

Laboratory flume experiments for detection and quantification of subsurface particle transport in steep-slope vineyards

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Abstract: Coarse-grained vineyard soils like in the Moselle valley, Germany, can be highly vulnerable to soil erosion. This is due to the non-sustainable soil management using heavy machinery and eliminating the vegetation cover on steep slopes. Through the particular combination of compacted subsoil and topsoil loosened by tillage, the vineyard experiences subsurface runoff after rainfall events. There is a knowledge gap concerning the identification and quantification of transported soil particles in the aforementioned subsurface runoff, as these processes are difficult to accurately measure under field conditions compared to surface runoff. In this paper, an experimental laboratory setup is presented including a newly developed sediment trap to measure and quantify the transport of fine soil particles in subsurface flow. The study showed substantial differences based on the water application method. Nevertheless, the first results show a subsurface sediment discharge of 1 g l^{-1} on average and $6\text{--}8 \text{ g l}^{-1}$ immediately after heavy soil disturbance (simulated tillage). It is highly recommended to conduct further experiments using the method that corresponds most closely to natural processes, the combined method of overflow and sprinkler, as well as installing the sediment trap in a vineyard to validate the findings. If the values can be confirmed, subsurface runoff is a significant contributor to the total soil erosion process and, compared to literature, is responsible for up to 50% of soil erosion in vineyards.

Keywords: Soil erosion; Subsurface flow; Subsurface runoff; Rainfall simulation; Sediment trap.

1 INTRODUCTION

Soil erosion is one of the most significant threats to vineyard soils (Emde, 1992; Cerdan et al., 2010; Rodrigo Comino et al., 2016b). Cerdan et al. (2010) compared results from a total of 2741 plot years by different authors and found that vineyards have erosion rates of $12.2 \text{ t ha}^{-1} \text{ y}^{-1}$, making them one of the most vulnerable agricultural systems to soil erosion (after bare land with $15.1 \text{ t ha}^{-1} \text{ y}^{-1}$). Other studies such as by Emde (1992) found a mean soil loss in vineyards of $151 \text{ t ha}^{-1} \text{ y}^{-1}$ over ten years, while Richter (1991) calculated only $0.2 \text{ t ha}^{-1} \text{ y}^{-1}$ over 144 years. These different results show a wide range of erosion rates and were determined by rainfall events of different intensity during the measurements (Auerswald et al., 2009). Soil erosion directly affects the nutrient content and thus the fertility of the soil (Kirchhoff et al., 2017; Novara et al., 2018). In particular, the loss of nitrogen, phosphorus and potassium is of great importance for agricultural land use (Mazur, 2018; Nazari et al., 2022; Siebers et al., 2023). Another issue for vineyard soils is the increasing use of heavy machinery for tillage that started in most industrialized countries in the 1950s (Van der Ploeg et al., 2006) and which leads e.g. to surface compaction and an increase in surface runoff that causes strong erosion patterns (Auerswald et al., 2009; Gall et al., 2022; Keller et al., 2019).

Such a region is the Moselle valley in Germany, where viticulture has a long tradition, is part of the cultural heritage and represents an important economic and tourist factor (Ashenfelter and Storchmann, 2010; Koch et al., 2013). The first viticulture in the Moselle valley is dated to the mid-second century AD and has therefore been present since the Roman Empire (Scott, 2002). Vineyards in the Moselle wine region are characterized by steep slopes (up to 30°) with shallow soils and a high presence

of coarse rock fragments ($>50\%$). The vineyards in the Moselle valley region are also characterized by an exceptionally high proportion of coarse-grained topsoil (Rodrigo Comino et al., 2016b). The hydrological properties of the soil, and therefore soil erosion, are significantly controlled by the coarse-grain content (Cerdà, 2001). In soils with a high proportion of coarse grains, characterized by larger pore spaces and a rather low fine-grain fraction, both water and sediment transport rates tend to be elevated. As a result, such soils are particularly vulnerable to erosion by water (Rodrigo Comino et al., 2017). The study by Kirchhoff et al. (2017) shows that soil erosion in vineyards lowers the soil by up to $0.5\text{--}2 \text{ mm}$ per year and thus accounts for 30% of the fine material loss, which directly affects the nutrient content and thus the fertility of the soil (Kirchhoff et al., 2017; Novara et al., 2018). Increased soil erosion due to the intensification of soil cultivation, the general use of heavy machinery or inappropriate land management has also been noted in the Moselle region (Kirchhoff et al., 2017; Rodrigo Comino et al., 2015). Rodrigo Comino et al.'s (2015) key findings are that up to 99.5% of rainfall infiltrates in such steep vineyard soil settings and doesn't contribute to surface runoff. The reasons are besides a high proportion of coarse rock fragments and the low thickness of the soil, the increased usage of heavy machinery in viticulture. The soils develop two distinct horizons, a deeper horizon that becomes increasingly compacted and an upper A_p horizon that gets regularly loosened by tillage to increase organic carbon in the subsoil. This results in runoff between these two horizons - the subsurface flow. It is largely controlled by the soil type and hence the distribution of macropores (Fox et al., 2010; Hardie et al., 2012), slope (Han et al., 2020) and soil moisture (Hardie et al., 2011). Subsurface flow flushes fine soil out of the soil matrix by suffusion, altering

the hydrological properties of the soil. Furthermore, the amount of fine material in vineyard soils is rather small (<31%, after Rodrigo Comino et al. (2015)), which increases the importance of measuring its loss. Compared to the extensively studied and well-known characteristics of surface runoff, subsurface flow in vineyard soils remains a crucial erosion factor that has not been systematically investigated. To date, there is no working in-situ method for quantifying this subsurface runoff and the fine material it transports. Some studies (Ma et al., 2022; Mazur, 2018; Pilgrim and Huff, 1983; Siebers et al., 2023) have already attempted to measure suspended sediment in subsurface flow, but all of these studies used highly intrusive measurement methods (e.g. benches, tile drainage, steel plates). Others have focused e.g. on hydraulic connectivity in experimental settings (Liu et al., 2019) or pipe erosion (Bernatek-Jakiel and Poesen, 2018).

With the following approach we address this knowledge gap in research and therefore developed a sediment trap to quantify subsurface flow and fine material discharge in an experimental setting (Figure 1), with the intention of adapting this system for field use to enable in-situ measurements. With this sediment trap we want to address the following research questions:

- Can the developed sediment trap accurately represent and measure subsurface flow?
- What is the relationship between surface runoff, general subsurface runoff (later called 'base flow'), and subsurface flow in the sediment trap in the studied system with respect to: a) water volume, b) sediment volume, c) particle size distribution?
- How do the measured parameters and flows differ among the various water delivery methods (overflow, irrigation, combination)?
- What is the contribution of subsurface flow to the erosion process?

2 MATERIALS AND METHODS

2.1 Study area

For this study we selected an area in Waldrach in the district of Trier-Saarburg in Rhineland-Palatinate, Germany, to serve as a template for the experimental design. Waldrach is located in the Ruwer valley and belongs to the Moselle wine region. It is part of the Rhenish Slate Mountains at an altitude of 200–300 m above sea level. The average annual precipitation and temperature are 765 mm and 9.3 °C, respectively (Rodrigo Comino et al., 2015). The study area is located at the European northern limit for commercial viticulture, up to which the pedoclimatic conditions are suitable for grape growing (Ashenfelter and Storchmann, 2010). With a slope gradient of up to 30°, the area belongs to steep slope viticulture (defined as >17°) (German Wine Ordinance § 34b in the version of the announcement of 21 April 2009 (BGBl. I)). Soils have been developed from Devonian argillaceous schist (Hunsrück Devonian strata), as well as Pleistocene terrace sediments (Cordier et al., 2012) and Cambisol leptic-humic (IUSS Working Group WRB, 2022) is the dominant soil type (Rodrigo Comino et al., 2015). For the laboratory setup fresh soil material of a steep vineyard of the study site was extracted once and transported to the lab facility.

2.2 Design of the experimental flume

The experimental setup was designed to mimic the field and soil conditions in Waldrach, in order to investigate the processes of subsurface transport of fine soil material and to develop

sediment traps for in-situ measurements. This overall setup will be referred to as the 'flume'. The flume consists of a 2.7 m × 0.9 m artificial flow channel with a depth of 0.2 m, which can (for technical reasons) just be adjusted to a maximum slope of 16°, as shown in Figure 1. At the top of the flume is a water basin from which a hose leads to the main flume basin. At the bottom of the flume is the outlet. At the top end and approximately in the last third of the main flume basin, a 2 mm × 6 mm mesh grid has been inserted to enclose the substrate. The purpose of the upper grid is to allow the water to flow as evenly as possible into the substrate, while the lower grid is to prevent the substrate from slipping down the slope. The dimensions of the inner flume are 1.93 m/1.85 m (L) × 0.85 m (W) × 0.19 m (H). An overflow structure at the top of the main flume basin also serves to ensure that the water flows evenly into the substrate, as can be seen in Figure 1c. As the flume bottom is intended to simulate a partially impermeable horizon in a vineyard, the flume was also covered with rough roofing felt to create more natural conditions on the smooth floor and to prevent the substrate from slipping over time. The water that runs off the flume bottom and thus ends up in the catch basin located at the end is referred to as the base runoff in the further course. Water samples were taken from this base runoff, which are referred to as 'samples base'.

Figure 1 (d) shows the sediment trap placed in front of the lower grid. The trap is made of an 0.86 m long PVC pipe with a 0.035 m × 0.65 m cut-out, wrapped with a 2 mm × 6 mm mesh grid. The pipe has an inlet for flushing the trap before each trial and also serves as a substrate drain, allowing water to flow out and water samples to be taken. This drainage is referred to in the following as the trap runoff and the water samples taken as the 'samples trap'. The trap is not in direct contact with the bottom of the flume, leaving a 50 mm gap between the pipe and the flume bottom, allowing water to flow into the catch basin as base runoff.

Also, a sprinkler system was added over the flume, as shown in Figure 1 (a, b). The sprinkler system comprises of two Lechler 460,608 nozzles, which simulate precipitation of 60 mm h⁻¹ per nozzle and thus approximately 2 l min⁻¹ or 150 l per trial (80 min). This value serves as a standard to ensure a high degree of comparability. Precipitation is controlled by a flow control system, which consists of a flow meter (Type KSK-1200HIG100, 0–125 l h⁻¹, Kobold Company), a needle valve (Kobold Company), and a manometer with 0–4 bar. The sprinkler nozzles were positioned parallel to the substrate surface, 0.75 m apart from each other and 0.70 m above the substrate surface (refer to Figure 1a, b). This positioning ensures optimal rainfall distribution of the nozzles, as demonstrated by Fister et al. (2011).

2.3 Experimental trials

To investigate the functionality of the constructed sediment trap, the first trials were carried out with water entering the flume via an overflow at a rate of 5 l min⁻¹ for 120 minutes (600 l per trial) ('overflow method', see Table 1). The second set of trials was performed only via the sprinkler system at 120 mm h⁻¹ for 80 minutes with the aim to improve the understanding of the substrate behaviour to different water inputs and to enhance the comparability of the flume setup to other literature rainfall simulations. In the final series of trials, we combined the overflow and sprinkler method ('combination method') to allow water to flow into the substrate as naturally as possible. The water volume was calibrated using a flow meter and various valves to a total of 5 l min⁻¹ for 80 minutes. The irrigation intensity was 2 l min⁻¹ (equals 120 mm h⁻¹), while the flow rate from the overflow was 3 l min⁻¹.

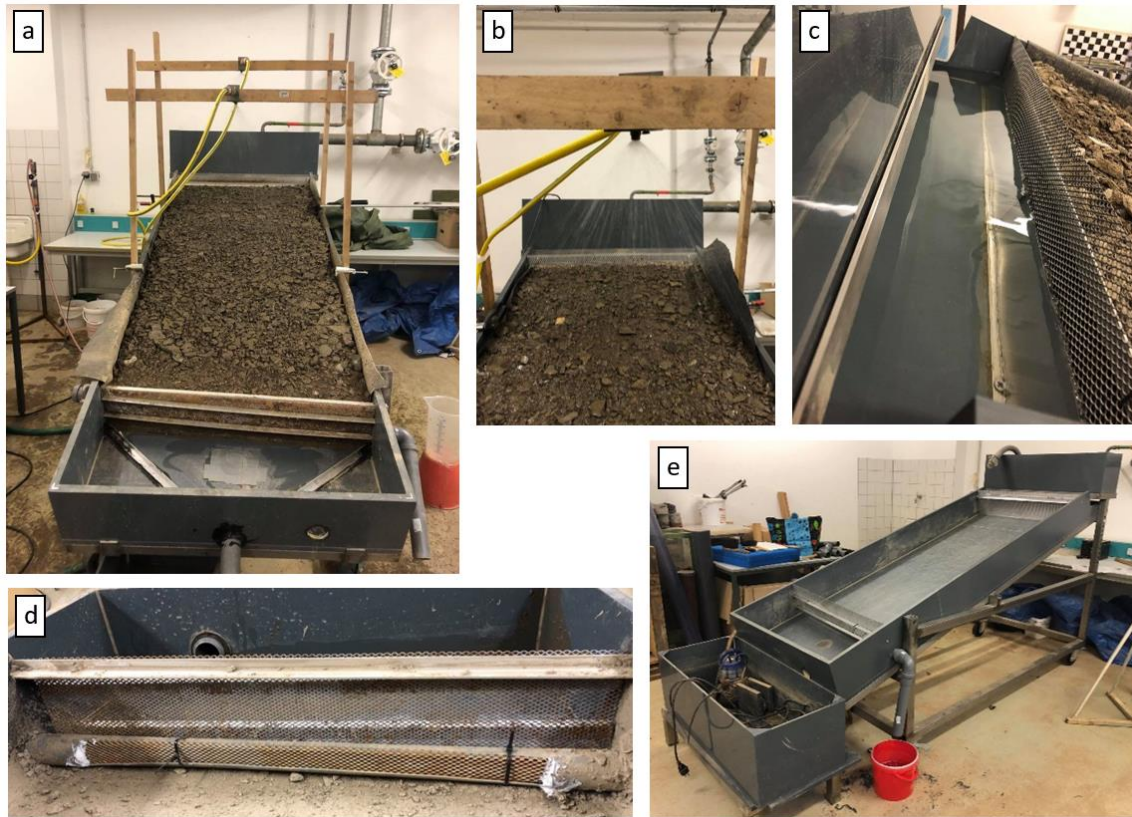


Fig. 1. (a) Experimental setup consisting of an artificial runoff channel (flume) filled with vineyard soil substrate, (b) a sprinkler system, (c) an overflow, (d) the sediment trap and (e) the empty flume with an inclination of 16°.

Table 1. Details of the trials. The header row displays the different trials, followed by the water application method used in the second row. The third row provides the duration of the experiment. Rows four to seven indicate whether a sample was taken and, if so, which one. Row eight indicates whether the discharge was measured, and row nine indicates whether a soil substrate sample was taken. The last row indicates whether tillage was simulated.

1	Trial Number	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Trial 6–8	Trial 9–11	Trial 12–14	Trial 15–17	Trial 18 & 19
2	Method	Overflow	Overflow	Overflow	Sprinkler	Sprinkler	Overflow	Overflow	Overflow	Sprinkler	Combination
3	Duration	3 h	3 h	3 h	1 h	2 h	2 h	2 h	2 h	1:20 h	1:20 h
4	Samples trap	✓					✓	✓	✓	✓	✓
5	Samples base		✓	✓	✓	✓	✓	✓	✓	✓	✓
6	Samples surface				✓	✓					
7	Samples GSA						✓	✓	✓		
8	Rate						✓	✓	✓	✓	✓
9	Soil substrat sample	✓							✓	✓	✓
10	Simulated tillage	✓					✓	✓	✓	✓	✓

To measure surface runoff, a metal trough was installed at the lower edge of the flume. This allowed surface runoff water to flow along the gutter and collect water samples ('samples surface').

2.4 Experimental measuring procedure

During each trial samples were collected from various sources: including the sediment trap; base runoff; catch basin at the end of the flume; and surface runoff, as specified in Table 1. Additional samples were taken for a subsequent grain size analysis (GSA) using the pipette method according to Köhn (DIN ISO 11277). The number of samples varied depending on the method and duration of the experiment. In addition to these

samples, the sediment concentration and rate of discharge per time was measured during the entire trial duration t [min]. Starting from trial 6, the soil substrate was manually dug with hand shovels to simulate regular vineyard tillage before each trial. From trial 12 on, additional soil substrate samples were taken during this mixing process for additional GSA and gravimetric water content. For two example trials, the total water volume was collected for comparison and total GSA. The intervals between individual trials were consistently maintained at one week, and the flume was always covered with a tarpaulin to prevent excessive substrate drying and induced weathering from drying and wetting cycles. The experiments were carried out between October 2020 and May 2021.

3 RESULTS

3.1 Sediment concentration

The substrate water content before each trial remained constant at 11% throughout the experiments.

The results of the experiments using the overflow structure showed a similar course in the trap-discharge and the remaining discharge at the end of the flume (base). Both started with a sediment concentration of 3.3 g l^{-1} in the base and 5.5 g l^{-1} in the trap discharge, followed by a decrease after 30 minutes to less than 1 g l^{-1} . The decrease in sediment concentration was also visually observed during the tests. Figure 2 displays an example of a trial with corresponding images from the catch basin at the end of the flume. At the start of the trial, a considerable amount of sediment was flushed out and flowed into the catch basin in the form of sediment plumes. Towards the end of the trial, the water became increasingly clear. Additionally, it is noticeable that the trap discharge in all overflow trials started with a higher sediment concentration than found in the base discharge.

The course of the sediment concentrations in the trials with the sprinkler system were similar to the previous trials for both the trap and base discharges investigated. There was a rapid drop in sediment concentration in the first 30 minutes, followed by a levelling off to less than 1 g l^{-1} . In contrast to the experiments with the overflow structure, the base discharges at the beginning of the trial had a higher sediment concentration (up to 11 g l^{-1}) than the discharges from the trap (up to 6.5 g l^{-1}).

Finally, overflow structure and sprinkling were combined in the third series of trials. However, only one reliable trial could

be conducted using this method, due to technical difficulties at the beginning and time constraints at the end. Figure 3 clearly shows the similarity between the two discharges in this trial. Both discharges started with a sediment concentration of around 5 g l^{-1} and decreased as well to less than 1 g l^{-1} . In addition, the decline in sediment concentration extends to the 50th minute and neither of the two discharges dominates the sediment concentration with this method.

Figure 4 presents a direct comparison of the mean values of the two discharges, trap and base, for all trials of the two methods, overflow structure and sprinkler. The sprinkler method produces a higher sediment concentration on average than the method with the overflow structure. This difference is particularly pronounced at the beginning of the trials. Furthermore, the comparison highlights the varying ratios of trap and base flow in the two methods. The sediment concentration in the trap is dominant during overflow, while the sprinkler method results in a higher sediment concentration in the base, particularly in the first 10 minutes of the trials. On average, 500 g of sediment was discharged in each trial. A total of 19 trials were conducted, resulting in a loss of approximately 10 kg of fine material. The average sediment concentration, calculated based on a total water flow of approximately 10,000 l, was 1 g l^{-1} . Sediment concentrations in all experiments decreased significantly within the first 30 minutes, starting with an initial sediment concentration of $6\text{--}8 \text{ g l}^{-1}$ and then settled to a low level until both sediment discharges were below 1 g l^{-1} , as can be seen in Figure 5.

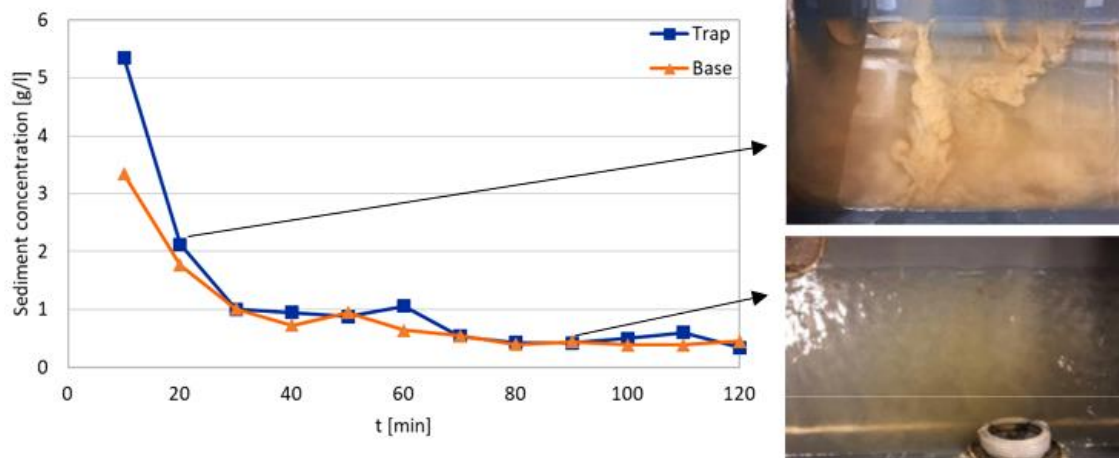


Fig. 2. Comparison of sediment discharge at the beginning and end of trial 10 with the overflow method.

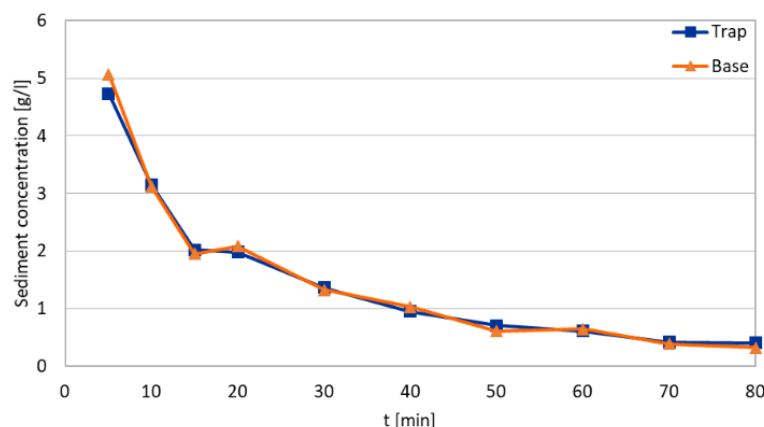


Fig. 3. Sediment concentrations of the combination method trial 19 (overflow + sprinkler).

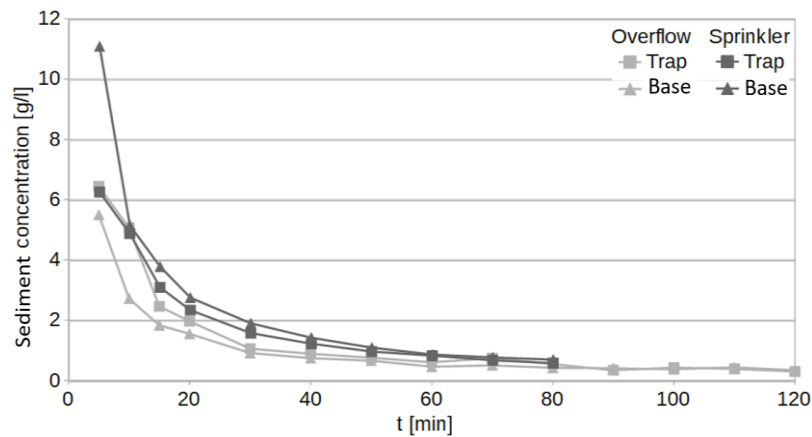


Fig. 4. Comparison of the mean sediment concentrations of the methods overflow and sprinkler.

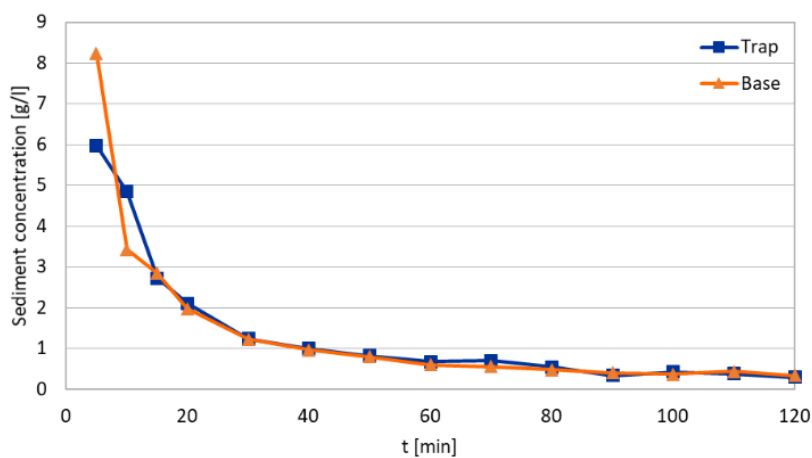


Fig. 5. Mean sediment concentration of all trials.

3.2 Discharge

In addition to the sediment concentration, the rate of discharge per time (ml s^{-1}) was recorded, as shown in Figure 6. The overflow method showed a much higher rate of base discharge ($\sim 70 \text{ ml s}^{-1}$) compared to the one measured with the trap ($\sim 30 \text{ ml s}^{-1}$). However, the two discharges gradually converged during the trial. The base flow decreased over time to $\sim 50 \text{ ml s}^{-1}$, while the trap flow increased to $\sim 40 \text{ ml s}^{-1}$. The discharge rate graphs of the sprinkler trials exhibit a distinct pattern compared to the overflow trials. Throughout all sprinkler trials, the trap rate remains consistently low ($< 5 \text{ ml s}^{-1}$), while the base flow experiences a sharp increase in the first 10 minutes and then maintains a high level ($\sim 30 \text{ ml s}^{-1}$). The runoff rates of the combination method display a combination of the overflow and sprinkler trial rates. Thus, the trap rate increases with time and approaches the base rate ($20\text{--}40 \text{ ml s}^{-1}$). This was also observed in the overflow trials. The base rate, like in the sprinkler trials, remains constant throughout the trial period ($\sim 50 \text{ ml s}^{-1}$). In all experiments, except for one trial in the overflow method, the base discharge rate exceeded the discharge rate from the trap.

3.3 Grain size distribution

Figure 7 (top) shows cumulative grain size distributions in millimetres (mm) for the two trials for which the total water volume was collected. The analyzed samples within the soil substrate and runoff samples show little variation in texture

composition, while the two sample types (substrate samples and the sediment samples) differ greatly from each other. The samples of soil substrate mainly consist of coarse sand ($\sim 30\%$), medium sand ($\sim 15\%$), and clay ($\sim 15\%$). In contrast, the runoff samples contain mainly fine soil with clay ($\sim 40\%$), fine silt ($\sim 30\%$), and medium silt ($\sim 20\%$). Figure 7 (bottom) shows that there is little change in the grain size distribution of the individual fractions of the soil substrate samples over time. Only a slight increase in the clay fraction and a simultaneous decrease in the coarse sand fraction over time can be observed. Figure 8 displays the grain size distribution of the two example trials, showing the sediment discharge of the trap and the base outflow.

The distribution of the grain size fractions indicates a clear decrease in the clay fraction over the entire trial period, while the other grain size fractions fluctuate slightly or remain constant.

In summary, the particle size analysis reveals a clear difference between the discharged material and the substrate material. The substrate did not have any measurable decrease of fine material, whereas the sediment discharged during the trials showed a clear decrease in clay content over time.

4 DISCUSSION

The evaluation of the sediment concentration indicates that base and trap discharges have a similar course in all three methods used. Thus, it can be assumed that the sediment trap successfully represents the subsurface discharge. However, the amount of sediment discharged per trial varies depending on the water application method used. For instance, the sprinkler

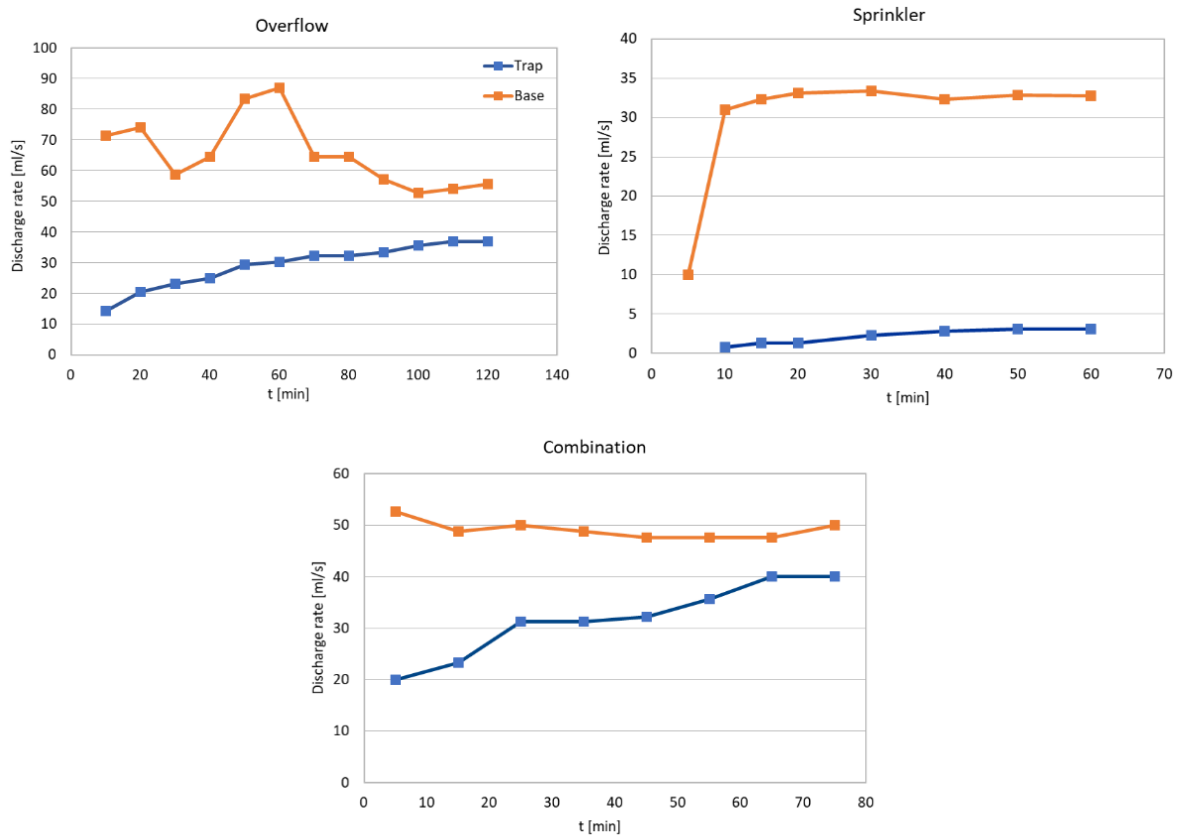


Fig. 6. Comparison of the discharge rate of the three different methods with representative examples (Overflow trial 10, Sprinkler trial 4, Combination trial 19).

method yielded higher sediment concentrations in the base, while the overflow method produced higher sediment concentrations in the trap. This can be explained by the overflow method channelling incoming water directly to the bottom of the flume, resulting in increased flow in the trap. While the sprinkler irrigation, on the other hand, distributes water more evenly throughout the substrate. Sediment concentration is highest when using the sprinkler system, particularly during base flow.

This is due to the impact of water droplets on the substrate surface and the resulting splash effect (Luk, 1979), which dissolves and kinetically mobilizes more fine material than the slow inflow of water via the overflow. Visual analysis of the flume surface confirms the absence of fine material at the surface after a short time. The sediment concentration in continuous water discharge declines strongly, indicating a supply-driven system. At the beginning of the trial, the trap or base flow transports a large part of the fine material (6–8 g l⁻¹, compare Figure 5), which is the highly mobile fraction, out of the system. The sediment concentration does not appear to be markedly affected by increased pore connectivity in the substrate resulting from higher moisture or saturation over time. The system seems to be primarily influenced by the availability of fine material, rather than being hydrologically-driven. The lack of observed change in the grain size distribution of the flume material suggests two possible explanations. First, the method used to measure grain size distribution may not be sufficiently sensitive. Detecting slight variations in grain size distribution might require a much larger sample aliquot, given the wide range of grain sizes present. To accurately identify minor changes in clay content, it is necessary to minimize the influence of large rock fragments, which can disproportionately affect the overall distribution.

Second, it is possible that the grain size distribution of the flume material did not change significantly. Instead, only the material within preferential flow paths may have experienced alterations. Although this localized change could be subtle and have minimal impact on the overall grain size distribution, it could still significantly influence sediment discharge. Material from these preferential paths, which may provide fresh sediment over time (e.g., through weathering), could be exported at a rate slower than the discharge events, thus contributing to observed sediment flux patterns.

Regardless of the method used, there is an increasing discharge over time into the trap, which is attributed to increased pore connectivity due to the loss of the fine material. The results of the different trials showed that the flow rate is strongly dependent on the method used. Furthermore, no clear relationship between trap and base flow can be defined. In all trials, except for one trial with the overflow method, the base discharge exceeded the trap discharge. This outlier is particularly striking because the ratio of trap and base outflow is opposite to the other trials using the overflow method. This can be explained by the fact that the gap between the trap and the flume bottom was blocked and considerably more water was flushed into the trap than in the other experiments. In this and one other experiment, the total amount of water and sediment was collected and analyzed. Despite the opposite course of the rate, the sediment concentration was very similar in both experiments. This suggests that the amount of water does not necessarily control the amount of sediment discharged. The results of the overflow method indicate that the base consistently carries more water than the trap, and the two discharges eventually merge. Initially, the water mainly drains directly onto the bottom of the flume and thus under the trap. As time passes, the substrate

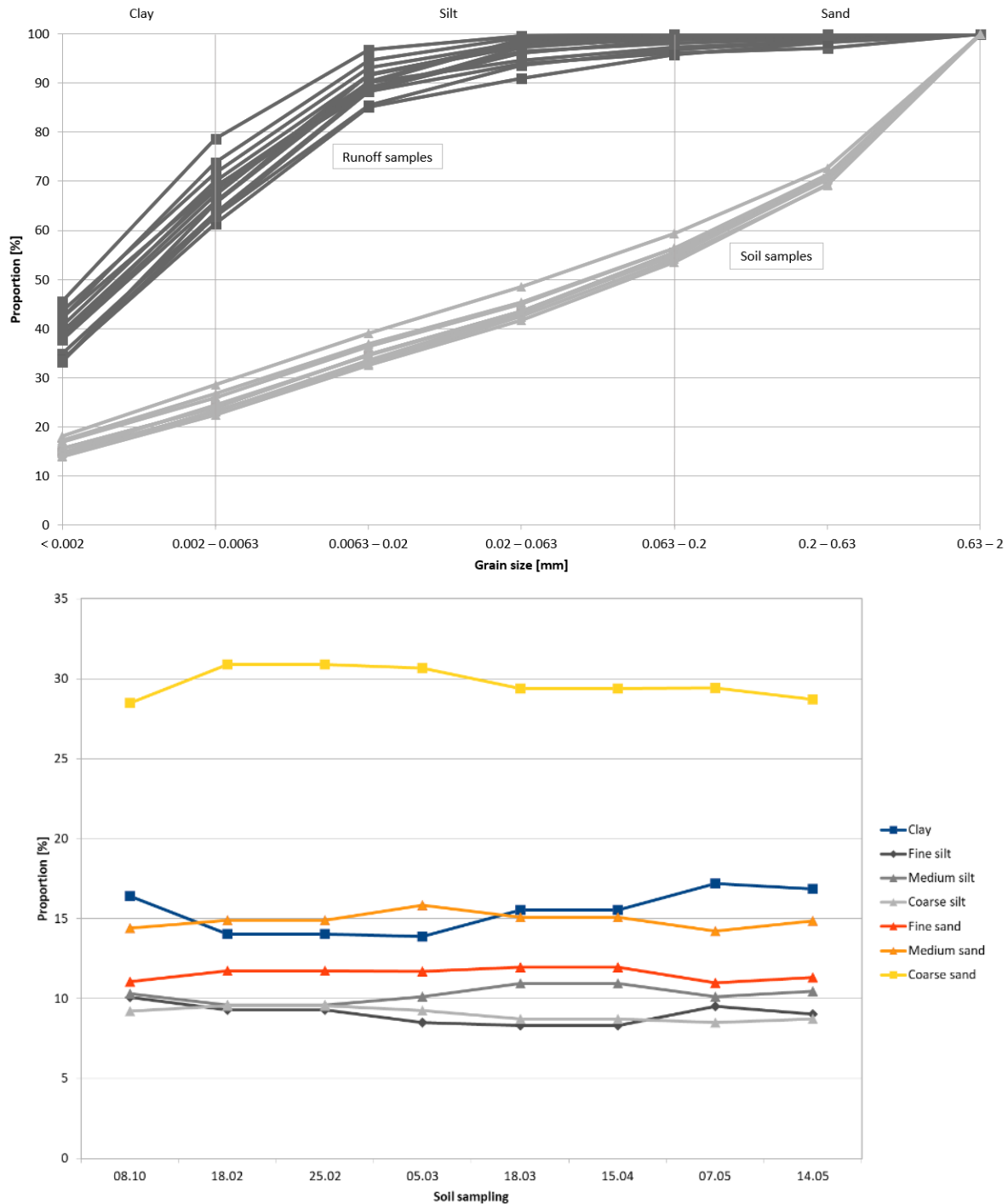


Fig. 7. (top) Grain size distribution diagram of the soil substrate samples ($n = 8$) and runoff samples ($n = 15$). The proportion of the individual grain sizes in millimetres (mm) is shown. Notably, the analyzed samples show little variation in texture composition within the sample classes 'soil samples' and 'runoff samples', while the two sample classes differ significantly from each other. The soil samples mainly consist of coarse sand, medium sand, and clay, whereas the runoff samples primarily contain the finest fine soil, clay, fine silt, and medium silt. (bottom) Proportion of grain sizes in the soil substrate samples. On the x-Axis, the date when the soil sample was taken is shown. Even upon closer examination of the individual grain size fractions of the soil samples over time, little change in the grain size distribution is apparent. Only a slight increase in the clay fraction and a simultaneous decrease in the coarse sand fraction over time can be observed.

becomes saturated until the saturated area at the bottom of the flume reaches the level of the trap. Consequently, more water flows into the trap, and the two drains converge. With sprinkler irrigation, water is distributed more evenly throughout the substrate, resulting in a lower saturated layer at the bottom of the flume and reducing the amount of water that can flow into the trap.

No measurable fine material was discharged from the substrate. However, a closer examination of the grain size

distribution over time reveals a slight decrease in coarse sand with a simultaneous increase in clay. The experiments were carried out for ~8 months, during which the substrate may have undergone swelling and shrinking due to regular use, leading to in-situ weathering in the flume. The interpretation of the results may be influenced by several factors. The transfer and mixture of vineyard soil from Waldrach might have altered soil characteristics, such as layering, pore space, and connectivity,

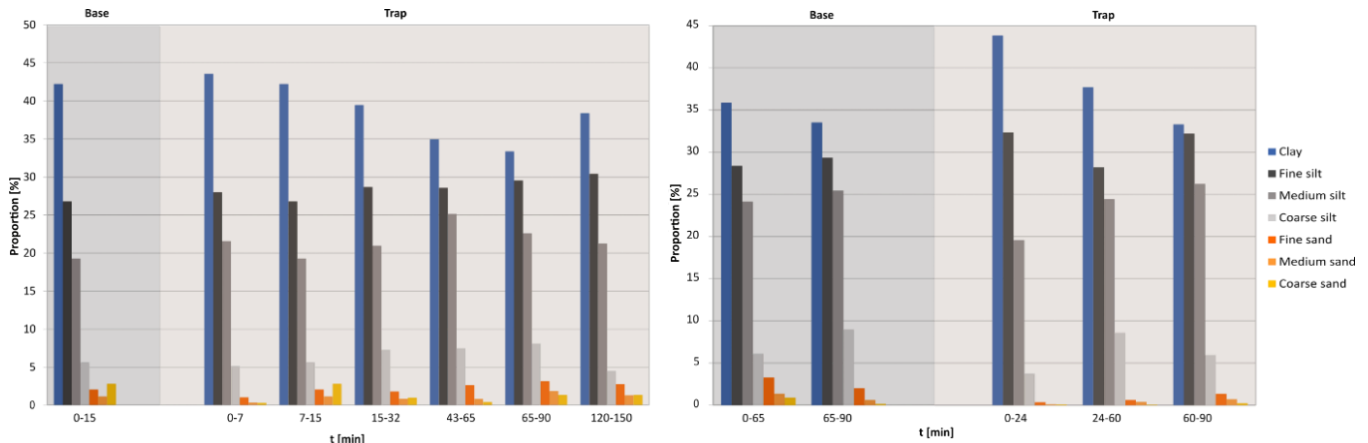


Fig. 8. Proportion of grain sizes in the runoff samples of the two example trials. The 'Base runoff' represents the runoff on the bottom of the flume, which is measured through the catch basin at the end of the flume. The 'Trap runoff' is the runoff that was measured with the sediment trap. In the distribution of the grain size fractions, it is noticeable that there is a clear decrease in the clay fraction over the entire duration of the trial, while the other grain size fractions fluctuate only slightly or remain at a consistent level.

which could have modified or buffered the hydrological response. Additionally, the experimental setup, with its impermeable flume bottom acting as a deeper, compacted soil horizon, likely increased subsurface flow by limiting deeper infiltration. The statistical validity of the soil substrate GSA samples may also be compromised, due to both the limited number of samples and the necessity to account for the very coarse grain fraction when analyzing smaller fractions. To address these issues, similar experiments could be conducted with adjusted setups or improved sampling protocols. Furthermore, testing the sediment trap in a field setting would be beneficial. Although the installation might be as invasive as other field experiments, it could significantly disturb the soil's hydro-mechanical properties. However, this disturbance could be minimized if the installation is timed to coincide with regular soil tillage, preventing additional disruption. The sediment trap, built with pipe and mesh and tested in the flume, requires no further adjustments for field deployment. The gently inclined pipe would need only to connect to a drainage system positioned beneath the soil surface, rather than at the flume's side. For better reproducibility and robust statistical analysis, conducting rainfall simulations using a known quantity of water on a well-defined soil surface would be essential. This setup would allow for efficient and quick measurements of sediment trap discharge. Alternatively, a simpler technical approach could involve long-term experiments. In this case, seasonal access would suffice, and a rain gauge could correlate total rainfall with the sediment collected in the trap. Sediment could be collected using a large filter with subsequent water drainage facilitated by a pipe.

Nevertheless, regarding a transfer of the measured sediment concentration to other field or lab environments, Pilgrim and Huff (1983) support the finding of 1 g l^{-1} , despite having a highly invasive measuring technique and not conducting their experiment on vineyard soils, but on Gaviota Loam and Altamont Clay Loam (US. Department of Agriculture, 1958). The theoretical study site of Waldrach enables a comparison to simulated rainfall experiments by Rodrigo Comino et al. (2015, 2016a). The authors used a lower rainfall intensity (40 mm h^{-1}) and where only able to measure surface runoff and its sediment concentration. In 2015 the concentration was $3.34\text{--}7.77 \text{ g l}^{-1}$ in Waldrach. During a remeasurement 2016 at the same site, an additional location in the Moselle region (Kanzem) and two study areas in Spain sediment concentrations of surface runoff ranged between $2\text{--}22 \text{ g l}^{-1}$. These values seem to be a magnitude larger compared to the measured concentrations in the flume. But

Rodrigo Comino et al. (2015) observed an infiltration rate of up to 99.5% for the vineyard soils, meaning that in turn the subsurface flow could carry a significantly larger amount of water with lower concentration compared to a low surface runoff with high sediment concentration. This highlights the importance of understanding subsurface and surface runoff relations and the need for implementing the sediment trap in the field.

Prior to conducting each experiment, the entire substrate in the flume was dug up to ensure comparability and reproducibility of the trials. The vineyards are tilled to a depth of approximately 0.2 m every six months (Rodrigo Comino et al., 2017), which is the same depth as the flume. The experiment and trial settings of 2 m^2 , 120 min trial duration and a flow rate of 2 l min^{-1} (5 l min^{-1} respectively) result in a total of 700 l (1200 l) of water that flew through the flume body. In comparison, the yearly precipitation of the study site in Waldrach is 765 mm (Rodrigo Comino et al., 2015). So, if we account for a similar soil body of 2 m^2 the total water volume flowing through that corpus is 1530 l, if we neglect further upslope inflow that might already experience a locally saturated sediment concentration. This comparison is fairly abstract but shows on the one side that the total water volume and experimental setup is to a first order comparable to the study site conditions. On the other side, it makes digging up the flume before each trial comparable to tilling the vineyard every six months. In terms of a tillage-free period of the vineyard, the first 30 minutes of the Flume trials correspond to several weeks to months in the vineyard with high sediment concentrations ($6\text{--}8 \text{ g l}^{-1}$, compare Figure 5) in the subsurface flow. Thus, at least directly after tillage, subsurface runoff takes a significant share of the total erosion event in the vineyard. The issue of high soil erosion on the soil surface immediately after tillage has been identified in various studies, also in the Mosel area (Ma et al., 2022; Novara et al., 2019; Seeger et al., 2019). Ma et al. (2022) conducted a similar experiment, using in-situ rainfall simulations on rather steep slopes (15%), to investigate the impact of soil surface roughness on the development of surface and subsurface flow. The study demonstrated that surface roughness has a significant impact on the development of subsurface flow, where 24% of rainfall becomes subsurface flow. Additionally, the study found that sediment yield increases after subsurface flow occurs through tillage-induced rough surfaces (Ma et al., 2022). These findings align with the results presented in this paper, which indicate that subsurface flow is the primary contributor to erosion immediately after tillage.

5 CONCLUSIONS

The vineyards in the Moselle wine region are extremely vulnerable to soil erosion due to various factors. While surface runoff has been extensively researched, subsurface flow in vineyard soils is a critical erosion parameter that has not been systematically addressed. This study used an artificial runoff channel and sediment trap to simulate and quantify runoff between the compacted and loose horizons within the vineyard soil. It was shown that the sediment trap could successfully be used to measure subsurface flow. Furthermore, we demonstrated that fine material is discharged through subsurface flow with an average sediment concentration of 1 g l^{-1} . This concentration is several times higher (6 to over 8 g l^{-1}) immediately after simulated tillage. The study found substantial differences in the results depending on the water application method used. Hence, it is recommended to conduct further experiments using the most natural method, which combines overflow and sprinkler, to support the findings. Additionally, it is necessary to install the developed sediment trap in the vineyard, to execute in-situ measurements of the natural subsurface runoff and sediment discharge. If these values can thereby be confirmed, subsurface flow is a crucial erosional process, especially after tillage and could account for up to 50% of vineyard soil erosion, compared to the literature.

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