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# Investigations on the effects of game browsing on surface runoff in Alpine forests

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## ABSTRACT

The hydrological effect of forests on reducing surface runoff and therefore mitigating flood hazards is well recognized in theoretical concepts, however its quantification for practical applications remains a challenge. Changes in the hydrological effect due to changes in the forest can be measured but hardly predicted, which makes it difficult to assess the impact of disturbances and management in protections forests against flood hazards. Game browsing is recognized as a problematic disturbance in protection forests that can impact the protective effect against gravitational hazards in the long term while its impact on the protective effect against flood hazards is yet poorly understood. Protection fences that exclude game browsing in the forest offer an opportunity to investigate its influence on the formation of surface runoff with paired rainfall experiments. They show distinct differences in the runoff formation for all investigated sites which can be attributed to the browsing exclusion by the protection fences. The surface runoff is up to three times lower inside compared to outside the fenced areas. Furthermore there is a systematic difference in the measured soil properties for all investigated sites. The hydraulic conductivity is clearly greater while the soil porosity, the topsoil depth and the humus height are slightly greater inside compared to outside the fenced areas. A statistical analysis of the surface runoff shows, that the measured differences are significant and that the factor of the protection fence is more important than the soil variabilities and the experiment conditions. This analysis reveals a clear trend of how the exclusion of game browsing within affects soil properties and reduces surface runoff. The differences in the soil properties are in line with the differences in the surface runoff and provide a physical basis for an explanation. The experiment design indicates that the differences in the soil properties are related to the game browsing, even if a detailed explanation of this relationship is missing. Nevertheless, it can be concluded from this investigation that the exclusion of game browsing can significantly decrease surface runoff therefore and impair the protective effect against flood hazard in the short term.

## Introduction

The hydrological effect of forests is recognized as an important factor for providing protection against floods and landslides ([1,2]). Forest cover can influence the amount of water runoff to a certain extent depending on a complex interaction of vegetation community, soil type and rainfall event ([3,4]). The mechanisms of reduction in water runoff are mainly attributed to the water retention provided by the increase of storage capacity as well as the decrease of flow velocity ([5,6]). An important contribution to those effects is related to the increased volumetric porosity and hydraulic conductivity of the rooted soil layers which allows more water to infiltrate deeper into the soil, where it is retained and drained with delay ([7,8]). A further contribution is related to the interception capacity and the infiltration capacity of the organic soil cover that can retain additional amounts of water and alter the connectivity to the underlying soil ([9,10]). Those considerations provide a rough overview about the different aspects of the hydrological effect of forests and hint at the underlying complexity, which makes a general quantification difficult.

Rainfall experiments allow specific measurements of the hydrological effect of forests in terms of runoff formation and are therefore an important component towards an improved understanding. Several studies with rainfall experiments in the forest show that the hydrological effect related to the rooted soil layers depends from forest properties in terms of species composition and tree distribution ([11,12]). In other studies with rainfall experiments, the organic soil cover in terms of tree litter and understorey vegetation is identified as a relevant factor that influence the hydrological effect of forests ([13,14]). Some studies show directly, that the change of forest properties due to disturbances can affect the hydrological effect of forests that lead to difference in the runoff formation ([15,16]). Such observations are in line with the previous considerations and imply that the runoff formation in forests can be influenced by disturbances but also by management.

Persistent disturbances that affect forest regeneration can cause changes in the forest stand as well as in the forest soil ([17,18]). In protection forests, such disturbances can impair the protective effect and therefore increase the risk for the endangered goods ([19,20]). A persistent disturbance with high actuality in the management of protection forests is game browsing, which has an adverse effect on forest regeneration in regions with high game density ([21,22]). In the context of gravitational hazards like landslides and rockfall, several studies quantify how game browsing can reduce the protective effect in the future due to the prevented forest regeneration ([23,24]). Since the hydrological effect of forests is less well understood than the mechanical effect against gravitational hazards, such studies lack for the protection forest against flood hazards.

This study investigates the influence of the exclusion of game browsing on the formation of surface runoff to examine whether and if so to what extent it alters the hydrological effect of forests and therefore its capability to mitigate floods. The basis for this study is a data set from paired rainfall experiments from four forested sites in the Alpine region with high level of game browsing, which are carried out systematically inside and outside of protection fences that exclude game browsing. Based on those data it is analysed if there are differences in the surface runoff depending on their exposure to game browsing and how those differences could be explained by the underlying soil properties.

## Results

### Surface Runoff measurements

The time resolved measurement of the surface runoff enables to capture runoff curves that show the runoff coefficient as a function of the cumulative rainfall height for different constant rainfall rates (Figure 1). They show that the surface runoff approximately follows a monotonically increasing curve as function of the cumulative rainfall height that converges towards a limit value. This implies an approximation to a steady state after a certain rainfall duration which indicates the convergence time. Furthermore the runoff curves show that the surface runoff does not start immediately but only after a certain rainfall duration which indicates the abstraction time.

For a non parametric analysis of the runoff curves, the runoff coefficient and the infiltration capacity in the steady state as well as the abstraction time required to start the runoff formation and the convergence time to reach the steady state were calculated for each curve and aggregated over the treatment (Table 1). Those characteristic values of the runoff curves show clear differences between the treatments within each site. The runoff coefficients in the steady state are always smaller in the fenced treatment than in the unfenced treatment. Complementary to the smaller runoff coefficients, the infiltration capacity is greater but except of the Tanas fenced A treatment smaller than the applied rainfall rate. This is accompanied by greater values of the abstraction time as well as the convergence time in the fenced treatment than in the unfenced treatment.

The extracted values of the runoff coefficients in the steady state from the measured curves provide a standardized basis to compare the rainfall experiments (Figure 2). The boxplots summarize the runoff coefficient in the steady state and clearly show the trend of smaller values in the unfenced treatments compared to the fenced treatments within each site. Furthermore they show that the runoff coefficient is not constant and depends from the rainfall rate, but no clear trend can be identified.

The rainfall experiments show clear differences in the runoff formation between the paired treatments for all investigated sites. The surface runoff rises later and flatter towards lower values in the fenced treatment compared to the unfenced treatment. These differences are most pronounced for the Tanas site, followed by the Faido site, the Mesocco site and the Eschen site.

### Soil parameterization

The values derived from the time resolved measurement of the soil moisture in terms of volumetric water content allow to quantify the variable soil conditions during the rainfall experiments (Table 2). This shows that the values of the soil moisture in the beginning of the rainfall experiments are almost similar within the paired treatments. Furthermore the measurements of the soil moisture show a trend with a greater increase from the beginning to the end of the run followed by a smaller decrease over the break after the run. This implies that there is generally more residual water stored than the mobile water build up while the rainfall experiments except in the Tanas unfenced B treatment.

The soil parameter from punctual measurements after the rainfall experiments provide a quantitative complement to compare the constant soil properties that are assumed to influence the hydraulic behaviour (Table 3). The measured values show a clear trend with greater values of the hydraulic conductivity inside the fenced treatment compared to the unfenced treatment for each site. A similar but less distinct trend is found for the soil porosity as well as the topsoil depth and the humus height, which are

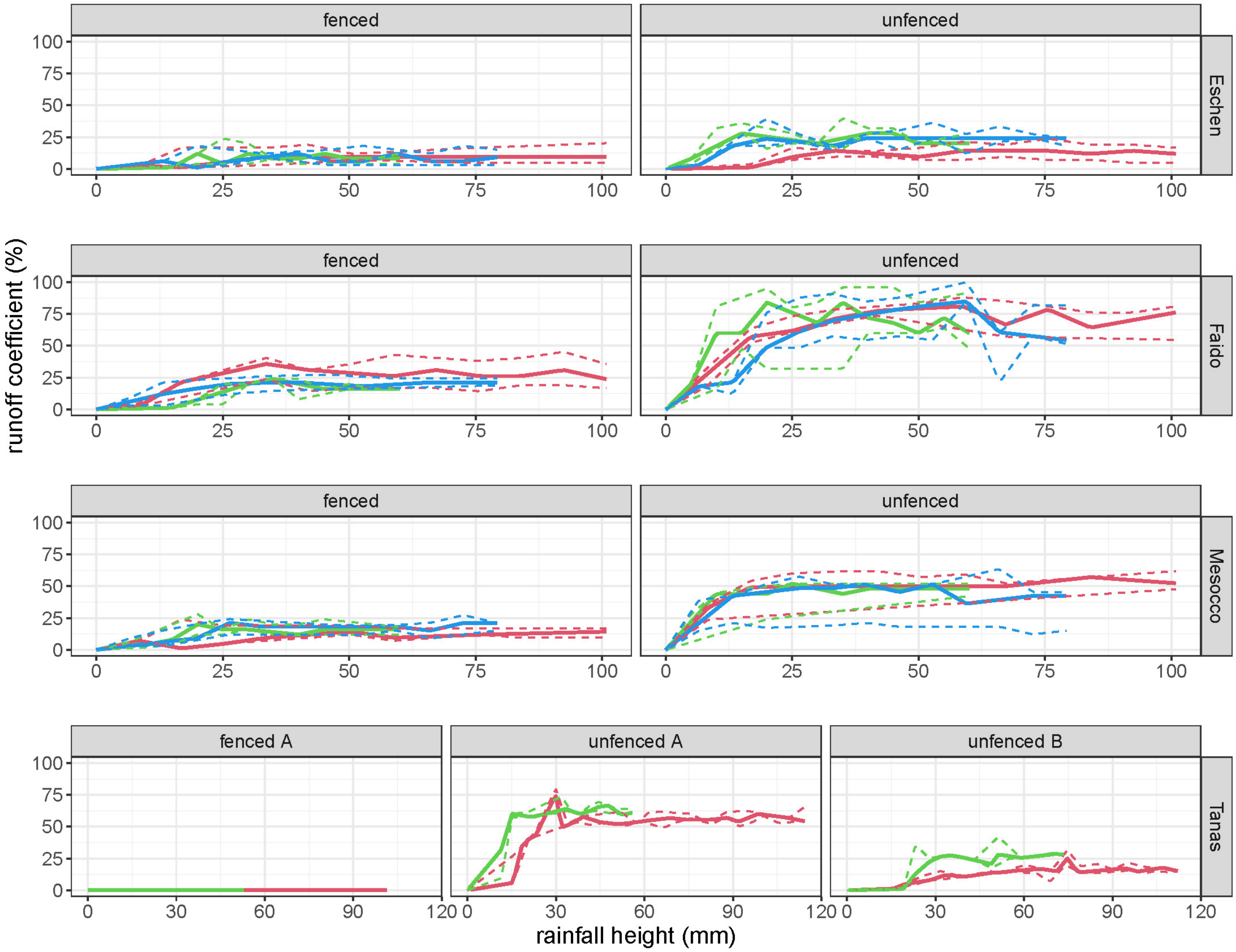

**Figure 1.** Runoff curves measured with the rainfall experiments for the different treatments without and with browsing protection fence. The curves show the median value (thick) and the 50 % prediction interval (dashed) for the first (red), second (green) and third (blue) runs, whereby for the Eschen, Faido and Mesocco sites the runs differ in the rainfall rate (100 mm/h, 60 mm/h and 80 mm/h for 1 h) while for the Tanas site they differ in the rainfall duration (1 h and 0.5 h with 100 mm/h).

equal or slightly greater in the fenced treatment than in the unfenced treatment.

Overall, those measured soil parameters show that the rainfall experiments are conducted under similar hydraulic conditions regarding the soil moisture but on areas with different hydraulic properties regarding the soil parameters. The similar values of the initial moisture are an important requirement to compare the measured surface runoff between the paired treatments and to apply a statistical analysis on the data.

### Statistical analysis

The statistical analysis of the runoff coefficients in the steady state with a permutational analysis of variance (PERMANOVA) allows to disentangle the influence of different factors related to the experiment design in each site (Table 4). This shows a clear trend for all investigated sites with the highest influence of the treatment defined by the protection fence, followed by the profile that captures the soil variabilities and the lowest influence of the run that accounts for the experiment conditions.

Almost all factor levels are significant regarding to the standard P-value threshold of 5 %, whereby the value is often slightly greater for the run than for the profile and the treatment. For each site, the explanatory power indicated by the R2-value as well as the effect strength indicated by the F-value increases from the factor level of the run over the profile to the treatment. In accordance with the measured differences of the surface runoff, this pattern is most pronounced for the Tanas site, followed by

| **treatment** | **runoff coefficient (%)** | **infiltration capacity (mm/h)** | **abstraction time (s)** | **convergence time (s)** |
|---|---|---|---|---|
| Eschen unfenced (n=69) | 20 ± 9 | 67 ± 19 | 426 ± 149 | 930 ± 194 |
| Eschen fenced (n=89) | 10 ± 6 | 74 ± 15 | 731 ± 212 | 1187 ± 344 |
| Faido unfenced (n=90) | 70 ± 19 | 24 ± 16 | 367 ± 125 | 880 ± 245 |
| Faido fenced (n=82) | 23 ± 8 | 63 ± 11 | 498 ± 263 | 1105 ± 394 |
| Mesocco unfenced (n=115) | 42 ± 18 | 46 ± 17 | 300 ± 0 | 715 ± 380 |
| Mesocco fenced (n=109) | 16 ± 6 | 67 ± 16 | 550 ± 250 | 1128 ± 351 |
| Tanas unfenced A (n=76) | 59 ± 7 | 46 ± 8 | 481 ± 98 | 771 ± 223 |
| Tanas unfenced B (n=76) | 18 ± 6 | 92 ± 10 | 498 ± 48 | 941 ± 98 |
| Tanas fenced A (n=2) | 0 ± 0 | 103 ± 3 | - | - |

**Table 1.** Key values of the runoff curves measured with the rainfall experiments by the mean value and the standard deviation of the runoff coefficient and the infiltration capacity in the steady state as well as the abstraction time and the convergence time.

the Faido site, the Mesocco site and the Eschen site.

## Discussion

From the analysis of the measured data follows, that the runoff formation at the slope scale is significantly influenced by the exclusion of game browsing in all investigated sites. The measurements of the surface runoff show systematic differences with greater values of the infiltration capacity as well as the abstraction time and the convergence time in the fenced treatments compared to unfenced treatments (Table 1). The protection fence has a strong influence on the surface runoff which masks the weaker influences of the soil variabilities and the experiment conditions (Table 4). Since the variable soil conditions regarding the initial moisture are similar for the paired treatments within the sites, the measured differences in the surface runoff can be attributed to the constant soil properties (Table 2). Those soil properties are variable within the treatments but systematically differ between the treatments (Table 3). Therefore the protection fence can be identified as the crucial factor that influence the measured surface runoff. In the context of established guidance for the assessment of runoff formation in the Alpine region, the measured differences would lead to a different hydrological classification ([25,26]). On the catchment scale, this can result in relevant differences in the assessment of flood runoff, sediment transport and also in slope stability.

The few comparable studies with hydrological measurements inside and outside of protection fences that exclude game browsing document similar findings in the measured surface runoff ([27,28]). Those studies show lower surface runoff within the protection fences that go along with smaller values of bulk density and greater values of hydraulic conductivity. A similar trend is evident from the soil properties surveyed in this study with greater values of hydraulic conductivity and less distinct also of soil porosity within the protection fences. This pattern regarding the soil properties is also found when the old growth like at the Eschen site or at least stand legacies like at the Mesocco and Faido site are still present.

While the measured differences in hydraulic conductivity and soil porosity provide a physical based explanation of the differences in the measured surface runoff, an explanation of how the game browsing affects those soil properties can not be derived from this study. One possible explanation could be mechanical compaction of the soil due to the animals footfall which can directly alter its hydraulic properties ([29,30]). Another possible explanation could be biological degradation of the soil that results from loss in vegetation cover due to the animals browsing, which can indirectly alter its hydraulic properties ([31,32]). Those aspects remain unclear because neither the browsing activity nor the vegetation cover were explicitly examined in this study, but the greater values of the humus height and the topsoil thickness inside the protection fences point to the biological degradation as the more feasible explanation.

From these findings it can be concluded, that the exclusion of game browsing by protection fences influence the for-

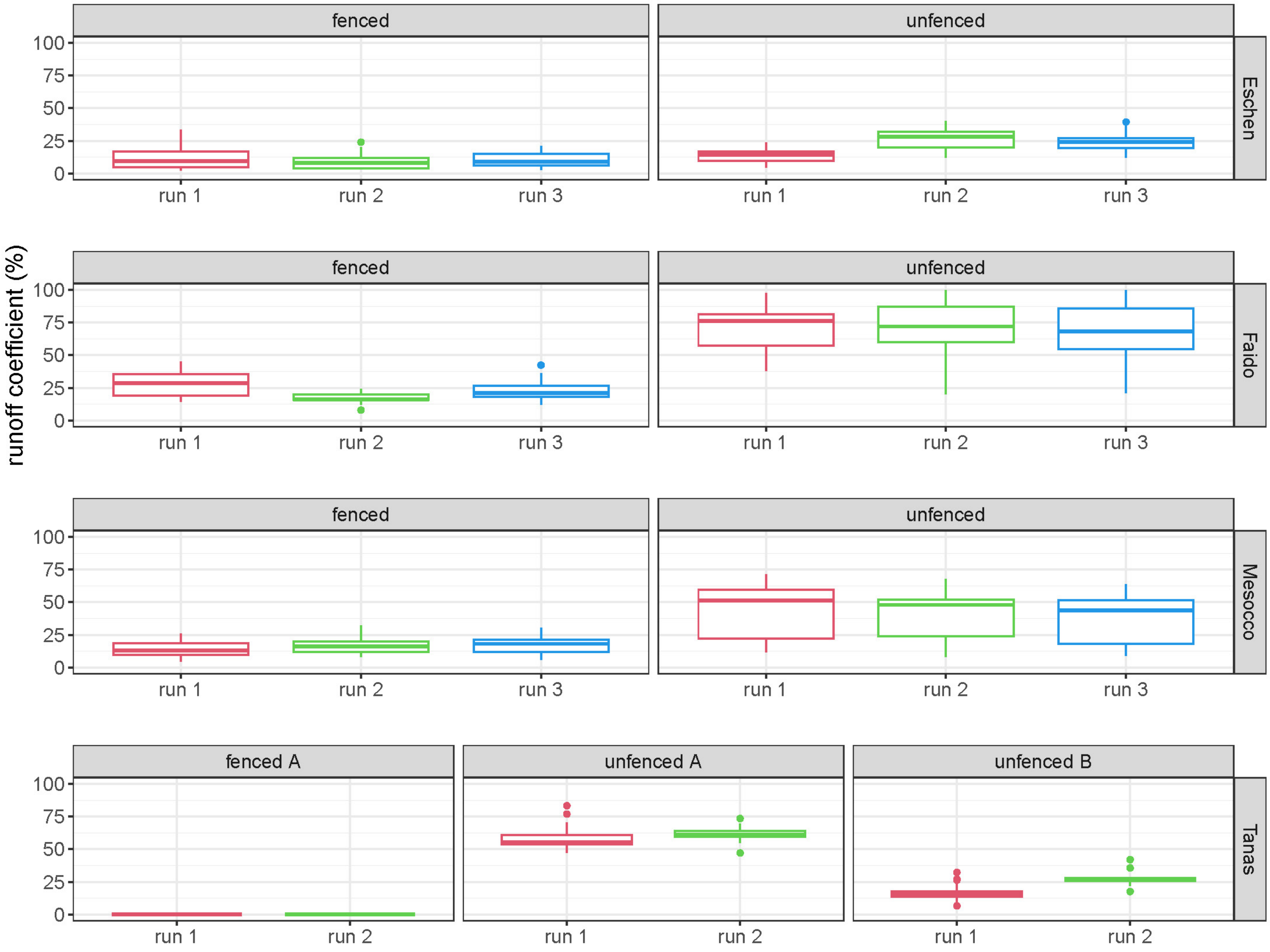

**Figure 2.** Runoff values measured in the steady state during the rainfall experiments for the different treatments without and with browsing protection fence. The values are separated into the first (red), the second (green) and the third (blue) run, whereby for the Eschen, Faido and Mesocco sites the runs differ in the rainfall rate (100 mm/h, 60 mm/h and 80 mm/h for 1 h) while for the Tanas site they differ in the rainfall duration (1 h and 0.5 h with 100 mm/h).

mation of surface runoff and leads to lower runoff amounts and slower runoff reaction. Both, the data from the rainfall experiments and from the soil parameters, capture this trend on all investigated sites in this study and show that the game browsing alters the soil properties of the superficial layers that influence the formation of surface runoff. Those findings imply that game browsing can influence the hydrological effect of forests in the short term within a few years. Persistent game browsing may also change a forest stand and therefore its hydrological effect in the long term over decades by alter the soil properties to a greater extent and especially into deeper layers. Both, the short term influence measured in this investigation and the long term influence assumed hypothetically, require further research for a more profound and quantitative understanding.

## Methods

### Study sites

A total of four sites with nine treatments were considered for this study. All investigated sites are located in the central European Alps, two of which in Switzerland, one in Liechtenstein and one in Italy (Figure 3). Each site comprises at least two treatments, a fenced treatment inside and an unfenced treatment outside of a protection fence to exclude game browsing. The protection fences were installed on sites with high game density where the old growth was completely removed. The unfenced treatment is always located on a neighboring area to the protection fence to be able to largely exclude other differences. It can

| treatment | initial moisture (%) | peak moisture (%) | final moisture (%) | mobile water (%) | residual water (%) |
|---|---|---|---|---|---|
| Eschen unfenced (n=9) | 28 ± 4 | 32 ± 3 | 32 ± 3 | 1 ± 1 | 4 ± 2 |
| Eschen fenced (n=10) | 32 ± 7 | 34 ± 5 | 33 ± 5 | 1 ± 1 | 2 ± 2 |
| Faido unfenced (n=9) | 15 ± 9 | 21 ± 12 | 19 ± 10 | 5 ± 3 | 5 ± 7 |
| Faido fenced (n=9) | 14 ± 8 | 20 ± 8 | 18 ± 8 | 2 ± 1 | 4 ± 4 |
| Mesocco unfenced (n=12) | 32 ± 5 | 36 ± 5 | 34 ± 4 | 2 ± 1 | 3 ± 3 |
| Mesocco fenced (n=12) | 34 ± 5 | 38 ± 4 | 37 ± 3 | 2 ± 1 | 3 ± 3 |
| Tanas unfenced A (n=2) | 18 ± 14 | 40 ± 1 | 32 ± 1 | 8 ± 1 | 14 ± 14 |
| Tanas unfenced B (n=2) | 14 ± 9 | 36 ± 1 | 23 ± 1 | 14 ± 1 | 9 ± 9 |
| Tanas fenced A (n=2) | 18 ± 11 | 37 ± 2 | 30 ± 2 | 7 ± 1 | 12 ± 9 |

**Table 2.** Key values of the soil moisture conditions during the rainfall experiments by the mean value and the standard deviation of the measured initial moisture (before the run), peak moisture (after the run) and final moisture (after the break) as well as the back calculated values for the mobile water and the residual water. The measurement of the soil moisture includes several sensors in different depths in the soil layers above the runoff collector from the rainfall experiments.

be therefore assumed that both treatments were similar regarding the soil properties and the vegetation cover before the old growth was removed and the protection fences were installed.

The protection fences create areas around 1000 $m^2$ with no access for the game, whose vegetation can be clearly distinguished from the surrounding area in terms of species and density. In the Eschen, Mesocco and Tanas sites, regeneration was also carried out by planting within the protection fences, but natural regeneration can also be found, which is hardly present outside the protection fences. In the Faido site, only natural regeneration is found. In the Mesocco and Faido site as well as the Tanas A treatment, the old growth is also removed in the unfenced treatment while in the Eschen site and the Tanas B treatment, the old growth is still present in the unfenced treatment.

All treatments are characterized by observed properties of the forest, the soil and the slope. This provides a systematic overview of the similarities and differences for the sites and treatments considered in this study (Table 5). The tree vegetation and the understorey vegetation refer to the dominant species that is identified in the field. For the soil type and the humus type, the World Reference Base soil classification according to the Food and Agriculture Organization of the United Nations (FOA) is applied based on the observations in the field ([33]). The slope exposition as well as the slope inclination are measured in the field and refer to the irrigation area of the rainfall experiments.

The characterization of the sites show that the paired treatments are similar regarding the soil type and the slope properties but different regarding the vegetation properties and the humus form. The situation with regard to the topographic disposition of the slope and the geological disposition of the soil can therefore be considered as similar for each site and the differences in the vegetation can be attributed primarily to the fencing and secondary to the planting.

### Soil investigation

A more detailed and quantitative investigation of the soil is conducted for each irrigation area of the rainfall experiments. This investigation includes the soil moisture measured while the rainfall experiments as well as the hydraulic conductivity, the soil porosity, the topsoil depth (A horizons) and the humus height (O horizons) measured after the rainfall experiments. In this study, different methods are applied to measure those parameters for the profile scale rainfall experiments of the Eschen, Faido and Mesocco sites and the slope scale rainfall experiments of the Tanas site.

| treatment | hydraulic conductivity (mm/h) | soil porosity (%) | topsoil depth (cm) | humus height (cm) |
|---|---|---|---|---|
| Eschen unfenced (n=4) | 4838 ± 3878 | 71 ± 6 | 14 ± 3 | 4 ± 1 |
| Eschen fenced (n=4) | 20222 ± 18263 | 71 ± 5 | 29 ± 6 | 4 ± 1 |
| Faido unfenced (n=4) | 1138 ± 1262 | 57 ± 8 | 8 ± 2 | 1 ± 1 |
| Faido fenced (n=4) | 7227 ± 12365 | 79 ± 10 | 18 ± 4 | 9 ± 1 |
| Mesocco unfenced (n=4) | 4949 ± 2859 | 73 ± 3 | 9 ± 3 | 5 ± 1 |
| Mesocco fenced (n=4) | 13981 ± 11753 | 74 ± 6 | 10 ± 2 | 8 ± 1 |
| Tanas unfenced A (n=1) | 280 ± 0 | 50 ± 0 | 2 ± 0 | 1 ± 0 |
| Tanas unfenced B (n=1) | 3390 ± 0 | 62 ± 0 | 5 ± 0 | 3 ± 0 |
| Tanas fenced A (n=1) | 4170 ± 0 | 68 ± 0 | 5 ± 0 | 4 ± 0 |

**Table 3.** Quantification of the soil properties by the mean value and the standard deviation of the measured hydraulic conductivity, soil porosity, topsoil depth and humus height. The values of the hydraulic conductivity and the soil porosity refer to the superficial soil layer of the irrigation area from the rainfall experiments.

| site | factor | F-value | R2-value | P-value |
|---|---|---|---|---|
| Eschen (n=158) | treatment | 104.207 | 0.29461 | 0.001 |
| | profile | 29.202 | 0.24768 | 0.001 |
| | run | 5.449 | 0.03081 | 0.006 |
| Faido (n=172) | treatment | 632.08 | 0.70416 | 0.001 |
| | profile | 31.30 | 0.10461 | 0.001 |
| | run | 3.33 | 0.00741 | 0.041 |
| Mesocco (n=224) | treatment | 451.83 | 0.46049 | 0.001 |
| | profile | 103.97 | 0.31790 | 0.001 |
| | run | 0.22 | 0.00045 | 0.816 |
| Tanas (n=154) | treatment | 1023.11 | 0.91227 | 0.001 |
| | run | 46.79 | 0.02086 | 0.001 |

**Table 4.** Analysis of the runoff coefficients in the steady state measured with the rainfall experiments with a permutational analysis of variance. The factors were considered as independent and assessed for each site separately.

The details for measurements of the soil parameter for the slope scale rainfall experiments at the Tanas site is documented in an earlier study ([16]). The measurements of the soil moisture and the horizon thickness are conducted with similar methods for the profile scale experiments. The soil moisture is also recorded by time domain reflectometry (TDR) sensors, whereby the manufacturer differ but the principle is the same. The horizon thickness is defined by expert opinion, whereby the person differs which can influence the definition. Still those methods are comparable, while they clearly differ for the measurement of the hydraulic conductivity and the soil porosity.

The hydraulic conductivity $k$ (mm/h) for the profile scale rainfall experiments is measured by a single ring infiltrometer with variable head. Therefore a cylinder mantle with a diameter of 100 mm is rammed half into the soil surface to force a vertical flow and the infiltration time $t$ (h) for a certain infiltration height $h$ (mm) of water is measured. Those are used to estimate the hydraulic conductivity under the assumption that only gravitational forces control the infiltration process (Equation 1).

$$k = \frac{h}{t} \tag{1}$$

The soil porosity $n$ (%) for the profile scale rainfall experiments is measured by a phase mixture approach with water excess.

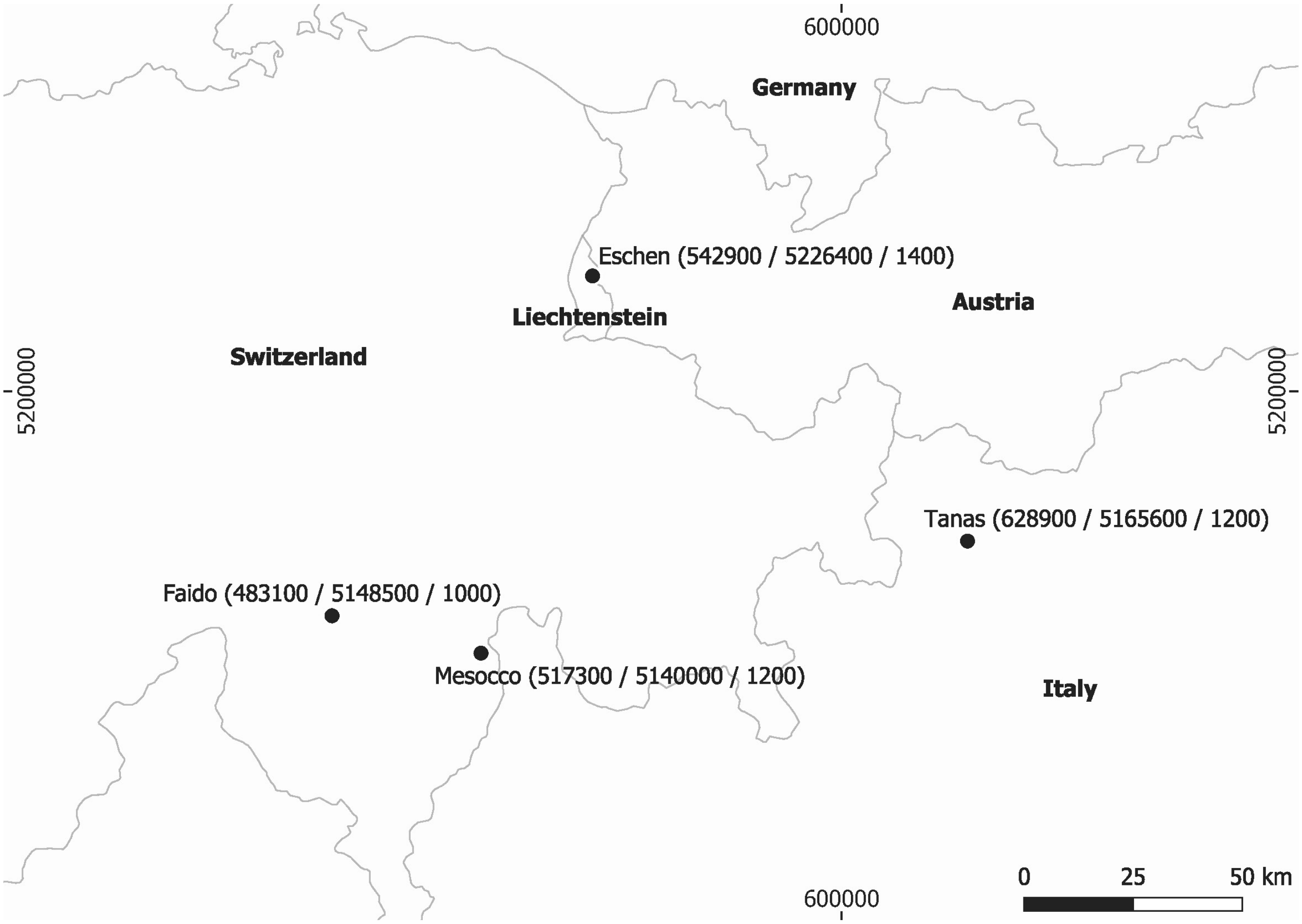

**Figure 3.** Map of the study sites in the Central European Alps in the UTM 32N coordinate system. The brackets contain the longitude and the latitude as well as the altitude above sea level for each site.

Based on some assumptions, this simple procedure allows to estimate the bulk density respectively the corresponding soil porosity. Therefore a soil sample with a defined bulk volume $v_b$ ($m^3$) by a cylinder mantle is placed in a graduated bottle. The graduated bottle is filled with water and mixed to dissolve the solids. From this mixture of two phases, the total volume $v_t$ ($m^3$) as well as the total mass $m_t$ (kg) are measured and it is assumed, that the total volume is the sum of the water volume and the solid volume and that the total mass is the sum of the water mass and the solid mass. Furthermore a constant water density $\rho_w$ of 1000 $kg/m^3$ and a constant solid density $\rho_s$ of 2700 $kg/m^3$ are assumed. This allows to calculate the bulk density respectively the corresponding soil porosity (Equation 2).

$$n = 1 - \frac{m_t - \rho_w * v_t}{v_b * (\rho_s - \rho_w)} \tag{2}$$

Due to the different methods, the parameters can only be compared to a limited extent between the sites. It must be considered that the hydraulic conductivity and the soil porosity for the profile scale rainfall experiments are measured with rather simple and straight forward approaches while for the slope scale rainfall experiments those parameters are measured with rather complex and standard compliant procedures. Still those soil parameters can be compared between the paired treatments within the sites and therefore provide valuable information about the context of the measured surface runoff in this experimental setup.

### Rainfall simulator

The rainfall experiments are conducted with rainfall simulators, whereby two different systems are used to collect the data for this study (Figure 4). For the rainfall experiments in the Eschen, Faido and Mesocco sites, a small rainfall simulator is

| treatment | tree vegetation | understorey vegetation | soil type | humus type | slope exposition | slope inclination |
|---|---|---|---|---|---|---|
| Eschen unfenced | Picea abies | - | luvisol | moder | west (287 °) | steep (40 °) |
| Eschen fenced | Acer pseudoplantanus | herb species | luvisol | mull | west (289 °) | steep (35 °) |
| Faido unfenced | Castanea sativa | grass species | podsol | mull | south (205 °) | steep (38 °) |
| Faido fenced | Castanea sativa | fern species | podsol | mull | south (185 °) | steep (38 °) |
| Mesocco unfenced | Picea abies | grass species | umbrisol | moder | east (98 °) | steep (37 °) |
| Mesocco fenced | Acer pseudoplantanus | herb species | umbrisol | mull | east (84 °) | steep (32 °) |
| Tanas unfenced A | - | grass species | umbrisol | mull | south (171 °) | steep (26 °) |
| Tanas unfenced B | Pinus nigra | grass species | umbrisol | moder | south (189 °) | steep (29 °) |
| Tanas fenced A | Quercus pubescens | herb species | umbrisol | mull | south (187 °) | steep (27 °) |

**Table 5.** Characterization of the sites by the classification of the observed vegetation, soil and slope properties.

applied on profile scale while for the rainfall experiments in the Tanas site, a large rainfall simulator is applied on slope scale. Both systems have in common, that a defined area can be irrigated at a controlled rate and duration and the of surface runoff as well as the soil moisture can be measured with temporal resolution. But there are also significant differences in the technical setup of those two systems and in the experiment design how they are applied.

Similar of both systems is that they measure the surface runoff in a depth between 0.2 m and 0.5 m, depending on prominent horizontal boundaries and skeletal content. Therefore the term of surface runoff in this study also includes subsurface runoff in the superficial soil layer and should be therefore considered as near surface runoff. Furthermore, both systems operate with similar rainfall rates over similar rainfall durations which correspond to strong but short extreme events. Those simulated rainfall events are repeated in several runs that are separated by breaks of 1 h in order to approximate similar soil conditions at field capacity after the first break.

The profile scale rainfall simulator is developed by the University of Bern ([34]). This system irrigates an area of 1 m$^2$ with a length of 1 m parallel to the fall line and a width of 1 m parallel to the contour line. The simulated rainfall is produced by capillaries under suction on a plate above the irrigated area. The rainfall experiments are conducted in 3 runs with different rainfall rates of 100 mm/h, 60 mm/h and 80 mm/h over a rainfall duration of 1 h. The surface runoff is measured on the lower edge of the irrigated area over 1 m in fix time increments of 0.083 h.

The slope scale rainfall simulator is developed by the Federal Research Center for Forests ([35]). This system irrigates an area of 50 m$^2$ with a length of 10 m parallel to the fall line and a width of 5 m parallel to the contour line. The simulated rainfall is produced by nozzles under pressure on a frame around the irrigated area. The rainfall experiments are conducted in 2 runs over different rainfall durations of 1 h and 0.5 h with a rainfall rate of 100 mm/h. The surface runoff is measured on the lower edge of the irrigated area over 5 m in fix volume increments of 0.05 m$^3$.

Because of the differences between the two systems, a comparison of the data between the sites is only possible to a limited extent. This is mainly due to the different irrigation mechanism, the system dimension and the experiment setup while the runoff measurement and the experiment sequence are rather comparable. Furthermore the slope scale rainfall experiments do physically cover a slope section by one large irrigation area while the profile scale rainfall experiments statistically capture a slope section by several small irrigation areas. Still the data between the paired treatments within the sites are comparable and allow to investigate the influence of the protection fence on the measurements for each site.

**Figure 4.** Examples of the rainfall experiments on profile scale in Faido (top left), Mesocco (top right) and Eschen (bottom right) and on slope scale in the Tanas (bottom left). For each site the example is pictures in the fenced treatment.

### Data analysis

Based on the measured and area standardized values for the rainfall rate $i$ (mm/h) and the surface runoff $q$ (mm/h), runoff coefficients and runoff curves are calculated. The effective runoff coefficient $\psi_e$ (%) is defined as runoff indicator for the analysis of the data from the rainfall experiments. This is calculated by dividing the surface runoff by the rainfall rate (Equation 3). It is a standardized quantity but may still depend from the rainfall duration, the rainfall rate and the soil moisture in the initial state as well as from the spatial scale ([36]).

$$\psi_e = \frac{q}{i} \tag{3}$$

Furthermore the infiltration capacity $\phi$ (mm/h) is calculated to compare the surface runoff measured with the rainfall simulator to the hydraulic conductivity measured with the infiltration experiment to characterize the soil properties. Therefore the infiltration capacity is defined as the difference between the rainfall rate and the surface runoff (Equation 4). This quantity is not equal but related to the hydraulic conductivity since the hydraulic conductivity determines the possible infiltration capacity on a homogeneous surface in the steady state ([37]).

$$\phi = i - q \tag{4}$$

For the comparison of the surface runoff without dependencies from the rainfall duration, only the values of the effective runoff coefficient in the steady state are taken into account. This requires a non parametric definition of the steady state which is based on the assumption that it was approximately reached if the effective runoff coefficient is greater than the cumulative runoff coefficient $\psi_c$ (%). Therefore the cumulative runoff coefficient is defined by dividing the sum of the surface runoff by the sum of the rainfall rate (Equation 5). This approach allows a definition of the steady state based on the runoff curves without the need to introduce an additional parameterization. The non parametric discussion of the runoff curves does further provide characteristic time measures with the abstraction time $t_a$ (s) when the surface runoff begins and the convergence time $t_c$ (s) when the surface runoff reaches the steady state.

$$\psi_c = \frac{\Sigma(q)}{\Sigma(i)} \tag{5}$$

The dependencies from the soil moisture and the rainfall rate can not be eliminated without the application of an additional parameterization. While the rainfall rate is controlled by the rainfall experiment, the soil moisture is not and can have an arbitrary influence on the measurements. Therefore the initial soil moisture must be at least compared to make sure that the deviations are neglectable between the treatments within the sites. In addition to the initial moisture $\theta_i$ (-), the peak moisture $\theta_p$ (-) at the end of the run and the final moisture $\theta_f$ (-) at the end of the break are also taken into account. Those values allow to estimate the mobile water $w_m$ (-) as well the residual water $w_r$ (-) under the assumption of a capillarity controlled matrix domain and a gravity controlled macropore domain ([38]). The mobile water is defined as the difference between the peak moisture and the final moisture based on the assumption that the macropores but not the matrix are drained during the break after a run within one hour (Equation 6). From this follows the definition of the residual water as the difference between the final moisture and the initial moisture based on the assumption that it is absorbed from the matrix (Equation 7).

$$w_m = \theta_p - \theta_f \tag{6}$$

$$w_r = \theta_f - \theta_i \tag{7}$$

For the statistical analysis, a permutational analysis of variance (PERMANOVA) was applied with the effective runoff coefficient in the steady state as principal variable and the treatment, the profile and the run as independent factor levels. The factor of the treatment captures the influence of the protection fence that excludes game browsing within a site. The factor of the profile accounts for the soil variabilities within a treatment. The factor of the run considers the experiment conditions within a profile. By including the run as factor level, the dependency of the surface runoff on the rainfall rate and the soil moisture is indirectly taken into account. The PERMANOVA is a non parametric approach that does not require the homogeneity of variances and the normality of the residuals ([39]). The calculated F-values, R2-values and P-values of the PERMANOVA form the basis to investigate whether and if so to what extent the considered factors influence the surface runoff. This statistical analysis was conducted with the adonis function from the vegan package in the R language and environment ([40]).

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## Author contributions

D.M. conceived and conducted the experiments, analysed the results, wrote and reviewed the manuscript G.M. conceived and conducted the experiments, analysed the results, wrote and reviewed the manuscript B.K. conceived the experiments, analysed the results, reviewed the manuscript M.S. conceived the experiments, analysed the results, reviewed the manuscript

## Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

## Additional information

### Competing interests

The authors declare no competing interests.