Technical Note: ~~Best of both worlds?~~ Combining undisturbed soil monoliths for hydrological indoor ~~runoff~~ experiments

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Abstract. An ~~major~~ important decision in soil hydrological research is whether to conduct experiments outdoors or indoors. Both approaches have their advantages and trade-offs. Using undisturbed soil monoliths combines some of the advantages of outdoor and indoor experiments, however, there are often size limitations. Acquiring large monoliths necessitates heavy machinery, which is time-, cost- and labour-intensive. However, small- to medium-sized soil blocks, however, can be obtained using less demanding methods.~~While push methods can be used for small- to medium-sized soil blocks, acquiring larger monoliths necessitates heavy machinery.~~ A promising approach is the combination of smaller blocks to a single large monolith, thereby optimizing cost and labour efficiency as well as representativity and upscaling potential. To this end, we compared the runoff properties of medium-sized (1 ×~~x~~ 0.5 ×~~x~~ 0.35 m) grassland soil monoliths cut in half and re-combined with uncut blocks. We conducted artificial runoff experiments and analyzed the chemical composition and amount of the outflow from four flow pathways (surface runoff, subsurface interflow, percolating water, ~~laterally exported water~~lateral flow). Furthermore, we studied ~~and~~ surface runoff velocity parameters using a salt tracer. Our results suggest that the effects of the re-combination procedure are negligible compared to the variation in the data caused by the inherent soil heterogeneity. ~~Further research is needed for a definite conclusion. Nevertheless, w~~We propose that the benefits of combining soil monoliths outweigh the potential disadvantages.

1 Introduction

An important ~~cardinal~~ question in soil hydrological research is whether to conduct experiments outdoors or indoors, i.e., *in situ* or *ex situ*. Both are frequently used in artificial rainfall or runoff experiments (e.g., examining erosion or nutrient export) and have each specific strengths and weaknesses. The main advantage of outdoor experiments is that the studied soils have developed naturally and are fully integrated into the surrounding landscape. They are shaped by physico-chemical processes and biological activity and, thus, have developed three-dimensional characteristics (e.g., vertical gradients, macropore network, root system, etc.) that cannot easily be reproduced artificially (Green, 2014; Katagi, 2013). Accordingly, the results obtained

have an inherent real-life relevance. A downfall is that it can be challenging to find sites with desired conditions, especially ones that are homogeneous over a larger area, so replicate plots can be installed. Frequently, there is only a narrow time frame

30 of constant weather conditions, especially concerning temperature and precipitation (Kuhn et al., 2014).

The main advantage of indoor trials is a higher control over variables and ~~an~~ independency from the weather. Furthermore, there is the possibility of testing the same soil under different situations which would be difficult or downright impossible in the field, for example different slopes. Another ~~major~~ significant benefit is better access to infrastructure, resources, and measuring instruments, saving time and work required (Douglas et al., 1999). Indoor experiments may also be preferred in

35 studies that examine nutrients or pollutants, as these can be collected and discarded without getting into the environment. On the other hand, it is challenging to simulate outdoor conditions with indoor experiments, especially if disturbed soil is used and vegetation is grown artificially (Johnson et al., 1995; Poorter et al., 2016). Owing to limited plot sizes, there is also the question to which extent results can be extrapolated to relevant larger scales (Lewis and Sjöstrom, 2010).

Using undisturbed soil monoliths combines some of the advantages of outdoor and indoor experiments: naturally developed

40 soils combined with high flexibility and control over variables. For upscaling purposes and a more accurate representation of soil processes and their variability, it would be desirable ~~advisable~~ to use soil volumes that are as large ~~soil slabs~~ as possible; however, the amount of work needed increases substantially with size. The collection of large monoliths (over 1 m³) necessitates heavy machinery such as hydraulic rams, excavators, and cranes (Belford, 1979; Darch et al., 2015; Schneider et al., 1988). For smaller monoliths it is possible to use ~~push~~ methods that require only ~~can be used, which are usually~~

45 ~~accomplishable with~~ minimal use of technical gear. For instance, push methods can be applied in which a sampling frame is driven into the ground with a mallet, or a frame may be built around a pre-cut soil volume (Douglas et al., 1999; Palmer et al., 2011). Furthermore, the less heavy the monoliths are, the ~~Blocks below 300 kg are~~ easier they are to handle, store, and discard (Allaire and van Bochove, 2006). Cylindrical soil monoliths are often used for lysimeters while runoff/erosion studies commonly employ rectangular blocks (Allaire and van Bochove, 2006; Douglas et al., 1999). A promising approach for runoff

50 research appears to be taking ~~the combination of~~ two or more equal sized smaller monoliths at a site and combining them in~~to~~ a single large block, thereby optimizing cost and labour efficiency as well as representativity and upscaling potential. However, the contact areas between the individual monoliths may affect runoff and transport processes, such as infiltration and sediment movement.

Here, we report on the potential to combine undisturbed soil monoliths to acquire larger soil units for studying runoff and

55 nutrient transport. To this end, we collected six monoliths (1.0 ~~x~~ 0.5 ~~x~~ 0.35 m) in grassland, representing vegetated filter strips (Prosser et al., 2020). Three monoliths were cut in half and re-combined again, and the others remained uncut. We conducted artificial runoff experiments with tracer applications and flow velocity measurements to examine whether re-combined and uncut blocks behave differently. In principle, the contact zone between two individual blocks could act as a large macropore, promoting preferential flow and, thus, a higher share of percolating water at the expense of surface runoff.

60 However, our main hypothesis was that – done properly – the re-combination procedure has no directional effect on runoff properties. Accordingly, we hypothesized that (1) re-combined monoliths do not differ regarding the amount of ~~(share of)~~

outflow at the different flow pathways or their proportional share, (2) re-combined monoliths do not show a faster onset of percolating water or (3) a faster increase of tracer concentration within the percolating water, and that (4) there is no difference in surface runoff velocity between treatments. Additionally, we discuss general issues related to indoor runoff experiments.

2 Methods

2.1 Monolith sampling & preparation

The six monoliths were taken from a permanent grassland near the town of Wieselburg, Lower Austria, Austria (see Table 1 for main soil properties). We used a push method for monolith collection, similarly to the method used in by Tiefenbacher et al. (2021). A custom-built steel frame (1.0 x 0.5 x 0.4 m) with a cutting edge was placed on the soil surface and driven into the ground using body weight and a mallet. To ease penetration and minimize compaction and disturbance, the soil around the frame was gradually removed with spades. Once the desired depth was reached, a bottom plate was inserted with a rack and pinion jack. The frame was towed onto a trailer using wooden ramps and an electrical winch. In the workshop, the monoliths were transferred to plywood boxes. Three of the monoliths were cut in half vertically to obtain two 0.5 x 0.5 x 0.35 m sized blocks. The blocks were interchanged so that the left front of the left block faced the right front of the right block. They were then re-combined by applying a viscous soil-water mixture to the facing fronts and tightening the fit of the plywood box (see Supplement A for details on sampling and cutting). For a proper re-combination, the blocks must be of equal width and depth. Furthermore, the monoliths, and the soil used for the soil-water mixture, need to be taken from the same site close to one another.For the soil water mixture, we used soil from the sampling site. Monoliths were watered regularly. However, the soils occasionally dried up to some extent at the surface during hot summer days.

Table 1: General siteSite and material characteristics. TOC – total organic carbon; CaCO$_3$ – calcium carbonite. Coarse material > 2 mm; Sand 2–0.063 mm; Silt 0.063–0.002 mm; Clay < 0.002 mm.

Soil type	Coordinates		Annual rainfall	TOC	CaCO$_3$	pH	Coarse material	Grain size distribution		
	Latitude	Longitude						Clay	Silt	Sand
stagni-calcaric cambisol	48°07'02"N	15°09'00"E	700 mm	1.8 %	< 0.92 %	6.3	0.05 %	38.2 %	57.3 %	4.5 %

2.2 Experimental setup

The runoff experiments were carried out in two experimental sets, each comprising a full round of experiments (runoff and tracer measurements) on all six monoliths. During the first set, two flow pathways were recorded at the lower end of the monolith, the *surface runoff* (SRF) and *subsurface interflow* (INT). For the second set, we further sampled and distinguished

between *percolating water* that went through the whole soil body vertically (PER) and water that infiltrated into the soil body, but left the monolith again at the side due to *lateral flow* pathwayslaterally exported water (LAT).

90   The experimental setup consisted of an overflow tank, a steel frame that allowed the collection of surface water, and a horizontal plate inserted at the middle of the block to collect subsurface interflow., and fFor the second set also a bottom steel frame was used for the collection of percolating water and laterally exported waterlateral flow (Fig. 1). The frames were 2 cm smaller than the monoliths on each side, preventing both runoff water from being drained by a gap between the box and the monolith, and laterally exported waterlateral flow to flow get into the collector for percolating water. As a precautionary

95   measure, we sealed the potential space between the frame and the soil with a sodium silicate solution ("('water glass"';'; see Supplement B for preliminary experiments on applicability). The inclination slope was based on adjusted typical slopes of VFS in Austria and was adjusted to to 3 % during the first set and to 4 % during the second set.
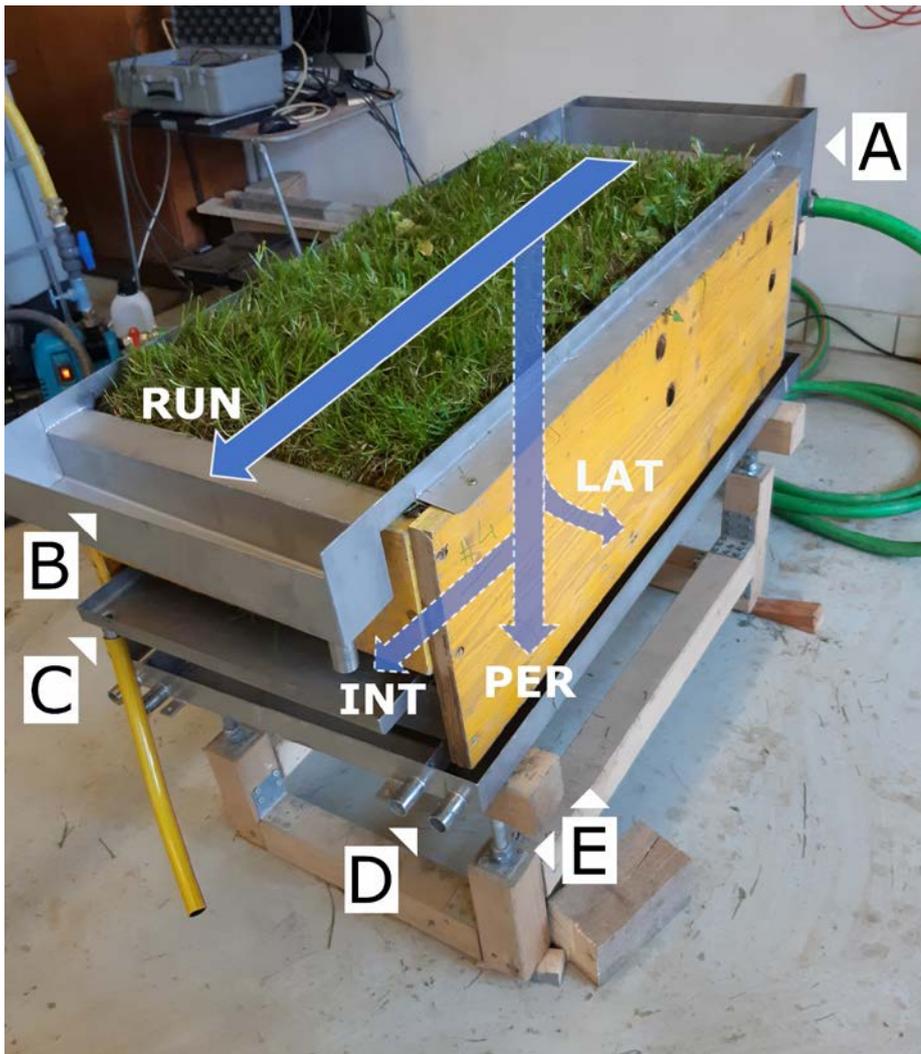
Fig. 1: Setup of runoff experiments with flow pathways (arrows). [A] Overflow tank; [B] metal frame with surface runoff (RUN) collector; [C] metal plate for subsurface interflow (INT) collection; [D] bottom frame with collectors for percolating water (PER; inner outlets) and ~~laterally exported water~~lateral flow (LAT; outer outlets); [E] rack with slope-adjustable gear.

Before each experiment, the monoliths were transferred to a water pool until fully saturated and then left to drain ~~dry~~ for 24 h to obtain comparable field capacity conditions for the soil water content (see Tiefenbacher et al., 2021). Each experimental set comprised three phases. During the first phase, an electric pump distributed runoff over the monolith through the overflow

105 tank. A constant flow of 5 l min^{-1} was applied using~~adjusted via~~ a valve and water meter. ~~We used d~~Deionized water spiked with ortho-phosphate (0.5 mg l^{-1}) was applied to mimic typical local agricultural runoff, as well as ~~and~~ bromide (~700 mg l^{-1}) as a conservative tracer. Outflow was collected and measured using buckets, which were exchanged every minute during the first ten minutes after the onset of an outflow and afterwards in increasing intervals. Additional samples were taken for chemical analysis after approximately 2, 5, 10, and 30 minutes. ~~Note that t~~The subsurface interflow was very low; as the

110 chemical analyses required a minimum amount of water, taking samples often took substantially longer than the one-minute interval, and not all samples could have been taken. The second phase started after 45 minutes and lasted for approximately 15 minutes, during which surface flow velocity (cm s^{-1}) measurements were carried out in three replicates for each monolith. For this, 10 ml of a potassium chloride solution (7.455 g KCl l^{-1}; 12,900 µS) ~~were~~ was applied at the upper end of the monolith, and the conductivity at the overflow tank (baseline value) and in the surface runoff collector was monitored (see Supplement

115 C for details). In the last phase, the monoliths were flushed with deionized water for 60 minutes to remove physically retained chemicals.

2.3 Chemical & statistical analysis

Water samples were analyzed for bromide and phosphate concentration. Bromide was determined by ion chromatography, soluble ortho-phosphate was determined photometrically, following national standards.

120 ~~We conducted n~~Non-parametric Kruskal-Wallis tests on the sum of outflow values were conducted to check for statistically significant differences between treatments. Bonferroni-adjusted Dunn's post-hoc tests were used to localize significant differences between individual monoliths. ~~We used the quotient of outflow (of the respective flow pathway) to actual inflow, termed standardized outflow, t~~To account for slightly different inflow rates between monoliths, a standardized outflow value was calculated, by dividing the measured outflow rate at a flow pathway by the actual inflow rate. For the statistics and

125 boxplots, ~~we calculated~~ discharge values for each flow pathway for every minute were calculated from the raw data and only ~~used~~ values between minutes 5 and 45 were used to eliminate the initial phase where flow rates were not yet stable. For the tracer experiments, ~~we calculated~~ the velocity of the leading edge and the centroid, were calculated following Abrantes et al. (2018). Figure generation and statistical testing were carried out using Python 3.9.12 embedded in Spyder 5.1.5 environment. Libraries used were *scipy*, *scikit_posthoc* (statistics), *matplotlib*, *seaborn* (figures), *numpy* and *pandas* (data handling).

130 Statistical significance was set at the α = 0.05 level.

3 Results

Here, we only report results from the second experimental set. Details on the first set can be found in Supplement D, but are referred to when deemed appropriate.

3.1 Water flow

135 Generally, surface runoff ~~(SRF)~~, percolating water ~~(PER)~~, and ~~laterally exported water~~lateral flow ~~(LAT)~~ responded quickly to the runoff application; the time until an outflow was recorded was commonly around one minute. Both treatments had a similar beginning of ~~SRF~~surface runoff outflow at around 69 s, but re-combined blocks had a 38 s earlier onset of lateral flow ~~re-combined blocks~~and 35 s later onset ~~showed an earlier onset of LAT and a later record~~ of ~~PER~~percolating water on average. Subsurface interflow ~~(INT)~~ was always the latest to start (Tab. 2).

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Table 2: Results of outflow measurements. Time to runoff gives the time until a runoff was recorded for the respective flow pathway. Share of total water exports gives the percentage that each flow pathway contributes to the total outflow from a monolith. Total water budget is the difference between the applied runoff and the sum of all outflow for each monolith **(i.e., a positive value means a net water uptake, negative values a net water release)****.**

Position	re-combined				uncut			
	#1	#3	#5	mean	#2	#4	#6	mean
Time to runoff [s]								
~~SRF~~surface runoff	63	88	55	68.7	80	60	67	69.0
~~INT~~subsurface interflow	420	200	-	310.0	267	-	910	588.5
~~PER~~percolating water	67	74	60	67.0	41	30	25	32.0
~~LAT~~lateral flow	50	64	40	51.3	74	124	69	89.0
Share of total water export [%]								
~~SRF~~surface runoff	86.4	82.6	74.0	81.0	66.9	89.4	69.4	76.9
~~INT~~subsurface interflow	< 0.1	0.2	0.0	0.1	0.1	0.0	0.1	< 0.1
~~PER~~percolating water	6.5	9.8	14.6	10.3	28.4	9.3	23.7	19.1
~~LAT~~lateral flow	7.1	7.4	11.4	8.6	4.6	1.3	6.8	3.9
Total water budget [%]								
	+0.77	-6.82	-9.49	-5.18	+9.12	-16.54	-5.21	-4.21

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Irrespective of treatment, ~~SRF~~surface runoff always contributed the most to total water outflow at each monolith, followed by ~~PER~~percolating water and ~~LAT~~lateral flow. Generally, ~~INT~~subsurface interflow was very low; the highest share was 0.4 %,

while two blocks had no subsurface outflow. ~~At re-combined monoliths,~~ ~~LAT~~lateral flow contributed more to total outflow ~~compared to~~than uncut blocks at re-combined monoliths (Tab. 2).

150 A similar overall picture was found for standardized outflow, with ~~SRF~~surface runoff having the highest outflow, followed by ~~PER~~percolating water, ~~LAT~~lateral flow, and ~~INT~~subsurface interflow (Fig. 2). No significant differences between re-combined and uncut blocks were found for ~~SRF~~surface runoff (H = 0.43, P = 0.51) and ~~PER~~percolating water (H = 2.33, P = 0.13). ~~LAT~~lateral flow was slightly below statistical significance (H = 3.86, P = 0.049) and tended to have a higher outflow (Fig. 2). However, there is an overlap of re-combined and uncut blocks, and post-hoc tests revealed high heterogeneity in the data~~:~~.

155 ~~Significant~~ significant differences between blocks of the same treatment and, *vice versa*, insignificant differences between blocks of different treatments were found for ~~LAT~~lateral flow and all other flow pathways (Supplement E). Statistical testing was not feasible for ~~INT~~subsurface interflow, due to monoliths with zero outflow. Uncut blocks exhibited substantially higher within-group variances for ~~SRF~~surface runoff and ~~LAT~~lateral flow.

Four of the six monoliths had a higher water uptake than outflow, but no trend between re-combined and uncut blocks was 160 discernible, again due to substantial inner-group variation (Tab. 2).

3.2 Bromide and phosphate

Bromide concentration in the outflow increased with time, approaching 100 % of inflow concentrations. Some blocks also showed bromide concentrations slightly higher than 100 % (Supplement F). Bromide concentrations were high right from the first measurements (i.e., two minutes after the onset of outflow), irrespective of the flow pathway. ~~Lowest~~ The lowest initial 165 bromide concentration was 77 % of inflow bromide concentration (block #2, ~~LAT~~lateral flow); the highest initial concentrations were 98 % (block #5, ~~LAT~~lateral flow) and 99 % (block #1, ~~SRF~~surface runoff). There was a tendency that phosphate concentrations in the outflow decreased with time when they were initially higher than the inflow phosphate concentration, as well as a tendency to increase when they were lower; in both cases approaching 100 % of the inflow phosphate concentration. Phosphate enrichment in the outflow was substantial, with up to more than twice the inflow concentration for 170 particular samples (Supplement F). No directional difference between re-combined and uncut monoliths was found for neither bromide nor phosphate concentration.

3.3 Salt tracer

Although some blocks showed reasonably consistent results in the tracer experiment (e.g., blocks #2-4), there was also substantial inner-block (replicates) and inner-group (treatment) variation (Fig. 3). Consequently, there is much overlap and no 175 directional difference identified between re-combined and uncut monoliths regarding leading-edge or centroid velocity (Supplement G).
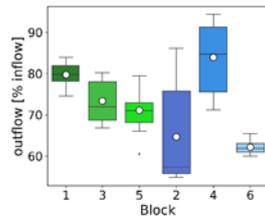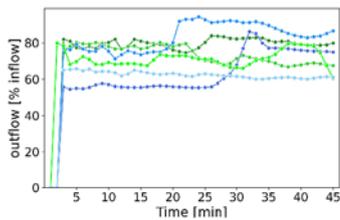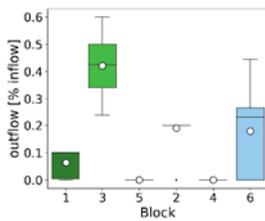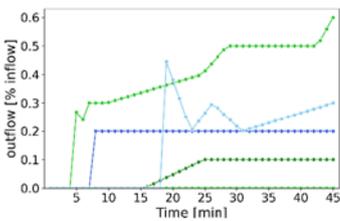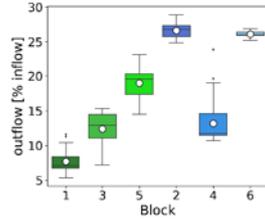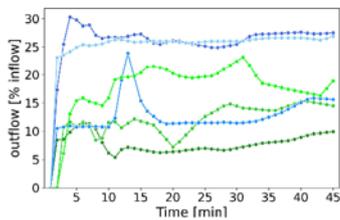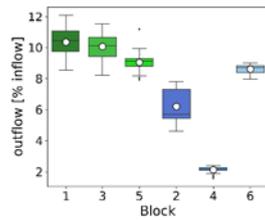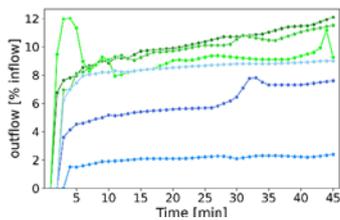
Fig. 2: Outflow rate at the respective flow paths. Green – re-combined blocks, blue – uncut blocks. Different shades denote different blocks. Note that boxplots integrate over minutes 5 to 45. White circles – mean; black line – median; box – 25-75 percentiles; whiskers – 5-95 percentiles; diamonds – outliers.

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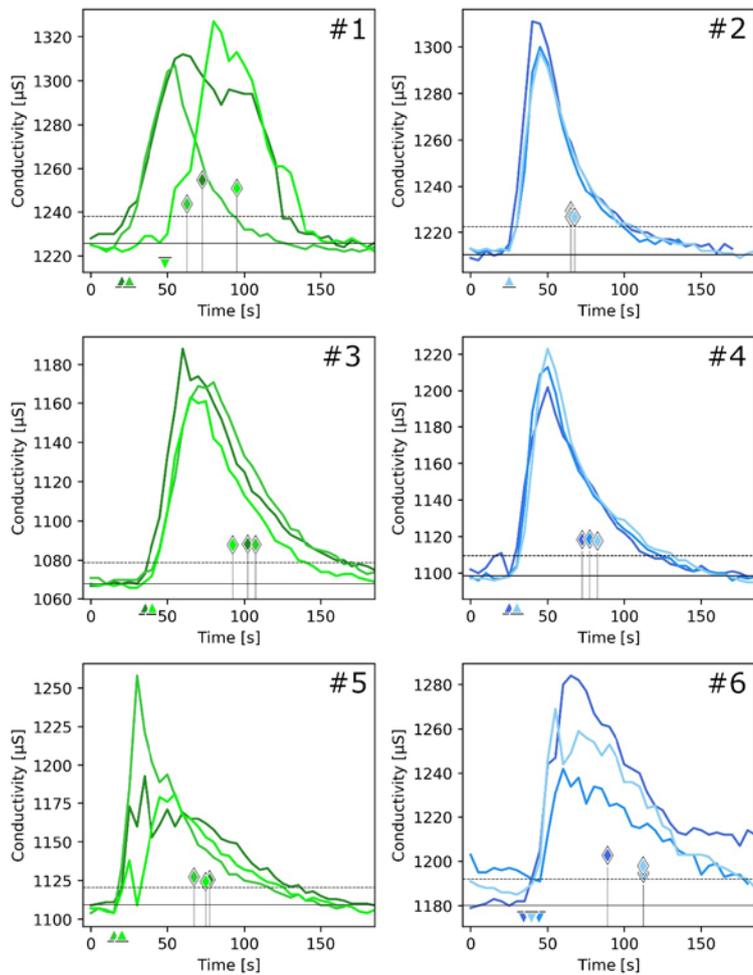
Fig. 3: Amplitude passage of salt tracer experiments. Green – re-combined blocks, blue – uncut blocks. Different shades indicate different replicate trials (1-3). Triangles denote timepoint of leading-edge passage; diamonds denote centroids. Black line – quiescent value; dashed line – threshold for leading-edge (see Supplement C for details).

4 Discussion

4.1 General remarks ~~on indoor runoff experiments~~

For a successful combination, the single blocks must be of equal width and height. While the sampling device usually fixes the width, acquiring similar heights may be more difficult. Uneven soil surfaces produce small barriers or ridges when
190 monoliths are combined, which can interfere with runoff patterns. Furthermore, monoliths will have different heights at the front and back end if they are not taken at a right angle to the soil slope. Some adjustments can be made in the laboratory (e.g., different bottom plates to even height differences). Nevertheless, we strongly advise avoiding such issues in the first place by an *a priori* assessment of site conditions and careful sampling. This also includes a sampling design that allows the extraction of monoliths close to one another, limiting the effects of more significant scale gradients.

195 In principle, we expect the combination method to apply to a large variety of soil types, but we cannot yet provide textural limits. However, combining two soil blocks requires removing the bordering at one side. Thus, structurally weak soils that could collapse without a frame are not suitable for this method.

We recommend that soil monoliths are kept outside in a sheltered but sunny location. Blocks need to be watered regularly for plant vitality and to avoid drying ~~up~~and an emergence of cracks in the soil structure that would affect runoff properties and
200 impede the repair of the combined monoliths (Bottinelli et al., 2016; Pires et al., 2007). ~~a~~As the blocks are isolated, they are much more prone to detrimental effects than they would be *in situ*. In practice, ~~this~~ maintenance can be challenging, for instance over weekends when the workshop or laboratory is vacant. As a general rule, a management plan becomes essential for experimental success if the monoliths are to be kept over a more extended period of time.

Another issue that concerns runoff experiments is the sealing of the soil body. Commonly, the gap between the soil monolith
205 and the box or lysimeter wall is filled using resins, bentonite clay, foams, or other materials. The primary reason for this is to avoid ~~that~~ water ~~is~~ being drained via the gap and, thus, does not interact with the soil body (Singh et al., 2018). By filling the gap, the monolith is laterally sealed. ~~In a natural system, a given volume of soil would exchange water with the surrounding soil through the matrix and macropore flow (Beven and Germann, 1982, 2013). In a (more or less) homogeneous environment, lateral water imports and exports from macropore flow would be roughly the same, while the matrix flow would be~~
210 ~~predominately vertical as the surrounding soil would have the same amount of soil moisture. In a sealed soil monolith, water that macropores would have laterally exported is kept within the soil body while matrix flow is also directed vertically. Therefore, one could argue that sealing is necessary to approximate the water budget of a natural system.~~ In our study, we did not seal the gap between the box and the soil for two reasons: Firstly, a direct drainage of water via the gap is already impeded by the frame which is smaller than the monolith and forces the runoff to flow over – and into – the soil. Secondly, we aimed
215 to mimic a vegetated filter strip (VFS). ~~Despite still prevailing assumptions of runoff occurring as uniform sheet flow, it is, in fact, much more~~ It is likely that the runoff enters a VFS in concentrated form due to flow convergence (Pankau et al., 2012; Ramler et al., 2022). In this scenario, only the VFS soil under the concentrated flow would receive runoff water, which could

then infiltrate into the soil and be laterally exported. In turn, this part of the soil would receive less water from the surrounding soil, which intercepts rain but no runoff water. Accordingly, we propose that this approach provides better conditions for our specific aims. We suggest that future runoff studies ponder whether sealing is appropriate or necessary.

4.2 Combining soil blocks

Generally, our main hypothesis that combining monoliths has no directional effect on the runoff properties was supported. Nevertheless, there was a trend of higher ~~LAT~~lateral -outflow at re-combined blocks, accompanied by a faster onset of ~~LAT~~lateral flow and a later onset of ~~PER~~percolating water. It appears that the re-combination procedure favours ~~LAT~~lateral flow and restricts ~~PER~~percolating water outflow. ~~However, w~~We speculated that a potential difference between treatments would be caused by the contact area between two blocks functioning as an extensive macropore. This would promote preferential flow and quick drainage, leading to a higher amount of percolating water and ~~laterally exported water~~lateral flow at the expense of surface runoff – which was not the case. One explanation for the higher share of ~~laterally exported water~~lateral flow found for re-combined monoliths would be macropores in the upper half of the contact area and a less permeable lower section which would cause the macropore flow to be diverted sideways. Although this cannot be ruled out, we argue that it is not very probable that this happened.

Furthermore, there is no indication to reject the other hypotheses: The re-combined blocks neither showed a faster rise of bromide concentrations nor a slower surface runoff velocity. ~~Instead, we~~We suspect that the observed differences ~~are~~ were caused by a generally high heterogeneity of the soils, low sample size (n=3), and stochastic effects, e.g., the amount and orientation of macropores such as earthworm channels. For most variables, there was also substantial inter-group overlap and considerable within-group – and in some cases also within-block – variation. ~~Moreover, there was an overlap of standardized outflow values of at least one block from each treatment for all flow pathways. Accordingly, we suggest that the re-combination procedure did not lead to directional differences and, thus, had no adverse effect on runoff properties.~~
~~Furthermore, there is no indication to reject the other hypotheses: The re-combined blocks neither showed a faster rise of bromide concentrations nor a slower surface runoff velocity. For most variables, there was a substantial inter-group overlap and considerable within-group – and in some cases also within-block – variation. Again, this points to a generally high soil heterogeneity, even though all monoliths were taken in close proximity at the same site.~~ Moreover, the water budget of the monoliths and the results from the first experimental set (and partly from the water glass trials) provide similar results ~~; high variation in the data and no directional differences between treatments~~ (Supplement B+D). The direct comparison of both experimental sets further highlights the heterogeneity within the same monolith soil and the influence of repeated experimental procedures (Darch et al., 2015; Sharpley, 1997). However, this is not a peculiarity of our experiments but rather a common issue in soil research (Luk and Morgan, 1981). Sources of this natural variability of the soil are manifold, including vegetation patterns, edaphon activity, (micro-)relief, soil aggregation, and their often complex interactions with runoff (Boix-Fayos et al., 2006; Bryan and Luk, 1981). Furthermore, there may be anthropogenic impacts before, during, and after the monolith

250 collection (Luk and Morgan, 1981; Rüttimann et al., 1995). The inherent variability ~~that~~ can only be compensated by increasing the sampling size to average the effects of micro-scale differences in the soil samples (Boix-Fayos et al., 2006; Bryan and Luk, 1981). Nevertheless, this also ~~means~~ implies that the data noise ~~potentially~~ added by the (re-)combination procedure is ~~probably~~ negligible~~.~~, We conclude that the re-combination procedure did not lead to directional differences and, thus, had no adverse effect on runoff properties, suggesting that combining two (~~or~~ and probably more) blocks is a viable and practicable way to

255 obtain single larger soil monoliths. ~~Accordingly, we suggest that the re-combination procedure did not lead to directional differences and, thus, had no adverse effect on runoff properties.~~

Irrespective of treatment, all flow pathways (except the subsurface interflow) had a rapid onset of outflow, commonly around one minute after the start of the experiments, which ~~. This~~ can only be achieved through preferential macropore flow for the percolating water and ~~laterally exported water~~ lateral flow. This is further backed up by the high amounts of bromide and

260 phosphate already in the first samples (taken after appr. 2 min), which shows that the emerging water originated primarily from the applied runoff and not from the water retained in the soil. As a side note, the enrichment of phosphate found for some blocks also demonstrates that VFS surface- and subsoils can switch from phosphorous sinks to sources (Andersson et al., 2015; Reid et al., 2018).

~~After the first set, we were concerned that the high share of percolating water would be due to a flawed setup, causing~~
265 ~~substantial amounts of water to leak from the system. To this end, we began to apply water glass to the contact areas of the metal frame and the soil and attached an additional metal frame at the bottom to distinguish between actual percolating water and laterally exported water. However, we still recorded a high share of percolating water (between 8 and 27 %) during the second set. Due to the setup, water collected as percolating water must have necessarily travelled through the whole soil body vertically — most probably via macropores — and cannot originate from outside.~~ To ~~shed further light on this issue~~ examine the
270 effect of macropores in more detail, we replaced the plywood walls of one box with transparent polycarbonate panes for an additional preliminary trial. ~~We did not conduct a proper runoff experiment as during the first and second set, still, i~~It ~~quickly became~~ was apparent that most ~~laterally exported water~~ lateral flow outflow was restricted to specific outlets, i.e., through macropore channels that originate within the soil body and lead to the monolith edge (Video 1). Analogously, the same applies to percolating water.

275 ~~During the first set, the amount of percolating water was high and the onset of outflow was quick. Therefore, the macropores were not caused by drying or re-wetting processes.~~ It is possible, ~~though,~~ that the soil texture was affected by transport and handling~~. Nevertheless,~~, though we argue that the macropores have already been present *in situ*, e.g., amongst others, through a high activity of the soil fauna, as is characteristic for grassland soils (Lamandé et al., 2011; Menta, 2012). Active earthworms were continuously encountered throughout the experiment and were still found nine months after sampling. Wormholes play

280 an essential role in infiltration and can constitute a large share of the macropores within a soil, potentially generating a channel network with high flow rates (Roth and Joschko, 1991; Weiler and Naef, 2003). Furthermore, the collapse or sealing and, *vice versa*, the breakthrough and connection of earthworm channels (and other macropores; Jégou et al., 2002) may explain abrupt changes in outflow seen in some of the blocks (Fig. 2).

After the last experimental set, we left the monoliths without maintenance ~~before they were discarded~~, which caused them to dry up completely. Thereby, the re-combined monoliths cracked at the contact areas and developed a gap, exemplifying that a complete consolidation (i.e., repair) did not happen. A proper merging of individual blocks into a single monolith is probably impossible to achieve ~~in the laboratory~~, given the short ~~. However, this was not expected, as the~~ duration of the experiment – ~~although stretching over several weeks – was too short~~ in relation to the bio-geochemical processes that govern soil development (Pires et al., 2007; Sarmah et al., 1996). Nevertheless, we argue that such a high level of 'naturalness' is not necessary for runoff experiments; instead, it is sufficient that the combination procedure generates more advantages (e.g., better representativity of processes) than disadvantages (e.g., added data noise). ~~Consequently, the contact areas remain a determined breaking point for drying~~Experiments, however, should not be conducted under dry soil conditions. ~~A proper merging of individual blocks into a single monolith is probably impossible to achieve in the laboratory. However, we argue that such a high level of 'naturalness' is not necessary for the purpose of runoff experiments; instead, it is sufficient that the combination procedure generates more advantages (e.g., better representativity of processes) than disadvantages (e.g., added data noise)..~~

We used a comprehensive approach, analysing runoff characteristics, chemical loadings, and flow velocity and are, thus, confident in our conclusions. Nevertheless, there is room for further research, for instance applying different boundary and initial conditions, such as other soil types and flow rates, or a higher sample size and number of blocks to be combined. A comparison of large monoliths taken with heavy machinery with blocks of similar extent that are made up of combined smaller monoliths would be very interesting.

5 Conclusion

Working with undisturbed soil monoliths can be challenging and is always a compromise between available resources and sampling effort (e.g., sampling size, replicates, monolith dimensions). Combining medium-sized monoliths can help ~~to~~ maximize the representativity and upscaling potential of experiments, while minimizing financial and labour efforts. There are, however, some aspects that have to be considered. Individual blocks need to be of equal width and height. Furthermore, ~~p~~Proper storage and maintenance, especially regular watering, are crucial to keeping the monoliths in good condition and are, in turn, dependent on the research aim, the duration of the experiment, climate, and resources (e.g., staff, storage space). It is also important that the experimental setup matches the natural hydrological environment of the soil under investigation. In this study, for instance, we refrained from sealing the gap between the soil and box to mimic a grassland soil under concentrated flow (i.e., a vegetated filter strip).

We found general support for our initial hypotheses, as we have no indication that combining two soil monoliths has a directional effect on runoff properties. The observed differences between re-combined and uncut blocks were against expectations and lacked a clear explanation. We conclude that the inherent heterogeneity of the soils – even if from the same site – is substantially more considerable and overlays any effect ~~that~~ of the combination procedure ~~may have~~. Accordingly, the

advantages outweigh the possible adverse effects, and we recommend ~~the use of combined~~combining monoliths for indoor runoff studies and related research. Nevertheless, we encourage further research on this subject to better delimit the potential and possible limitations of this procedure, ~~e.g.,~~for instance using different experimental setups (e.g., number of monoliths), boundary conditions (e.g., flow rates, soil types, dimensions), or analysis methods (e.g., X-ray imaging). ~~(Bottinelli et al.,~~
320 ~~2016).~~

Code and data availability. The original contributions presented in the study are included in the article and Supplement; raw data and codes are available upon reasonable request from the corresponding author.

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Supplement.

Author contributions. DR and PS designed the study. DR conducted the experiments, analyzed the data and took the lead in writing and overall organization of the manuscript. All authors contributed to manuscript revision and read and approved the
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Competing interests. The authors declare that they have no conflict of interest.

Disclaimer.

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Review statement.

References

Abrantes, J. R. C. B., Moruzzi, R. B., Silveira, A. and de Lima, J. L. M. P.: Comparison of thermal, salt and dye tracing to
345 estimate   shallow   flow   velocities: Novel   triple-tracer   approach,   J.   Hydrol.,   557,   362–377, doi:https://doi.org/10.1016/j.jhydrol.2017.12.048, 2018.

Allaire, S. A. and van Bochove, E.: Collecting large soil monoliths, Can. J. Soil Sci., 86(5), 885–896, doi:10.4141/S05-062,

2006.

Andersson, H., Bergström, L., Ulén, B., Djodjic, F. and Kirchmann, H.: The Role of Subsoil as a Source or Sink for Phosphorus

350   Leaching, J. Environ. Qual., 44(2), 535–544, doi:https://doi.org/10.2134/jeq2014.04.0186, 2015.

Belford, R. K.: Collection and evaluation of large soil monoliths for soil and crop studies, J. Soil Sci., 30(2), 363–373, doi:https://doi.org/10.1111/j.1365-2389.1979.tb00993.x, 1979.

Beven, K. and Germann, P.: Macropores and water flow in soils, Water Resour. Res., 18(5), 1311–1325, doi:https://doi.org/10.1029/WR018i005p01311, 1982.

355   Beven, K. and Germann, P.: Macropores and water flow in soils revisited, Water Resour. Res., 49(6), 3071–3092, doi:https://doi.org/10.1002/wrcr.20156, 2013.

Boix-Fayos, C., Martínez-Mena, M., Arnau-Rosalén, E., Calvo-Cases, A., Castillo, V. and Albaladejo, J.: Measuring soil erosion by field plots: Understanding the sources of variation, Earth-Science Rev., 78(3), 267–285, doi:https://doi.org/10.1016/j.earscirev.2006.05.005, 2006.

360   Bottinelli, N., Zhou, H., Boivin, P., Zhang, Z. B., Jouquet, P., Hartmann, C. and Peng, X.: Macropores generated during shrinkage in two paddy soils using X-ray micro-computed tomography, Geoderma, 265, 78–86, doi:https://doi.org/10.1016/j.geoderma.2015.11.011, 2016.

Bryan, R. B. and Luk, S.-H.: Laboratory experiments on the variation of soil erosion under simulated rainfall, Geoderma, 26(4), 245–265, doi:https://doi.org/10.1016/0016-7061(81)90023-9, 1981.

365   Darch, T., Carswell, A., Blackwell, M. S. A., Hawkins, J. M. B., Haygarth, P. M. and Chadwick, D.: Dissolved Phosphorus Retention in Buffer Strips: Influence of Slope and Soil Type, J. Environ. Qual., 44(4), 1216–1224, doi:https://doi.org/10.2134/jeq2014.10.0440, 2015.

Douglas, J. T., Ritchie, R. M., Takken, I., Crawford, C. E. and Henshall, J. K.: Large Intact Soil Slabs for studying the Effects of   Soil   and   Plant   Properties   on   Surface   Runoff,   J.   Agric.   Eng.   Res.,   73(4),   395–401,

370   doi:https://doi.org/10.1006/jaer.1999.0433, 1999.

Green, D. L.: Modelling Geomorphic Systems: Scaled Physical Models, in Geomorphological Techniques, edited by S. J. Cook, L. E. Clarke, and J. M. Nield, pp. 1–17, Britisch Society for Geomorphology, London, UK., 2014.

Jégou, D., Brunotte, J., Rogasik, H., Capowiez, Y., Diestel, H., Schrader, S. and Cluzeau, D.: Impact of soil compaction on earthworm burrow systems using X-ray computed tomography: preliminary study, Eur. J. Soil Biol., 38(3), 329–336,

375   doi:https://doi.org/10.1016/S1164-5563(02)01148-2, 2002.

Johnson, D. W., Walker, R. F. and Ball, J. T.: Lessons from Lysimeters: Soil N Release from Disturbance Compromises Controlled Environment Study, Ecol. Appl., 5(2), 395–400, doi:https://doi.org/10.2307/1942030, 1995.

Katagi, T.: Soil Column Leaching of Pesticides, in Reviews of Environmental Contamination and Toxicology Volume 221, edited by D. M. Whitacre, pp. 1–105, Springer, New York, NY., 2013.

380   Kuhn, N. J., Greenwood, P. and Fister, W.: Chapter 5.1 - Use of Field Experiments in Soil Erosion Research, vol. 18, edited by M. J. Thornbush, C. D. Allen, and F. A. B. T.-D. in E. S. P. Fitzpatrick, pp. 175–200, Elsevier., 2014.

Lamandé, M., Labouriau, R., Holmstrup, M., Torp, S. B., Greve, M. H., Heckrath, G., Iversen, B. V, de Jonge, L. W., Moldrup, P. and Jacobsen, O. H.: Density of macropores as related to soil and earthworm community parameters in cultivated grasslands, Geoderma, 162(3), 319–326, doi:https://doi.org/10.1016/j.geoderma.2011.03.004, 2011.

385   Lewis, J. and Sjöstrom, J.: Optimizing the experimental design of soil columns in saturated and unsaturated transport experiments, J. Contam. Hydrol., 115(1), 1–13, doi:https://doi.org/10.1016/j.jconhyd.2010.04.001, 2010.

Luk, S. and Morgan, C.: Spatial variations of rainwash and runoff within apparently homogeneous areas, CATENA, 8(1), 383–402, doi:https://doi.org/10.1016/S0341-8162(81)80025-2, 1981.

Menta, C.: Soil Fauna Diversity - Function, Soil Degradation, Biological Indices, Soil Restoration, in Biodiversity
390   Conservation and Utilization in a Diverse World, edited by G. A. Lameed, IntechOpen, London, UK., 2012.

Palmer, R. E., Meisinger, J. J. and Magette, W. L.: Undisturbed Soil-Columns for Lysimetry: I. Collection, Field Testing, and Construction, Appl. Eng. Agric., 27(3), 379–389, doi:https://doi.org/10.13031/2013.37073, 2011.

Pankau, R. C., Schoonover, J. E., Williard, K. W. J. and Edwards, P. J.: Concentrated flow paths in riparian buffer zones of southern Illinois, Agrofor. Syst., 84(2), 191–205, doi:10.1007/s10457-011-9457-5, 2012.

395   Pires, L. F., Bacchi, O. O. S. and Reichardt, K.: Assessment of soil structure repair due to wetting and drying cycles through 2D tomographic image analysis, Soil Tillage Res., 94(2), 537–545, doi:https://doi.org/10.1016/j.still.2006.10.008, 2007.

Poorter, H., Fiorani, F., Pieruschka, R., Wojciechowski, T., van der Putten, W. H., Kleyer, M., Schurr, U. and Postma, J.: Pampered inside, pestered outside? Differences and similarities between plants growing in controlled conditions and in the field, New Phytol., 212(4), 838–855, doi:https://doi.org/10.1111/nph.14243, 2016.

400   Prosser, R. S., Hoekstra, P. F., Gene, S., Truman, C., White, M. and Hanson, M. L.: A review of the effectiveness of vegetated buffers to mitigate pesticide and nutrient transport into surface waters from agricultural areas, J. Environ. Manage., 261, 110210, doi:https://doi.org/10.1016/j.jenvman.2020.110210, 2020.

Ramler, D., Stutter, M., Weigelhofer, G., Quinton, J. N., Hood-Nowotny, R. and Strauss, P.: Keeping Up with Phosphorus Dynamics: Overdue Conceptual Changes in Vegetative Filter Strip Research and Management, Front. Environ. Sci., 10, 1–8,
405   doi:10.3389/fenvs.2022.764333, 2022.

Reid, K., Schneider, K. and McConkey, B.: Components of Phosphorus Loss From Agricultural Landscapes, and How to Incorporate Them Into Risk Assessment Tools   , Front. Earth Sci.   , 6, 135 [online] Available from: https://www.frontiersin.org/article/10.3389/feart.2018.00135, 2018.

Roth, C. H. and Joschko, M.: A note on the reduction of runoff from crusted soils by earthworm burrows and artificial channels,
410   Zeitschrift für Pflanzenernährung und Bodenkd., 154(2), 101–105, doi:https://doi.org/10.1002/jpln.19911540205, 1991.

Rüttimann, M., Schaub, D., Prasuhn, V. and Rüegg, W.: Measurement of runoff and soil erosion on regularly cultivated fields in Switzerland — some critical considerations, CATENA, 25(1), 127–139, doi:https://doi.org/10.1016/0341-8162(95)00005-D, 1995.

Sarmah, A. K., Pillai-McGarry, U. and McGarry, D.: Repair of the structure of a compacted Vertisol via wet/dry cycles, Soil
415   Tillage Res., 38(1), 17–33, doi:https://doi.org/10.1016/0167-1987(96)01018-5, 1996.

Schneider, A. D., Marek, T. H., Ebeling, L. L., Howell, T. A. and Steiner, J. L.: Hydraulic Pulldown Procedure for Collecting Large Soil Monoliths, Trans. ASAE, 31(4), 1092–1097, doi:https://doi.org/10.13031/2013.30828, 1988.

Sharpley, A. N.: Rainfall Frequency and Nitrogen and Phosphorus Runoff from Soil Amended with Poultry Litter, J. Environ. Qual., 26(4), 1127–1132, doi:10.2134/jeq1997.00472425002600040026x, 1997.

420 Singh, G., Kaur, G., Williard, K., Schoonover, J. and Kang, J.: Monitoring of Water and Solute Transport in the Vadose Zone: A Review, Vadose Zo. J., 17(1), 160058, doi:https://doi.org/10.2136/vzj2016.07.0058, 2018.

Tiefenbacher, A., Weigelhofer, G., Klik, A., Mabit, L., Santner, J., Wenzel, W. and Strauss, P.: Antecedent soil moisture and rain intensity control pathways and quality of organic carbon exports from arable land, CATENA, 202, 105297, doi:https://doi.org/10.1016/j.catena.2021.105297, 2021.

425 Weiler, M. and Naef, F.: An experimental tracer study of the role of macropores in infiltration in grassland soils, Hydrol. Process., 17(2), 477–493, doi:https://doi.org/10.1002/hyp.1136, 2003.