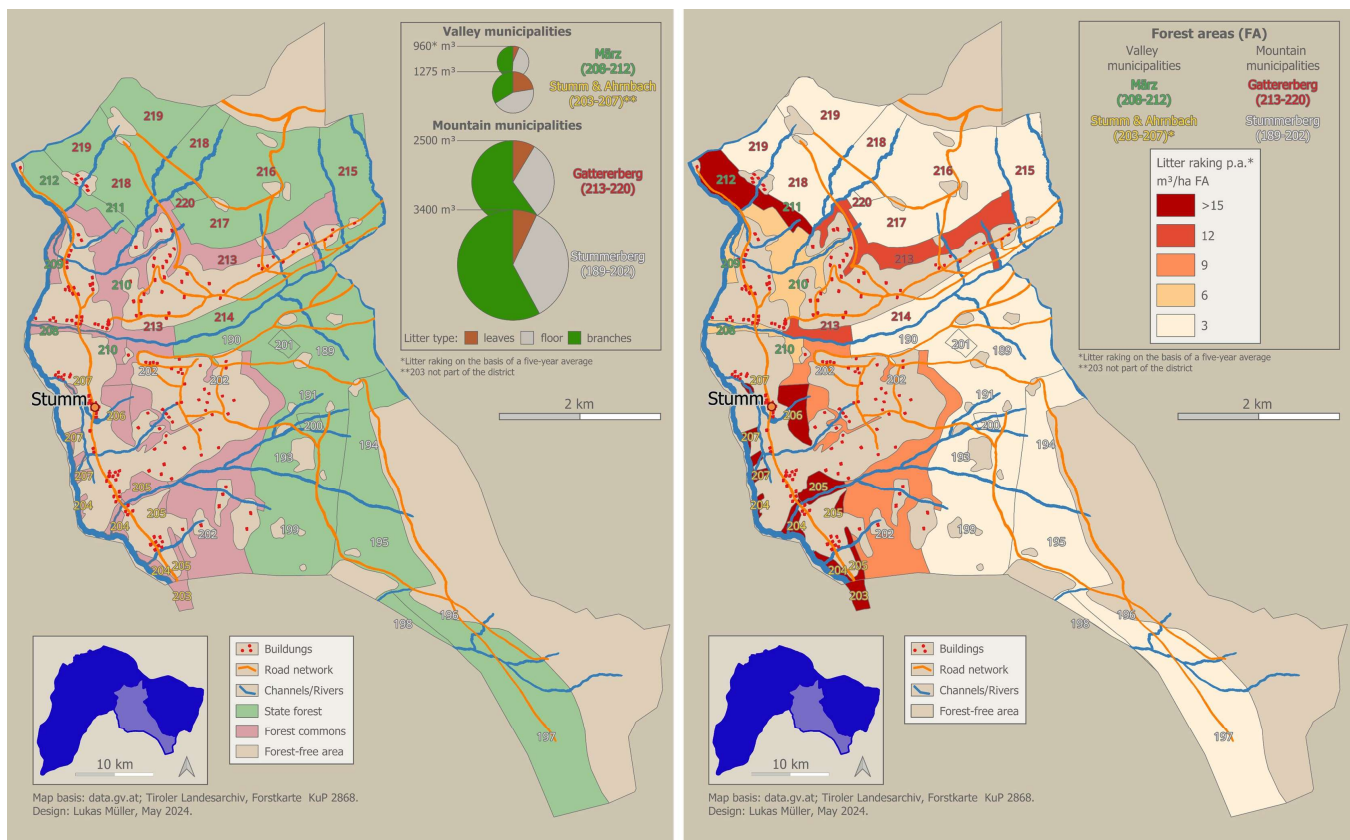


Figure 02: Comparison of absolute and relative quantities of forest litter in a historical forest district in the Zillertal (Gröber et al. 2024, modified).

Furthermore, both the availability of labour and the availability of substitutes for forest litter can be identified as factors influencing the quantity of litter removed from the forest. Overall, litter quantities reflect interacting social and environmental factors. Moreover, the repeated regulatory interventions against practices such as pollarding are read here as evidence of an enduring tension between agrarian need and administrative forest governance, and of the limited capacity of norms to suppress such practices. These interpretations are supported not least by the oral history interviews conducted, which link the end of these historical forest-use practices to the structural transformation in rural regions after World War II.

2.3.2. Forest ecology research

For centuries, forest ecosystems and agriculture were closely linked in Central Europe and especially in Alpine regions. Forest use practices such as litter raking or lopping provided additional nutrients for agriculture, thus supporting food production and human nutrition. At stand level, litter raking has dramatic ecological consequences by removing large quantities of nutrients and promoting soil acidification. Our litter raking experiments removed on average between 4.2 to 6.0 kg m⁻² organic material. For comparison, the annual litter fall on the test sites amounted between 0.47 to 0.53 kg m⁻².

Our experiments removed large amounts of carbon (2.4 – 3.5 kg m⁻²), nitrogen (71.5 – 119.5 g m⁻²), calcium (14 – 20.8 g m⁻²), phosphorus (3.6 – 5.8 g m⁻²), sulphur (3.9 – 14.7 g S m⁻²), potassium (4.3 – 6.5 g m⁻²) and magnesium (3.0 – 3.8 g m⁻²) promoting loss of soil acid neutralising capacity. In comparison to the total soil stock, one time litter raking removed 17 to 26% of total carbon, 13 to 20 % of total nitrogen, 17 to 32% of total calcium, 5 to 11 % of total phosphorus, 4 to 16 % of total sulphur, 1 to 10 % of total potassium and up to 2% of total magnesium. Considering plant available soil pools, the figures look even more dramatic, the one-time litter raking extracted 21 to 64% of the citrate-extractable phosphorus and 34 -68% of the exchangeable potassium.

In addition, the experiments allowed us to quantify material properties (bulk density, elemental composition) of different kinds of forest bedding material. How significantly different types of forest litter can differ from one another, demonstrates the bulk density. Leaf litter exhibits a bulk density of 9 to 11 kg m⁻³, forest floor litter of 59 kg m⁻³ and chopped spruce twigs of 64 kg m⁻³. The material composition of forest floor bedding material can be seen in Figure 03.

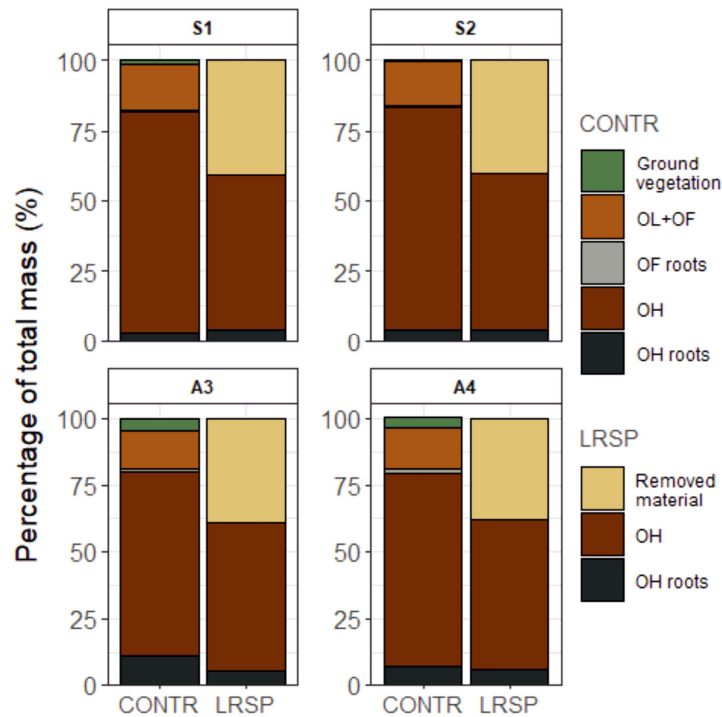


Figure 03: The allocation of the different forest-floor components on the control plots (CONTR) and the litter raking subplots (LRSP), on which one-time litter raking experiments were carried out.

Our experiments allowed us to investigate the effect of litter raking on microorganisms one year after the intervention. Even if we removed large amounts of organic material and thus nutrients, we could not detect a significant effect after one year of the intervention on mycelia growth of ectomycorrhiza, pH or plant available nutrients. We assume that the intervention does not have an immediate effect on the remaining topsoil. The consequences of the intervention may be noticeable later, when the influx of nutrients is cut off. To investigate further developments on the sites, samples were taken in 2026 approximately 3 years after the intervention.

Dendrochronological analyses have produced similar results. Two years after the litter was removed, no effects on the width of the annual rings could be detected. Here, we also assume that any effects will become apparent at a later stage.

2.3.3. Hydrological research

The rainfall simulation experiments and hydrological modelling provided complementary insights into the effects of historical forest use practices on runoff generation and flood response. A key achievement was the incorporation of experimental findings on historical secondary forest uses into an expert-system, which served as the basis for scenario based hydrological modelling at catchment level.

One of the most important and unexpected findings emerged from the rainfall simulation experiments. Contrary to the initial hypothesis, litter raking did not generally increase surface runoff. Only two of the four experimental plots showed a temporary increase shortly after litter removal, while one year later all plots had returned to their pre-treatment surface runoff behaviour (Fig. 04).

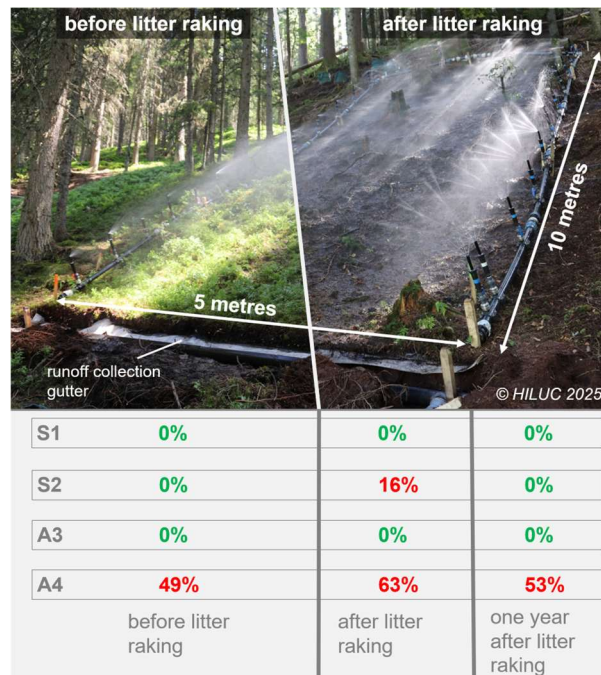


Figure 04: Results of the HILUC litter raking rainfall simulation experiments, showing the measured percentage of surface runoff (Müller et al. 2026 [under review]).

Instead, the experiments revealed that the hydrological response was primarily controlled by the hydraulic properties and connectivity of the underlying organic and mineral soil horizons rather than by the litter layer itself. Litter removal accelerated soil moisture dynamics and could promote deeper infiltration or interflow where soil structure remained favourable, whereas sites with high antecedent soil moisture (e.g. A4) or hydraulic bottlenecks exhibited faster and more concentrated surface runoff responses. These findings demonstrate that soil hydraulic properties are the dominant control on surface runoff generation following litter removal.

The results of the detailed investigations into the water-holding capacity of large, undisturbed humus monoliths, can be used to estimate the maximum water retention capacity during rainfall events. It was also found that, for humus layers thicker than 15 cm, even when the lower centimetres have dried out, the humus layer can still store even greater quantities of water.

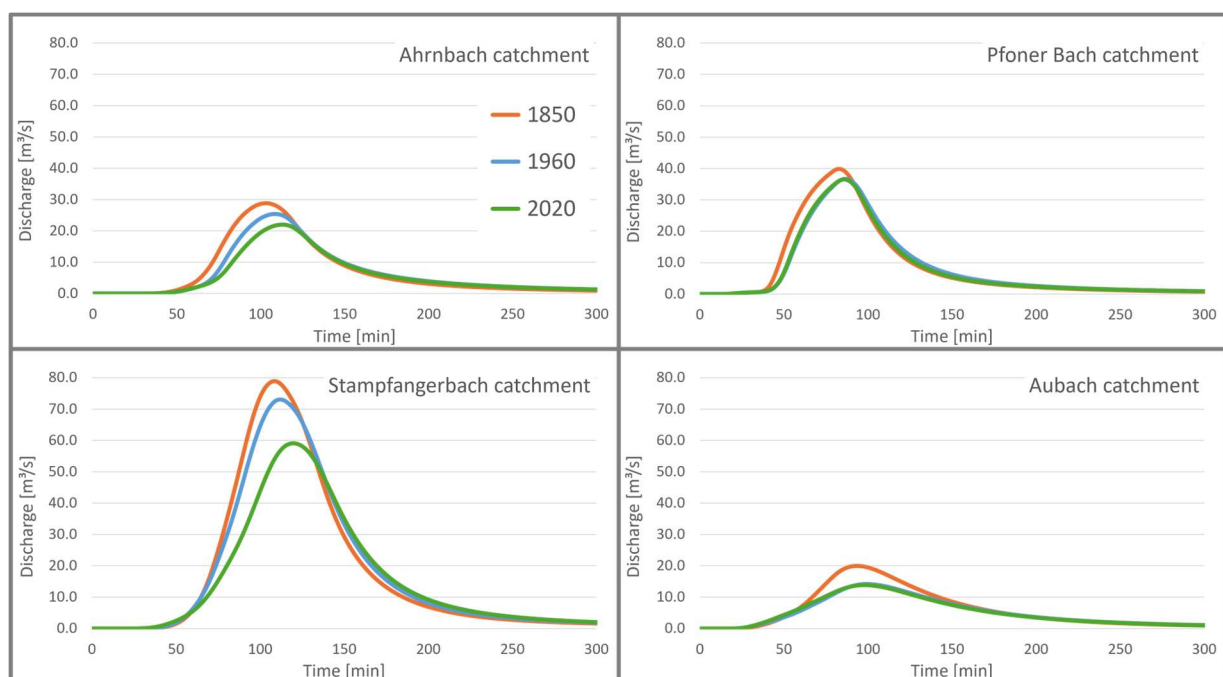


Figure 05: Discharge hydrographs for the four catchment areas and for the three time periods, based on scenario-based modelling using ZEMOKOST, taking into account the discharge coefficients assessed by the expert system (unpublished content).

The scenario based hydrological modelling showed consistent differences between the reconstructed land-use periods (Fig. 05). In all four test catchments, the 1850 scenario produced the highest peak discharges, reflecting the more intensive historical use of forest resources. In the Ahrnbach (Stummerberg) and Stampfangerbach (Söll) catchments, peak discharge decreased progressively from 1850 to 1960 and reached its lowest values under the 2020 scenario. In contrast, the Pfoner Bach (Pfons) catchment showed only minor differences between the 1960 and 2020 scenarios because forest grazing remained an important land-use component throughout all three periods. Forest grazing is still practised today in this study area. Similarly, in the Aubach (Going) catchment, the 1960 and 2020 hydrographs were nearly identical, indicating that changes in land-cover and land-use intensity largely compensated for each other.

2.3.4. Inter- and transdisciplinary outcomes

In addition to the outcomes already mentioned, three further aspects should be highlighted here:

The archive data can serve as a valuable basis for reconstructing historical material flows from forests to agriculture. In total, the people of the Fügen-district removed in the past on average every year 1486 kg C ha⁻¹, 4.6 kg N ha⁻¹, 0.5 kg P ha⁻¹, 5.4 kg Ca ha⁻¹, 2.0 kg K ha⁻¹ or 0.7 kg Mg ha⁻¹ through the harvest of forest products. Mid-19th century fertilisation practices transferred annually on average 179 – 281 kg C, 3.4 – 5.4 kg N, 0.6 – 1.0 kg P, 5.4 – 8.4 kg Ca, 2.2 – 3.5 kg K and 0.8 – 1.3 kg Mg of forest nutrients to one hectare of agricultural land.

Dendrochronological surveys have shown that it was difficult to find areas that were only used for litter raking but not for lopping. Although there were no mentions of lopping in the records, the tree-ring widths nevertheless showed clear signs of it. It was therefore not possible to investigate the pure effect of litter raking on tree growth.

Although the absence of historical discharge records prevented an exact reconstruction of past flood events, the combined experimental and modelling approach enabled a robust evaluation of historical land-use impacts. Rather than reproducing individual floods, the developed scenarios quantify how different historical management practices modified runoff generation and flood potential. These results provide an important scientific basis for assessing future land-use changes and the role of sustainable forest management in natural flood mitigation.

2.3.5. Summary and synthesis

At this point, reference is made to the executive summary of this report. It should also be emphasised that it was possible to link the three subprojects effectively, thereby generating results that went well beyond the respective subject areas.

Historical research confirmed that, for some areas, detailed records exist regarding the condition and use of the forests around 1840, which can be analysed in a variety of ways. On this basis, secondary forest uses were comprehensively described for parts of Tyrol for the first time. The results also led to the selection of four test areas in Tyrol in the municipalities of Pfons, Stummerberg/Fügen, Söll and Ellmau (Fig. 01). Through interviews with elderly eyewitnesses, it was possible to reconstruct how and where these practices were carried out, which provided important input for the experiments conducted as authentically as possible within the project.

On the basis of historical sources, detailed conclusions were drawn on the condition and nutrient balance of the forests, as well as material flows from forests into agricultural land around 1840. It became apparent that annually only a small proportion of the total forest area within the study area of Fügen in the Zillertal (Fig. 01) was required to meet the demand for litter. However, there was certainly significant over-exploitation in individual forest areas. Agriculture – and thus the food supply – benefited from this historical practice.

Rainfall simulation experiments showed that forest grazing significantly increases surface runoff, depending on the intensity of grazing. Litter raking has a significantly smaller effect; in some cases, it has even no influence on the formation of surface runoff. Thus, an unexpected finding from our rainfall simulation experiments was that the forest floor may be capable of fully absorbing heavy rainfall even after one time litter raking, depending on the site characteristics. Modelling of surface runoff based on mapping and the modification of input data according to historical land uses revealed different peak runoff values for the time periods 1850, 1920 and 2020. In all four test areas, runoff peaks around 1850 were highest. This is likely to be linked to the widespread practice of forest grazing at that time.

2.4. Discussion of Findings in Relation to Recent Scientific Discourse

2.4.1. Historical subproject

Fundamentally, the historical work carried out within the project addresses a research desideratum, since the sources known to date have scarcely allowed the reconstruction of nineteenth-century land-use patterns and intensities in Alpine regions at this level of detail, or their interpretation in environmental and social-historical terms. Although records of land use exist in the form of cadastral surveys for most of present-day Austria and for most areas of the former Habsburg Monarchy, this is not the case for Tyrol (Bauer 2017; Scharr 2020).

As a result, the specific historical condition of Tyrolean forests prior to the preparation of modern forest management plans in the twentieth century remained a blind spot, with the available evidence restricted to normative sources. In this respect, the detailed archival research and analysis of sources significantly expand the evidentiary basis for forest history by arguing that sources for forest use in the last two centuries constitute a rich base of maps, statistics, descriptions, laws, and practical instructions. In turn, this broadens the empirical foundation for historical reconstruction beyond the canon of legal texts that has dominated previous studies (Oberrauch 1952; Maier & Pamer 2024). In particular, it strengthens source-based regional history by showing the analytical value of administrative records such as forest descriptions as detailed records of local conditions, forest states, and property/use regimes for precisely defined woodland areas. Thus, the potential outlined in a preliminary study (Maier et al. 2021) regarding the historical sources analysed was fruitfully realised.

The results presented in section 2.3.1 refine and extend the reconstructions hitherto available primarily for the Swiss Alpine region (Gimmi & Bürgi 2007; Gimmi and others 2008; Stuber & Bürgi 2012). Particularly noteworthy is the added value of the chosen micro-historical approach, which made it possible to capture small-scale patterns of forest use. At this level of resolution, substantial differences could be shown both in the collection of different types of forest litter and in the quantities removed from the forests. The latter depended not only on topographic factors but also on economic and social-historical factors. This is evident, among other things, in the sparing of communally used areas, as indicated by the analysis of the sources.

Methodologically, the study introduces an interdisciplinary, GIS-enabled workflow that operationalises historical research by georeferencing and integrating spatialised historical information. It offers an exemplar for quantifying and spatially modelling historical forest litter extraction and its local impacts, making past interventions representable and opening them to long-term, interdisciplinary analysis of ecosystem development.

2.4.2. Forest ecology subproject

This study advances the field by reuniting experimental ecology with historically authentic practice: reconstructing farmer-guided litter raking with authentic tools under real field conditions enables process-realistic inference about what was actually removed (selective OL/OF and ground vegetation with incidental OH; OL/OF and OH are horizons of the organic layer). Literature gaps were filled by empirically determining the characteristics of the forest bedding material (bulk density, composition, carbon concentration). The final combination of field experiment results with historical data made it possible to calculate material flows from the forest to agriculture. As quantitative data about the historical gathering of forest bedding material is rare, it is often estimated or modelled (Krausmann 2004; Gimmi and others 2008; Gimmi and others 2013; Gingrich and others 2015). Our research therefore makes it possible, for the first time, to calculate historical forest material flows using actual historical data. In addition, the corresponding historical map enabled an analysis of the spatial distribution patterns of human forest bedding material use.

The study strengthens landscape-scale inference by linking harvesting needs to spatial variability and the required raked area, enabling more robust upscaling than assuming uniform use and it also shows that twig harvesting reduced pressure on forest-floor litter (e.g., litter raking practice). We clarify the legacy interpretation by showing that, even after decades, deeper mineral soil still lacks carbon, while the organic layer and upper mineral soil have largely recovered. This matches earlier reports of long-term soil carbon loss and adds finer detail on where it persists.

Short-term monitoring shows delayed responses: one to two years after raking, we found no changes in ectomycorrhizal mycelia, pH, plant-available nutrients, or tree-ring widths, suggesting effects may appear later when nutrient inputs decline. Archival inventory data enable precise reconstruction of historical management and indicate that raking intensity in the Fügen district was lower than previously expected; additional inventories across Tyrol are needed to test this pattern and build a broader mid-19th-century baseline. Open questions include how repeated raking accumulates over time, when microbes and tree growth begin to respond under different climate and deposition conditions, how to account for twig harvest alongside litter raking, how to standardize compaction to

align bulk-density estimates and how transferable these results are across forest types and elevations in process-based models for hindcasting and scenarios.

2.4.3. Hydrological subproject

Our findings refine current understanding by showing that the hydrological response to litter removal is governed less by the litter layer itself than by the hydraulic properties, connectivity and antecedent moisture of the underlying soil. While previous studies generally reported increased surface runoff following litter removal (e.g., Li et al. 2014; Sayer 2006), we observed only temporary increases at sites with unfavourable soil hydraulic conditions. Well-structured forest soils largely maintained their infiltration capacity despite the partial removal of organic layers, emphasizing the dominant role of soil structure and preferential flow pathways in controlling runoff generation.

These findings complement earlier studies demonstrating the high buffering capacity of Alpine forests soils (Wittich 1951; Beven & Germann 1982; Strunk 1992; Ginter et al. 1979; Weiler & Naef 2003; Aoki et al. 2006; Schüller 2006; Jost et al. 2012; Sebald et al. 2019) by identifying the conditions under which this buffering function may be temporarily reduced. They therefore provide an improved process basis for incorporating historical land-use effects into hydrological models and flood-risk assessments.

A limitation of this study is that litter raking was applied only once, although historical evidence indicates that accessible forest stands were repeatedly raked over decades (Pitterle 1988; Kopp 2024). Repeated litter removal, particularly under prolonged dry conditions, may enhance soil water repellency, which has been identified as an important driver of reduced infiltration and increased surface runoff (Wang et al. 2020; Nainar et al. 2021; Kajiura & Tange 2022). Quantifying these cumulative effects remains an important objective for future research.

In contrast, forest grazing has a very strong effect on surface runoff disposition. Across both the compiled rainfall simulation experiments by BFW and the additional HILUC rainfall simulation experiments, forest grazing consistently produced the highest surface runoff response, suggesting that livestock-induced soil compaction may outweigh the hydrological impacts of other forest-use practices. These findings identify forest grazing intensity as a critical management factor controlling infiltration and surface runoff generation.

Beyond the plot scale, the scenario-based hydrological modelling demonstrates how experimentally derived process understanding can be transferred to the catchment scale. Although historical flood events cannot be reconstructed exactly because of limited historical discharge and precipitation data, the modelling provides a process-based framework for quantifying the hydrological consequences of historical forest-use change. Integrating field experiments with scenario-based modelling enables physically plausible assessments of historical forest use impacts where direct observations are unavailable and offers a transferable framework for evaluating future land-use and climate-change scenarios. Future work should improve historical precipitation reconstructions and integrate additional process information to further reduce modelling uncertainties.

2.4.4. Inter- and transdisciplinary approaches

In the preceding chapters, the project's interdisciplinary findings were already compared with research from the literature. This revealed that the approach adopted here, based on highly detailed historical studies, yielded new insights in both ecological and hydrological conditions that had not been so clearly identified in previous studies. In this respect, our study not only offers a local/regional reconstruction of relevant human–environment relationships, but also provides a methodological framework for how studies of this kind can be conceptually structured.

2.5. Connection to International Programs (UNESCO, UN, Future Earth, LTER, EU, ect.)

In order to assess in advance whether our research concept could be implemented in this way, our consortium submitted an application for the cross-border HiLaK project (EU INTERREG V-A Austria–Bavaria 2014), which was successfully carried out from September 2020 to April 2021 (Maier et al. 2021).

As outlined in the application, there are numerous links between our topic and relevant international programmes. The UN Sustainable Development Goals, in particular goals 15, 13, 3, and 4. Under SDG 15, sustainable management of forests and halt and reverse land degradation are explicitly mentioned.

The project also enhances and complements the interests of the three working groups (Forest and Water, Hazard and Disaster Risk Management in Mountains, Protective Functions of Forests) of the Working Party on Management of Mountain Watersheds (WPMMW) of the European Forestry Commission of the FAO with regard to the

sustainable development of mountain watersheds by providing important information to ensure long-term maintenance of environmental services within torrential catchments.

With regard to the surface processes relevant to the project, the project is very closely linked to the concepts of the Critical Zone Collaborative Network (CZNet). The current DFG Research Group Forest Floor (DFG FOR 5315) (2022–2026), with which we were in contact, also highlights the importance of this interface between the above- and below-ground parts of forest ecosystems and the significance of human interventions in this interface. Furthermore, the results – particularly those from the forest ecology subproject – could support the arguments put forward by the IAASA's Integrated Assessment and Climate Change (IACC) Programme (IACC's central goal is the development of response strategies and alternative pathways towards a low-carbon economy).

Our findings may also be of interest to the World Bank Group. Through workshops, this group provides representatives from emerging economies with knowledge on topics such as optimised forest management, including in relation to protection against natural hazards. In this context, our findings can shed light on the extent to which long-term humus and nutrient losses are caused by secondary land uses, and how this can also alter runoff potential.

Researchers of our team are active in the networks of Alpine Soil Partnership, Mountain Research Initiative, LTSER, CIPRA, Alpine Convention, Institute of Rural History, European rural history organisation, Permanent European Conference for the Study of the Rural Landscape (PECSRL) and additional environmental history networks which ensures that the results of our project have been communicated in these networks.

Through our project, we also aimed to make a significant contribution to LTSER research, in particular by establishing the litter raking experimental plots at the LTSER site in the Tyrolean Alps (TA), comprising nine locations. Unfortunately, it became apparent that no catchment area within this site met our requirements, namely a very good historical data record and a sufficiently high proportion of forest cover. Promising catchment areas, for example from the Ötztal valley, were generally characterised by too large a proportion of land above the tree line. Nevertheless, by selecting the test area in the upper Zillertal, our project builds on the legacy of the transnational EU EFFRE project EGAR on land use and natural hazards in the Zillertal.

The litter-recovery sites from our project are clearly located and are therefore available for further monitoring and research. We also have further activities planned. The plots have the potential to provide valuable insights into the regenerative capacity of forest sites following nutrient losses and controlling factors such as climate change.

2.6. Publications

2.6.1. Peer-Reviewed

Already published

Schrott, Roman; Gröber, Maximilian; Müller, Lukas; Simon, Alois; Katzensteiner, Klaus; Scharr, Kurt; Geitner, Clemens (2026): The Effect of Mid-Nineteenth-Century Forest Use Practices on Carbon Stocks of Mountain Forests in the Alps. *Ecosystems*, 29, 66. <https://doi.org/10.1007/s10021-026-01082-y>

Gröber, Maximilian; Müller, Lukas; Schrott, Roman; Scharr, Kurt; Simon, Alois; Markart, Gerhard; Katzensteiner, Klaus; Meißl, Gertraud; Geitner, Clemens (2024): Vom Wald auf den Acker, aber nicht mehr zurück. Zur Rekonstruktion historischer Waldstreunutzung in Tirol um 1850. In: *Tiroler Heimat. Zeitschrift für Regional- und Kulturgeschichte Nord-, Ost- und Südtirols* 88, S. 201–226.

In progress

Müller, Lukas; Geitner, Clemens; Schrott, Roman; Markart, Gerhard; Kohl, Bernhard; Gröber, Maximilian; Meier, Raphael; Meißl, Gertraud (2026): How does forest litter extraction commonly used in the past affect the runoff reaction to heavy rainfalls? *Hydrological Processes*. In revision.

Schrott, Roman; Gröber, Maximilian; Müller, Lukas; Simon, Alois; Katzensteiner, Klaus; Scharr, Kurt; Geitner, Clemens (2026): Forest as an integral component of Alpine agriculture - Quantifying the impact of historical land use practices on forest ecosystems and the transfer of nutrients into agricultural land. Under review.

Müller, Lukas; Geitner, Clemens; Schrott, Roman; Markart, Gerhard; Kohl, Bernhard; Scharr, Kurt; Gröber, Maximilian; Simon, Alois; Katzensteiner, Klaus; Meißl, Gertraud (2026): Past Forest Use and Runoff: How Are They Connected?. *Ecohydrology* (planned). In preparation.

Jia, Shoujun; Müller, Lukas; Schrott, Roman; Meißl, Gertraud; Rutzinger, Martin; Geitner, Clemens (2026): Exploring the potential of terrestrial laser scanning for spatial-frequency-temporal characterization of forest floor. Remote sensing of environment. In preparation.

2.6.2. Academic Theses, Other Publications, and Public Contributions

Not peer-reviewed publications (third mission)

Scharr, Kurt; Gröber, Maximilian; Geitner, Clemens; Katzensteiner, Klaus; Markart, Gerhard; Meißl, Gertraud, Müller, Lukas; Schrott, Roman; Simon, Alois (2026): Vom Nutzen des Waldes – Ergebnisse eines Forschungsprojektes der Universität Innsbruck. In: Tiroler Heimatblätter. Submission.

Bachelor theses

Lechner, Niklas. Szenarienbasierte Quantifizierung des Einflusses von Waldweideflächen auf das Abflussgeschehen des Pfoner Baches. Vergleich des modellierten Abflussgeschehens auf Basis eigener Kartierungen mit PSINOT-Daten unter Verwendung des Programms ZEMOKOST. 2026.

Kulle, Marie. Analyse der saisonalen Streudynamik unter Berücksichtigung der Streuentnahme in Bergwäldern Tirols. Eine Untersuchung subalpiner und montaner Standorte. 2025.

Kopp, Emma. Historische Nutzung des Waldes im mittleren Zillertal am Beispiel der Streunutzung und Waldweide. 2024.

Lengefeld, Philip. Untersuchungen von Waldböden in den Alpen an zwei Standorten in den Gemeinden Söll und Stummerberg hinsichtlich physikalischer, chemischer, biologischer und hydrologischer Eigenschaften. 2024.

Meier, Raphael. Bodenfeuchte, Bodentemperatur und Streuentnahme im Wald: Analyse der Bodenfeuchte und Bodentemperatur von vier Flächen im Rahmen eines Streuentnahmeexperimentes in Tirol von Juli bis November 2023. 2023.

Master theses

Thommes, Celina. „Auf Kosten [...] des Waldbodens“? Über die Wahrnehmung der Auswirkungen übermäßiger Waldstreunutzung in Tirol zur Mitte des 19. Jahrhunderts. 2025.

<https://ulb-dok.uibk.ac.at/ulbtirolhs/content/titleinfo/11852561>

Heinrich, Maria. Rekonstruktion der Landnutzung und -bedeckung auf Basis historischer Luftbildaufnahmen aus dem Jahr 1967 am Beispiel vom Einzugsgebiet Ahrnbach in der Gemeinde Stummerberg/Zillertal. 2024.

<https://ulb-dok.uibk.ac.at/ulbtirolhs/content/titleinfo/10538062>

Marx, Johanna. Hydrologische Wirkung der organischen Auflage von Waldböden: Feld- und Laboranalysen an vier ausgewählten Standorten in Tirol. 2024.

<https://ulb-dok.uibk.ac.at/ulbtirolhs/content/titleinfo/9580263>

Public lectures

Geitner, Clemens; Co-AutorInnen: Gröber, Maximilian; Katzensteiner, Klaus; Kohl, Bernhard; Markart, Gerhard; Meißl, Gertraud; Müller, Lukas; Scharr, Kurt; Schrott, Roman; Simon, Alois: Einfluss historischer Waldnutzungspraktiken auf den Wasser- und Nährstoffhaushalt der Böden in Gebirgslagen Tirols: Ergebnisse eines inter- und transdisziplinären Projektes. Jahrestagung der Bodenkundlichen Gesellschaften Österreichs und der Schweiz, Dornbirn, 22.04.2026.

Markart, Gerhard, Bernhard Kohl, Maximilian Behringer, Veronika Lechner, Christian Scheidl, Leon Schleich, Clemens Geitner: Einfluss von Standort und Bewirtschaftung auf Abfluss, Hydrologie, Erosionsvorbeugung. Fachtagung Schlanders, Südtirol, 21.05.2026.

Meißl, Gertraud: From local site conditions to catchment response. Kolloquiumsvortrag an der Universität Zürich, Zürich, 06.03.2026.

Geitner, Clemens: Das Projekt HILUC (Hydrological Impact of Historical Land Use and Climate) Ziele, Konzept und Kooperationen. Innsbrucker Hofburggespräche: Abfluss in Einzugsgebieten – Einfluss von Standort und Bewirtschaftung, Innsbruck, 25.06.2026.

Gröber, Maximilian: Erschließung von Waldzuständen und -nutzungen des 19. Jahrhunderts in Tirol durch historische Quellen. Innsbrucker Hofburggespräche: Abfluss in Einzugsgebieten – Einfluss von Standort und Bewirtschaftung, Innsbruck, 25.06.2026.

Müller, Lukas: Szenario-basierte Abflussmodellierung der Auswirkungen historischer Landnutzung in den Jahren 1850, 1960 und 2020 für kleine alpine Einzugsgebiete. Innsbrucker Hofburggespräche: Abfluss in Einzugsgebieten – Einfluss von Standort und Bewirtschaftung, Innsbruck, 25.06.2026.

Schrott, Roman: Einfluss historischer Waldbewirtschaftungspraktiken auf die historische Kohlenstoffspeicherung und Nährstoffversorgung in den Wäldern Tirols. Innsbrucker Hofburggespräche: Abfluss in Einzugsgebieten – Einfluss von Standort und Bewirtschaftung, Innsbruck, 25.06.2026.

Müller, Lukas; Meißl, Gertraud.; Schrott, Roman; Gröber, Maximilian; Kohl, Bernhard; Markart, Gerhard; Scharr, Kurt; Katzensteiner, Klaus; Simon, Alois; Geitner, Clemens: Quantifying surface runoff in Alpine catchments from historical forest use data on the basis of an expert system. International Mountain Conference (IMC2025), Innsbruck, 17.09.2025.

Schrott, Roman; Katzensteiner, Klaus; Gröber, Maximilian; Müller, Lukas; Simon, Alois; Scharr, Kurt; Meißl, Gertraud; Kohl, Bernhard; Markart, Gerhard; Geitner, Clemens: Combining historical data with field experiments to quantify the influence of historical forest use practices on carbon fluxes from Alpine forest ecosystems to agricultural land. International Mountain Conference (IMC2025), Innsbruck, 17.09.2025.

Gröber, Maximilian; Müller, Lukas; Schrott, Roman: Wissen - Wasser - Wald: Ein Blick auf den Einfluss historischer Waldbewirtschaftung in Tirol aus der Sicht von drei Fachdisziplinen. Tiroler Geschichtsverein, Innsbruck, 18.03.2025.

Schrott, Roman; Müller, Lukas; Gröber, Maximilian; Markart, Gerhard; Scharr, Kurt; Katzensteiner, Klaus; Meißl, Gertraud; Simon, Alois; Kohl, Bernhard; Geitner, Clemens: The influence of historical litter raking on forest ecosystems and runoff formation in Alpine catchment areas in Tyrol using inter- and transdisciplinary approaches. Geographiewerkstatt 2024 - Discussing Geographic Method(ologie)s: Integration, Experimentation, and Innovation, Innsbruck, 08.03.2024.

Gröber, Maximilian; Müller, Lukas; Schrott, Roman; Scharr, Kurt; Meißl, Gertraud; Markart, Gerhard; Simon, Alois; Geitner, Clemens: Sekundäre Waldbewirtschaftung in Tirol - inter- und transdisziplinäre Ansätze zur Analyse und Bewertung historischer Praktiken. FSP-Tag „Kulturelle Begegnungen – Kulturelle Konflikte“ in Kooperation mit dem FZ Regionalgeschichte Europaregion Tirol-Südtirol-Trentino, Innsbruck, 24.10.2024.

Geitner, C.; Müller, L.; Simon, A.: Das Projekt HILUC – Hydrological Impact of Historical Land Use and Climate. Agrargemeinschaft Matrei am Brenner, Matrei am Brenner, 19.03.2024.

Gröber, Maximilian; Müller, Lukas; Schrott, Roman: Historical Land Use and Flood Generation. The Example of the Crown Land of Tyrol. The geohistory of the Polish lands in the partition epoch (1772-1918). The geohistory of the Polish lands in the partition epoch (1772-1918), Krakau, 22.11.2023.

Poster presentations

Geitner, Clemens; Gröber, Maximilian; Katzensteiner, Klaus; Kohl, Bernhard; Markart, Gerhard; Meißl, Gertraud; Müller, Lukas; Scharr, Kurt; Schrott, Roman; Simon, Alois: Ökologische und hydrologische Auswirkungen historischer Waldbewirtschaftung – Methoden und Ergebnissen des inter- und transdisziplinären ÖAW-Projektes HILUC (Hydrological Impact of Historical Land Use and Climate), Posterausstellung im Waldcampus Österreich, Traunkirchen, 12. März bis 13. Mai 2026.

Meißl, Gertraud; Müller, Lukas; Gröber, Maximilian; Katzensteiner, Klaus; Kohl, Bernhard; Markart, Gerhard; Scharr, Kurt; Schrott, Roman; Simon, Alois; Geitner, Clemens: Hydrologische Auswirkungen historischer Waldbewirtschaftungen. 6. Workshop zur Alpen Hydrologie, Obergurgl, 19.-20.11.2026

Schrott, Roman; Gröber, Maximilian; Müller, Lukas; Simon, Alois; Katzensteiner, Klaus; Scharr, Kurt; Geitner, Clemens: Combining historical data with field experiments to quantify element fluxes from Alpine forest ecosystems to agricultural land based on historical forest use practices. Annual Meeting of the Austrian Soil Science Society, Innsbruck, 03.12.2025.

Müller, Lukas; Geitner, Clemens; Gröber, Maximilian.; Katzensteiner, Klaus; Kohl, Bernhard; Markart, Gerhard; Scharr, K.; Schrott, R.; Simon, A.; Meißl, G.: Wie wirkt sich die Entnahme von Waldstreu nach historischem Vorbild auf die Niederschlags-Abfluss-Reaktion von Wäldern aus? 5. Workshop zur Alpen Hydrologie, Obergurgl, 21.11.2024.

Schrott, Roman; Gröber, Maximilian; Müller, Lukas; Simon, Alois; Katzensteiner, Klaus; Scharr, Kurt; Markart, Gerhard; Meißl, Gertraud; Geitner, Clemens: The influence of (historical) forest litter raking on carbon and nutrient fluxes in Alpine forest ecosystems – first results. Wald.Boden.Klima.Wandel - Tagung & Exkursion - Bundesforschungszentrum für Wald (BFW), Götzis, 22.10.2024.

Schrott, Roman; Müller, Lukas; Gröber, Maximilian; Markart, Gerhard; Scharr, Kurt; Katzensteiner, Klaus; Meißl, Gertraud; Simon, Alois; Geitner, Clemens: Quantification of the impact of historical litter raking on forest soils and runoff generation in Tyrol - concept, sites and methods. Jahrestagung der Österreichischen Bodenkundlichen Gesellschaft, Wien, 29.09.2023.

Other publications

Wissenswert: Vergessene Praktiken der Waldnutzung
<https://www.uibk.ac.at/de/public-relations/kommunikation/wissenswert/>

Universität Innsbruck: Waldnutzung und Hochwasser: HILUC-Projekt untersucht Zusammenhänge.
Forschungsvideo 18. Okt. 2023.
<https://www.youtube.com/watch?v=hP1kduiGLu4>

2.7. Generated Data-Sets/Models/Tools

No definitive conclusions can yet be drawn on this point. The wide range of data collected, researched or modelled as part of the project is analysed and discussed in the relevant publications and is therefore available to the academic community. Depending on the topic and the journal in which the work is published, the complete raw data may also be available in some cases; for example, in Schrott et al. (2026, in press), which includes a DOI and a supplementary repository containing all the analysis data. In this instance, the FAIR principles are therefore met. For all other publications, these principles are reviewed and, where possible and appropriate, adhered to as fully as possible.

2.8. Limitations and Uncertainties

In a project of such methodological scope, there are a wide range of limitations and uncertainties. Some key points are outlined below.

During the analysis of the historical sources, it became apparent that forest litter extraction was in part recorded at the municipality rather than the woodland-parcel level and often in different historical units of measurement, producing uncertainties that restrict cross-regional comparison. These differences stem primarily from the incomplete standardisation of the nineteenth-century state apparatus, which meant that the accuracy of the data depended on the care exercised by the historical actors—i.e., the forestry officials who compiled the manuscripts. Accordingly, the analyses had to consider not only forest uses themselves but also the economic-historical context, particularly livestock husbandry, in order to render the reconstructed quantities of litter extraction plausible.

The possibilities for reconstructing floods in small-scale Alpine catchments proved particularly limited. Owing to the historical absence of systematic gauging stations, an attempt was made to reconstruct flood events for the test areas using other forms of natural-hazard documentation. The existing literature was insufficient for this purpose. A review and analysis of additional historical sources documenting natural hazards (parish, municipal, and fire-brigade chronicles, as well as police reports) was likewise unsuccessful, because events were often recorded only once they exceeded a certain damage threshold. Consequently, the prospects of finding informative sources in sparsely populated or settlement-remote Alpine areas proved correspondingly low.

One limitation of the scientific investigations was the small number of test plots on which, on the one hand, soil samples were taken and, on the other, hydrological measurements of surface runoff and soil moisture were carried out. This was partly because such interventions require the relevant permissions from landowners, which were not easy to obtain. Furthermore, the fieldwork (particularly the removal of litter from 400 m² plots and the rainfall simulation experiments using a large-scale system) was so labour-intensive that, despite the large team, it was not possible to work on any further test plots. For carrying out the rainfall simulation experiments, the transport of

equipment, the existing forest tracks, the water supply and a plot of 50 m² that is as homogeneous as possible play a decisive role.

Given the small number of plots, the generalisability of the results is, of course, limited and must be interpreted with due caution. On the other hand, the test plots were selected to represent typical substrates and altitudinal zones, so that generalisation appears possible, at least for comparable stands that are widespread in Tyrol. The plots were also chosen to be as representative as possible of the two catchment areas, Stampfangerbach and Ahrnbach. Furthermore, our approach was not primarily aimed at drawing conclusions for the entire area of a catchment, but rather at first understanding the new conditions and processes associated with the use of litter. This could be carried out in detail for the analysis of material stocks and flows. With regard to the surface runoff measurements, these were integrated into an existing system for estimating surface runoff (Markart et al. 2004, 2011), thereby significantly broadening the data set.

When it comes to extrapolating our hydrological findings from the plots to a larger area, one of the greatest uncertainties lies in identifying areas characterised by slope runoff. As our measurements have shown, these areas – which are not easily captured during mapping – exhibit higher proportions of surface runoff. The substrate of the soil formation also plays a significant role. In particular, very densely packed substrates (e.g. lake sediments) would need to be examined separately with regard to surface runoff. The impact of woodland grazing through soil compaction also depends on the substrate type and should be analysed in greater detail.

With regard to the assessment of the surface runoff disposition for the time period 1850, we incorporate, in addition to our current measurements, results from over 90 rainfall simulations from the BFW rain simulation database for forest sites in the Eastern Alps. Surface runoff coefficients were assigned on the basis of this data set and the detailed description of land use and forest conditions around 1850. This assignment can be considered plausible and realistic for the testbeds. Degree of accuracy is the higher the more detailed the historical description of the areas. The classification of historical land use and its intensity, as well as, for example, damage to stands (gaps, lack of ground cover, erosion, pasture intensity), could only be carried out at plot level. The assumed surface runoff class is therefore based on the assumption of the same intensity of land use across the entire plot. However, we must assume that past land uses varied on a very small scale.

Our project focused primarily on secondary land uses within the forest. However, there are also larger areas above the tree line within the catchment areas. For these, it was far more difficult to obtain reliable data on spatially differentiated past land use, for example regarding the number of grazing animals. In this context, it was therefore necessary to rely time and again on plausible assumptions, combined with the analysis of land cover from aerial photographs.

The final hydrological modelling of peak discharges is, in turn, subject to uncertainties that relate not only to the input data but also to supplementary assumptions and the specific model settings. This will be communicated accordingly during the discussion of the results.

3. Transdisciplinary Process Reflection and Social Impact

Preliminary remarks on the transdisciplinary process in the HILUC project: The interdisciplinary project team, comprising experts in history, forest ecology and hydrology, had already been discussing the project's issues for several years. In addition, there was a small joint EU-funded pilot project (Maier et al. 2021) designed to assess the feasibility of this research approach. Even during that project, contact was sought with regional stakeholders and experts, particularly in the fields of forestry and land use. The individuals and institutions involved in this way are listed in the proposal (Table 4), along with their roles, activities and the nature of their involvement. This list forms the basis of our co-design.

The following chapters summarise and discuss the transdisciplinary activities most relevant to the project. The following abbreviations from the proposal are used for the planned partners:

FLD = Regional Tyrolean Government Forest Department
WLV = Torrent and Avalanche Control
LMF = Local Municipality Forest Manager
LMC = Local Municipality Chroniclers
LMM = Local Municipality Members
WCÖ = Forest Campus Austria, Traunkirchen

New collaborations that developed during the project are highlighted separately.

3.1. Concept and Goals of Initial Co-Design

The FLD was closely involved in the development of the concept and the proposal, particularly with regard to the possibility of litter raking experiments and the soil sampling concept. For the current project, the tasks and roles of the transdisciplinary partners were defined in the proposal. During the course of the project, these tasks have evolved, partly depending on the level of activity of the respective partners.

In the first few months of the project, the main focus was on finding suitable test sites for our research questions. FLD and WLV played a key role in the selection process due to their expertise and helped to steer the decisions. LMF and LMM were involved in the specific selection of test plots in the respective catchment areas, the latter represented by the mayor of the municipality of Söll and the landowner. The mayor is particularly keen to bring science closer to tourists in the region (long-term plan for a Science Centre with associated field laboratories). We were therefore in close contact with him and, at his request, organised a number of excursions to our test plots (including for the general public, the Young Geographical Society and the Forestry Women's Association, with a view to introducing science to a wider audience). Our activities were also reported on several occasions in the local newsletter.

3.2. Ongoing Integration and/or Capacity Building

When the project began, a regular meeting lasting approximately two hours was established, which took place once a month. This placed quite a heavy demand on everyone's schedules, but it proved beneficial for cohesion within the project, as it ensured that all partners were kept continuously informed and were able to contribute their suggestions. For each of the roughly 30 regular meetings, the topics to be discussed were announced in advance. Online participation was always an option. Four transdisciplinary partners made regular use of this option. Among them, the FLD was very regularly involved in decision-making processes.

There were individuals and institutions that were not originally part of the project but went on to play a significant role, for example:

- A landowner who made his land available for our experiments, even though this placed a burden on the site. However, he considers forest research important and took part in the experiments with interest.
- The Söll Rural Youth Association helped us collect litter in the forest and, in doing so, had the opportunity to learn about the quantities of forest litter that had been used in agriculture over a long period of time.
- The Söll Fire Brigade, with whom we had to organise the water supply for our rainfall simulation experiments because an alternative plan could not be implemented.

Particular mention should be made of the eyewitnesses who were interviewed about historical practices relating to the use of the forest. The interviews proved very fruitful and were incorporated into the final project exhibition. Particularly striking was the joy and gratitude shown by these elderly people that, after some 50 years, someone was taking an interest in the work they had done back then. They even demonstrated to us in the forest, using old tools, exactly how the work had been carried out. We were able to show the short film we made of this time and again during presentations.

Building on the HILUC project, two small and one large project were developed and approved: the WASTL project on 200 years of changing forest structure, forest use and ecosystem services, and the LaWa project on the forest's memory of agricultural practices (using dendrochronology), both funded by the Mountain Agriculture Research Centre in 2024 and 2026. The large-scale DIMF project focuses on deadwood and its assessment. It builds on themes and collaboration partners from HILUC and is again funded by the Austrian Academy of Sciences (ÖAW) under the Earth System Science Call 2024.

3.3. Outreach/Social and/or Policy Impact

Chapter 2.6.2 brings together the relevant contributions. These include, amongst other things, a detailed project film available on the university's media platform, radio interviews, short talks, excursions to the test sites, panel discussions following a film on the topic of forests in the municipality of Söll, and project features in local newsletters.

Particular mention should be made of the in-depth lecture at the Historical Society, as well as four lectures at the BFW's Hofburg Talks (2026) and a project workshop with Mathias Bürgi. These events enabled the project to reach a wider specialist audience.

The large poster exhibition at the Waldcampus in Traunkirchen, which ran from 13 March to 13 May 2026 and marked the conclusion of the project, reached students on various training courses at the facility as well as the general public at the opening. The exhibition was subsequently shown in July 2026 at the Regional Mountain Conference in Obergurgl/Tyrol. Further dates, e.g. in the municipality of Söll, are under discussion. In addition, the posters can be found on our project website.

Through the LFD staff, it is ensured that the content of the HILUC project is directly incorporated into the training of forest wardens. This ensures that the findings reach precisely those individuals who are responsible for Tyrol's forests at local authority level.

3.4. Challenges, Lessons Learned and Reflection

Interdisciplinary and transdisciplinary projects usually involve a larger group of people. This makes it difficult, if not impossible, to agree on a schedule. For the project lead, the organisational burden is often too great to manage alongside their other usual tasks. Developing a shared understanding of the project requires a great deal of dialogue and the building of trust. The PhD students therefore played a very active role in the project's organization, in addition to their purely academic work, meaning that a three-year period is simply not sufficient.

Scientific questions arise in the minds of researchers; for stakeholders, they are often only of limited relevance. Conversely, ideas frequently emerge from the practical side that cannot be clarified scientifically or lie far beyond the project's original concept. There is often too little time for clarifying discussions, meaning that projects may, under certain circumstances, begin without a clear shared objective. As the project progresses, it is not uncommon to notice that the interest of individual transdisciplinary partners also wanes. The time required to change this is often not available if the project is to remain on schedule.

In our project, the very regular meetings to which all partners are invited have contributed significantly to its success. Equally important was the good collaboration between the three PhD students, which ultimately reduces the workload because they benefit from each other's expertise and can also use the joint publications to support their own qualifications.

3.4. Continuation and Long-Term Impact

The project's impact extends beyond its duration and is felt at various levels. Here are the key points:

Through the staff of the LFD, it is ensured that the content of the HILUC project is incorporated directly into the training of forest wardens. This ensures that the findings reach precisely those individuals who are responsible for Tyrol's forests at local authority level.

The results will be incorporated into the forthcoming revised edition of the field guide by Markart et al. (2004, 2011), so that they can be applied in this widely used work for estimating surface runoff. This also applies to the incorporation of the results into the work by Markart et al. (2026), which was published in 2020 and is currently being revised.

The new large-scale ÖAW project DIMF will further explore related aspects, in some cases even on the same test plots, thereby also disseminating the findings to date.

Further research is taking place to a certain extent on the well documented existing test plots. The Institute of Forest Ecology at BOKU is currently investigating microbiological diversity and additional microbiological indicators. Further dendrochronological studies are also planned. As the litter raking intervention is quite unique under current conditions, there is ongoing interest in these test plots.

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