



# Modeling soil erosion after mechanized logging operations on steep terrain in the Northern Black Forest, Germany

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Received: 29 June 2018 / Revised: 19 December 2019 / Accepted: 13 February 2020 / Published online: 11 March 2020  
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## Abstract

Climate change makes it necessary to re-evaluate the erosion potential of forest infrastructure. We used the Forest Service WEPP interfaces (FS WEPP) to compare soil erosion potentials of two competing logging practices in steep terrain in the Northern Black Forest, Germany: (1) Felling with harvesters and logging with forwarders in slope line with optional traction supporting winches. (2) Felling by chainsaw, logging with a cable winch, and further transport of logs via forest dirt roads. After forest harvest we measured erosion, runoff, and DOC concentration in runoff from 50 m sections of two machine tracks, two cable tracks, and a dirt road for 2 years. The erosion measurements were used to validate FS WEPP management options and a regionally adjusted CLIGEN input file. With these parameterizations we compared the erosion potential of the two practices on subcatchment scale by modeling return periods and total sediment export with FS WEPP. Model results show that logging operations with heavy machinery in slope line are less prone to soil erosion than logging operations including winch logging and additional dirt roads. The former produces less sediment in its worst-case configuration than the latter in its most moderate configuration by a factor of two. Model results also show that erosion prevention benefits from long periods of 10 years between two harvests.

**Keywords** Erosion · Logging · WEPP

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Communicated by Eric R. Labelle.

The project was funded by the Landesgraduiertenförderung Baden-Württemberg (LGFG, state graduate funding) and the Gesellschaft zur Förderung der forst- und holzwirtschaftlichen Forschung an der Universität Freiburg e.V. (GFH). Study sites were chosen in cooperation with the state's forest authorities of Baden-Württemberg (ForstBW) to represent an area where standard infrastructure measures for logging operations in steep terrain prone to erosion occur. Our gratitude to staff from Forst BW Maschinenhof Schrofel in Klosterreichenbach for providing expertise, machinery, and manpower for the logging experiments. Data sets were provided courtesy of Deutscher Wetterdienst (DWD, German Meteorological Service) as part of their cooperation program with research and education. Please contact the corresponding author for original and altered CLIGEN parameter files.

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## Introduction

In European Forestry it is a common view that stable forest ecosystems are not prone to soil erosion (Borrelli et al 2016). Rain erosivities in Central Europe are low, and practices promoting erosion like clear cuttings or prescribed fires are rare. However, studies from North America have shown that up to 90% of sediment delivered from forested watersheds derive from logging infrastructure (Grace 2003; Basher et al 2011) such as machine tracks and skid-trails (Safari et al 2016) or unpaved roads (Ramos-Scharron and MacDonald 2005). In the context of climate change mitigation an intensification of use of wood as energy source and construction material is suggested (Abbas and Handler 2018). This causes a higher pressure to expand wood harvest into less used sites in steep terrain. Together with an expected rise in erosive precipitation events, as observed, e.g., in Southern Germany (KLIWA 2016), those sites have a higher potential of erosion.

In German forestry two practices are most common in steep terrain of between 30 and 60% slope (Nemestothy 2014). The traditional technique includes felling of trees by chainsaw and dragging of logs out of the stand across cable

tracks with tractor-mounted cable winches. Logs are then transported by forwarders or skidders across gently sloped dirt roads built by bulldozers from parent material. In the following this entire practice is called winch logging.

More recent technological advances brought heavy machinery for cut-to-length logging like forest harvesters and forwarders into steep terrain operations (Thüringenforst 2008). For ergonomic and work safety reasons those machines work in slope line. The machines create their tracks themselves by cutting into the forest, making the dirt roads obsolete. Optionally the machines can be equipped with traction supporting winches (Visser and Stampfer 2015). These winches hold a steel cable which is strapped to an uphill tree before entering the machine track. The reeling speed of the traction winches is synchronized with the vehicle's wheel rotation. In case of traction loss the traction winch stabilizes the vehicles position and assists in continuing movement with further tractive power. This prevents wheel slippage which is considered a major cause for soil erosion (Schack-Kirchner et al 2012). In the following this practice, whether with traction winch or not, is called fully mechanized logging.

For further transport of wood out of the forest both practices use the existing system of paved or graveled forest roads. These surfaced roads are constructed parallel to contour lines and well equipped with sediment management measures like concrete crossdrains, sediment ditches or sufficient adjacent forest buffer for sediment deposition.

The two practices have different potential sources for soil erosion. Besides this there is an ongoing debate about the interval between harvests. Depending on age and growth of a stand harvest is planned once or twice per decade (Hochbichler et al 2015). Accordingly this results in periods for revegetation of tracks and roads of 5 or 10 years and affects the risk of erosion. Harvest options should be chosen based on data regarding their soil erosion potential. Until now only few experimental data are available to quantitatively evaluate different harvesting practices.

Besides, direct measurements of sediment yield evaluation should include modeling approaches, even more so in the prospect of a rise in erosive precipitation events. As modeling solution we deem the Water Erosion Prediction Project (WEPP, Flanagan and Nearing 1995) and especially the online available Forest Service WEPP Interfaces (FS WEPP, Elliot et al 2002) most feasible. Since WEPP version 2008.9 forest specific routines have been explicitly improved (Dun et al 2009). FS WEPP furthermore offers empirically pre-parametrized applications for standard problems in forestry, such as erosion from forest roads (module WEPP:Road) or from areas disturbed by skidding or forest fires (Disturbed WEPP). FS WEPP produces estimates for soil erosion and deposition along a given profile and for sediment leaving the profile helping

users to quickly assess changes in forest infrastructure or to dimension sediment retention capacities. FS WEPP output also includes calculation of return periods, meaning the magnitude of an event likely occurring, e.g., every 5, 10 or 100 years. As studies suggest that the first and second year after wood harvest are most critical to erosion (Phillips et al 2018), this feature is very valuable to forest professionals to assess the possible consequences of highly erosive events. While Larsen and MacDonald (2007) comments that Disturbed WEPP has become a widely accepted tool to model post-fire erosion, and FS WEPP has been rarely evaluated for application outside of the USA by the scientific community. However, we assume that soil, vegetation, and management routines and parameters of WEPP and FS WEPP are comparable to those found in Central Europe and can be fitted to meet situations found there.

WEPP comes equipped with a weather generator, CLIGEN (Nicks et al 1995). CLIGEN produces daily weather input to WEPP from long-term weather statistics. Developed in the USA, CLIGEN has received limited but positive evaluation around the world, such as in Australia (Yu et al 2000), Brazil (Favis-Mortlock and Guerra 1999), the UK (Brazier et al 2001), Korea (Kim et al 2009), and Taiwan (Fan et al 2013). Also discussed have been CLIGEN abilities to represent future climate change scenarios (Favis-Mortlock and Savabi 1996; Pruski and Nearing 2002; Yu 2005). However, in Haas et al (2018) we applied to CLIGEN a method presented by Yu (2002) and showed that it is not fully capable of modeling rain erosivity in the Northern Black Forest, Germany. We assessed the sensitivity of CLIGEN input parameters and developed statistically sound input parameter sets for the study region.

In this study we aim to evaluate the potential of FS WEPP to estimate sediment delivery and runoff production from logging infrastructure used in the two standard harvesting practices described above. For this we scientifically accompanied logging operations in steep terrain in the Northern Black Forest, state of Baden-Württemberg, Germany. After logging operations we measured sediment, runoff and dissolved organic carbon (DOC) for 2 years on the scale of single tracks and roads. Sediment and runoff measurements were then remodeled in FS WEPP to validate FS WEPP pre-parameterizations for our site. As input to CLIGEN we use the original and slightly adjusted input files presented by Haas et al (2018). The questions we want to address here are:

1. Can FS WEPP be applied to model erosion measured after forest harvesting operations?
2. Can the quality of FS WEPP estimates compared to measurements be improved by using adjusted climate input data?

Given satisfactory model performance on this scale the two harvesting practices are evaluated against each other on the scale of the entire subcatchment, addressing the question:

3. Is logging infrastructure used in fully mechanized logging operations less prone to soil erosion than logging infrastructure used in cable winch logging operations?
4. Do harvest intervals of, e.g., 5 or 10 years significantly influence sediment delivery?

DOC has proven to be a parameter suitable to quantify the impact of different logging practices or intensities on catchment scale as samples are easy to obtain from surface water bodies (Kreutzweiser et al 2008; Loeftgren et al 2014). Detailed assessment of DOC in the context of different logging techniques on plot scale is rare but could bring valuable insights into the extent of contribution of DOC discharge from infrastructure to total catchment DOC discharge. Particularly for the dirt roads, where DOC-rich topsoil has been removed during construction and low DOC concentrations in surface runoff are likely, additional insights beyond soil erosion can be expected. We want to take the opportunity of having continuous measurements of DOC on the scale of single tracks and roads for 2 years and additionally address the question:

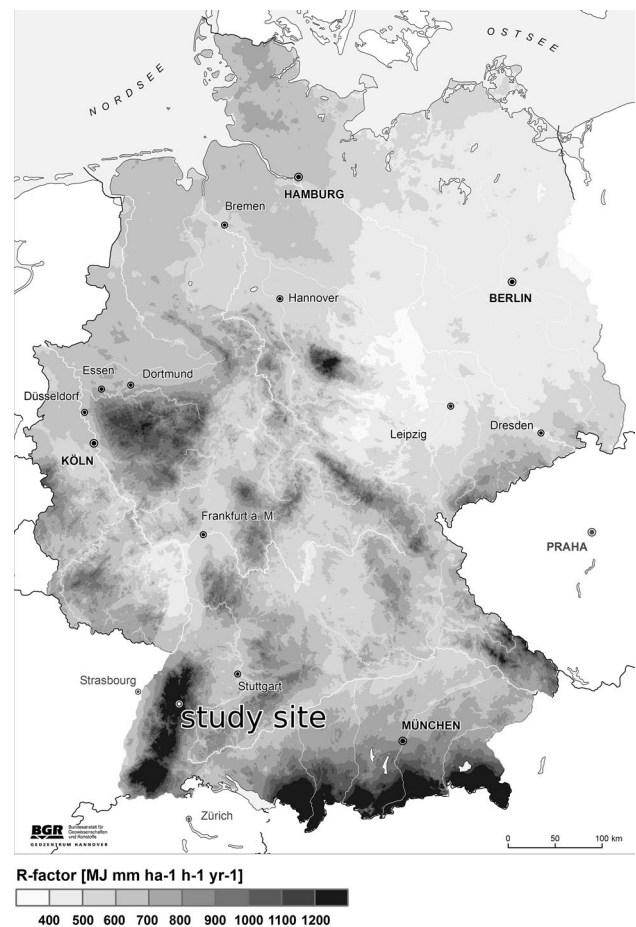
5. Can DOC in surface runoff from logging infrastructure help to quantify disturbances caused by the two logging practices?

## Material and methods

### Study site

The study site is located in the Northern Black Forest in south-western Germany at between 600 and 750 m ASL. The stand is a replanted long-rotation spruce stand on cambisols on Bunter sandstone (Gauer and Aldinger 2005) with sandy loam texture and 40% rock content. The stand was last harvested 8 years before the harvest presented in this study and was chosen in cooperation with state forest authorities from ForstBW as it best represents the situation in the region.

The climate of the region is Atlantic with annual precipitation sums locally exceeding 2000 mm (Gauer and Aldinger 2005). This leads to the highest rain erosivities in Germany outside of the Alps with  $1500 \text{ MJ ha}^{-1} \text{ mm h}^{-1}$ , expressed as R-factor from the Revised Universal Soil Loss Equation (RUSLE, Renard et al (1997), compare Fig. 1). Long-term mean annual precipitation at the climate station maintained by Deutscher Wetterdienst (DWD, German Meteorological Service) closest to our study site, Baiersbronn-Mitteltal



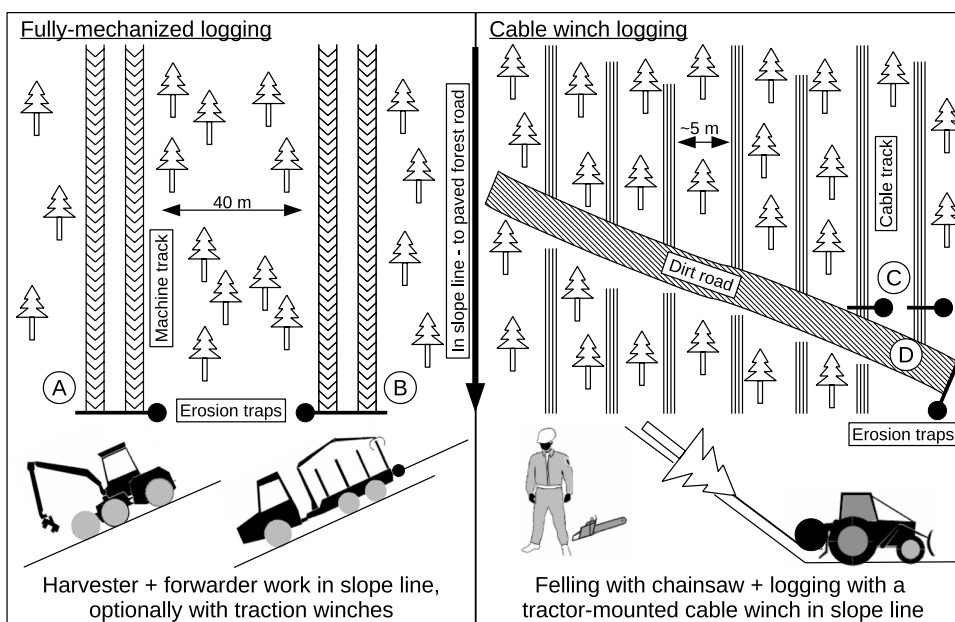
**Fig. 1** Map of the (R)USLE R-factor for rain erosivity in Germany (Kruse 2016). The study site in the Northern Black Forest lies within a region with the highest R-factors in Germany outside of the Alps

(BM, DWD station ID: Q522, 596 m ASL), was  $1750.9 \text{ mm}$  from 1981–2017. However, in Haas et al (2018) we calculated an R-factor of  $2025.4 \text{ MJ ha}^{-1} \text{ mm h}^{-1}$  from that precipitation, which is even higher than the regional estimates in Fig. 1.

### Logging experiments

For this study a harvesting operation in steep terrain in the beginning of May 2011 was accompanied scientifically and the two competing practices of fully mechanized logging and cable winch logging were analyzed (Figure 2). From an area of  $11.3 \text{ ha}$  a total of  $1000 \text{ m}^3$  wood was harvested, i.e.,  $88.5 \text{ m}^3 \text{ ha}^{-1}$ . By regulative order in the state of Baden-Württemberg machine tracks for fully mechanized logging have to be  $40 \text{ m}$  apart. To assess the harvest of  $1000 \text{ m}^3$  a total of 21 machine tracks were planned resulting in an average of  $50 \text{ m}^3$  per track, depending on track length. With the cable winch usually only 3–4 trees with 2–3  $\text{m}^3$  wood are transported on each cable track. Also, as the cable winches are limited in

**Fig. 2** Sketch of the two harvesting practices in steep slope compared in this study. Circled letters are the treatments outlined in Table 1. For cable winch logging additional dirt roads (D) are needed where tractors for winch logging and vehicles needed for further transport of logs stand and move. At the downhill end of treated tracks and roads equipment for sediment and runoff measurements (erosion traps) were installed. Machine symbols are modified from Thüringenforst (2008)



their range, additional dirt roads are needed here. These are constructed from parent material by bulldozers diagonally to slope line with slight slopes of 0-20%. The dirt roads divide the stand into smaller areas where cable tracks usually stay well below 100 m length. In our case this resulted in more than 300 cable tracks.

To evaluate the erosion potential of the two harvesting practices four treatments, which are part of the practices, were examined (Table 1): Passage of wheeled heavy machinery on a machine track in slope line (in the following treatment A) and passage of wheeled heavy machinery with traction support winches on a machine track in slope line (B) represent fully mechanized logging and were standardly applied in the entire harvesting operation at the site, anyway. To additionally evaluate cable winch logging at the same site a section of the site remained unharvested. There lumbermen felled four neighboring trees marked for harvest with chainsaws. Those trees were delimited and then dragged with a tractor-mounted cable winch to a

forest road, one after another along the same cable track (treatment C). To account for the additional forest dirt roads needed for cable winch logging a section of an old dirt road in the vicinity of the harvested stand was restored by a bulldozer to the state of a fresh dirt road in May 2012 as it is standard practice after logging operations (D). The wheeled bogies of the machines at treatment A & B were equipped with bogie tracks, which is a standard measure to gain additional traction in sloped terrain (Table 1).

Depending on the soil and soil surface disturbances caused by the treatments they differ in their potential to cause erosion (see Table 2).

For treatment A, B and C two repetitions were done, in the following called A1, A2, B3, B4, C5, and C6. For treatment D one repetition was done, in the following D7. To make sure that every machine track was exposed to the same stress the forwarder at treatment A and B passed the entire machine track with each passage, whether necessary or not.

**Table 1** Details to the four treatments. Machines in treatment A and B always passed the entire machine track, whether necessary or not. Load is sum of loaded wood from all passages. Width of a bogie track is 810 mm

Treat.	Machine	Empty mass (Mg)	Equipment	Passages	Load (Mg)
A&B	Harvester HSM 405H steep slope	20.5	Bogie tracks, traction winch (only B)	2	–
	Forwarder HSM 208F steep slope	19.2	Bogie tracks, traction winch (only B)	7	14
C	Forest tractor	–	Cable winch to drag logs to dirt roads or forest roads	4 trees per track	0.5–0.8 each
D	Dozer	–	Blade for dirt road maintenance	–	Previous traffic unknown



**Table 2** Sources for disturbances of soil and soil surface caused by the different treatments

Treat.	Disturbances
A & B	Both harvesters and forwarders cause continuously disturbed tracks oriented in slope line across entire harvested area. Machine tracks are potential sources for sediment and flow lines for runoff. Width of disturbances can potentially exceed tire or bogie track width as bulging also disturbs soil. Erosion can be promoted by wheel or bogie track slippage. In treatment B traction winches might reduce that. Disturbances are potentially reduced by slash mats. Erosion is potentially reduced by microrelief left by bogie tracks
C	Dragging of logs causes continuous disturbances in slope line. Dragged trees sometimes act like a plow. Cable tracks are potential sources for sediment and flow lines for runoff. Width of disturbance is significantly smaller than at treatments A & B. Also disturbed areas are not necessarily continuously connected as logs are sometimes lifted from the ground by obstacles
D	Dirt roads are made from compacted and bladed parent material. Disturbance is most severe. Disturbed areas are constantly around 4 m wide. Total length of disturbed area is significantly lower than with A, B & C and roads are only gently sloped. Road prism includes cut slope, road, ditch, and fill slope. Cut and fill slope revegetates quickly after construction, so main erosion happens from traveled road surfaces or after maintenance work. For ecological considerations, it is important that topsoil is usually moved to the fill slope during road construction. Eroded material hence predominately is subsoil material

During logging operations soil moisture was monitored with a capacitive soil moisture sensor (Delta-T ThetaProbe ML1) at various points along the track. After logging operations rutting width was measured at several points. At treatments A and B rutting width is calculated from rutting width of the left rut plus the right rut.

### Runoff and sediment measurements

After logging operations were finished, representative sections of 50 m were selected from all treatments, again relying on the judgment of forest professionals from ForstBW. The sections were delimited with a trench perpendicular to travel direction at their up- and downhill end. At the downhill end the trench was equipped with a sediment and runoff trap constructed from a rain gutter and plastic sheets driven into the soil profile to only allow surface runoff to enter into the gutter. The trenches covered the entire width of the disturbed areas collecting only sediment and runoff coming from the disturbed areas. As mentioned above we agree to the assumption that erosion from undisturbed forest soils is negligible. Hence all sediment and runoff considered in this study is always assumed to originate from the disturbed areas, i.e., machine and cable tracks, and the dirt roads. A wooden roof sheltered the trenches from rain. Runoff and eroded soil material was routed via a pipe of about 1 meter length into a large plastic barrel where the eroded soil material sedimented. The water level in the barrels was measured every 5 min with a capacitive probe. In case the barrel was completely filled a spillover routed excess water into a hose where a turbine measured the flow rate. Barrels and gutters were emptied regularly. Sediment was then air-dried in the laboratory and weighted.

For DOC measurements water samples were taken from the barrels at every visit to the plots. In the laboratory samples were filtered through a 0.45 µm cellulose acetate membrane filter and DOC was measured in an analyzer using thermo-catalytic oxidation (Analytik Jena multi N/C 2100s).

Measurements continued for 2 years from the start at treatments A-C and for 1 year at treatment D. In those 2 years fell an annual mean of 1738.0 mm precipitation. While this is very close to the long-term mean of 1750.9 mm, the precipitation was distributed to 1593.9 mm in the first and 1882.15 mm in the second year.

For further processing runoff data had to be checked for errors. Sources for errors were noise of the capacitive probes or precipitation entering the measurement system. Noise could be identified in the records and deleted manually, with a threshold of between 0.6 and 1.3 l/day. Recorded disturbances were corrected manually. Disturbances included damages to the measurements systems by freezing or precipitation entering the trenches or vessels after their roofs and lids had been damaged or blown off by wind. For the treatments with less complete records, i.e., A1, A2, C5, C6 and D7, the 90%-quantile proved to be a suitable threshold to eliminate further extreme values.

In all experiments data storage was done with LibreOffice Calc and MySQL relational databases. Calculations and data processing and presentation were done with R statistics version 3.2.2 (R Core Team 2015).

### WEPP modeling

WEPP is a continuous simulation physically based model that predicts erosion and sediment delivery from hillslope overland flow, in small channels, and on watershed scale (Flanagan and Nearing 1995). Besides the aforementioned CLIGEN, it includes components for hydrology, water balance, plant growth, and various management and cultivation methods. WEPP has received wide acceptance and evaluation until recently (Pandey et al 2016), has been applied in climate change assessment to model future climate change scenarios (Mullan et al 2016), and has shown to be transferable to various sites with minimal calibration efforts (Brooks et al 2016). To some extent it has also been evaluated in Germany (Ochs et al 2009; Al-Mukhtar et al 2014).

WEPP needs a large amount of input data. Without the empirically derived pre-parameterizations of the USDA Forest Services it often is difficult to apply. For erosion from forested watersheds, the FS WEPP interfaces (Elliot 2004) offer pre-parametrized modules for various forest specific problems. We used the modules Disturbed WEPP to model treatments A, B, and C, and WEPP:Road to model treatment D. For convenience reasons and as we wanted to apply local climate files built by Haas et al (2018) we used WEPP Windows which fortunately also includes all pre-parameterizations available in Disturbed WEPP and WEPP:Road. Model version used in both FS WEPP and WEPP Windows was 2010.100. FS WEPP uses CLIGEN version 4.31. In contrast to that we and Haas et al (2018) used version 5.3.

In Disturbed WEPP a pre-parametrized management is called treatment or vegetation, in WEPP:Road road design. To not confuse FS WEPP treatments with our treatments during harvesting operations we will stick to the WEPP term “management.” FS WEPP management options used in modeling (Table 3) were chosen according to the recommendations in the technical documentations to FS WEPP (Elliot et al 1999) and Disturbed WEPP (Elliot et al 2000).

Soil was classified in FS WEPP as sandy loam. According to the FS WEPP documentation this best describes decomposed granites and sand stone, and sand deposits. Particle size distribution is assumed to be 65% sand, 20 % silt, 10% clay, and 5% organic matter. The key parameters of sandy loam passed to WEPP are an effective hydraulic conductivity at the soil surface of  $60 \text{ mm h}^{-1}$ , initial saturation of 50%, and critical sheer stress of  $2 \text{ N m}^{-2}$ . Cover in Disturbed WEPP was left at the standard parameters which seemed appropriate and was only adjusted by the rock content of 40% as suggested in the Disturbed WEPP interface.

WEPP modeling was done in 3 steps:

1. Runoff and sediment measurements: The explicit topographic situations of the runoff and sediment measurement plots are modeled with FS WEPP management options recommended in the FS WEPP documentations.

Objective is the validation of management options and climate input choices.

2. Modeling of subcatchment return periods: daily extreme erosion events with return periods of 5, 10, 25, and 50 years are modeled for the FS WEPP management options in Table 3.
3. Modeling of subcatchment sediment: sediment delivery from the entire subcatchment by the two different infrastructure concepts after an appropriate management rotation of 5 years and 10 years.

In all modeling steps two different CLIGEN inputs were used: an input file prepared with the standard procedure as described in Yu (2005) and an input file adjusted by Haas et al (2018).

### CLIGEN input and weather data

Rain-related input parameters to CLIGEN consist of monthly values for mean, standard deviation and skewness coefficient of rain amount on a day where precipitation occurs, the monthly mean maximum 30-min rainfall intensity, and the probabilities of a wet day following a wet day and a wet day following a dry day. Also represented by 12 values is an empirical cumulative distribution of the time to peak ratio. Furthermore included are monthly mean and standard deviation of minimum and maximum air temperature, mean and standard deviation of solar radiation, dew point temperature, and statistics about wind speed, wind direction, and calm periods (Nicks et al 1995).

Yu (2002) presented a method to calculate daily  $EI_{30}$  values and R-factors from the (R)USLE (Renard et al 1997) from CLIGEN output via a double exponential function like the one WEPP uses to calculate daily rain patterns from CLIGEN output. In Haas et al (2018) we applied this method to calculate R-factors from CLIGEN runs parametrized with precipitation data from 3 climate stations close to the study site. Precipitation data came from climate stations maintained by DWD. We showed that CLIGEN fails to estimate

**Table 3** FS WEPP management options used in this study are as described in the FS WEPP technical documentations for Disturbed WEPP (Elliot et al 2000) and FS WEPP (Elliot et al 1999). Abbre-

viations are used in the following. Prefix C is used when management explicitly refers to cable tracks

Management	Properties	Abb.
Skid-trail	Disturbed WEPP: Compacted trail with vegetation below 0.15m height. Recommended for any site mechanically disturbed.	SKID / CSKID
Tall grass	Disturbed WEPP: Recommended as reasonable choice of a harvested forest after 2 years.	TALL / CTALL
20-year old forest	Disturbed WEPP: Well-established forest, ground covered with forest duff.	FOR / CFOR
Insloped road, bare ditch	WEPP:Road: Newly bladed road. All runoff is diverted to the ditch.	RBAR
Insloped road, veg. ditch	WEPP:Road: Older road where vegetation has returned to the ditch. All runoff is diverted to the ditch.	RVEG
Road w/ tall grass	Not available in WEPP:Road, taken from Disturbed WEPP with topography of the road sections.	RTALL

R-factors correctly. As a consequence CLIGEN input parameters were modified with statistical methods to reproduce observed R-factors. In this study we use the original CLIGEN parameter file (in the following termed  $CLI_{org}$ ) and an adjusted parameter file ( $CLI_{adj}$ ) prepared for the station closest to the study site, Baiersbronn-Mitteltal (BM, DWD station ID: Q522, 596 m ASL, termed site B in Haas et al 2018).  $CLI_{adj}$  is derived from the mean adjustment factors of the top 10 performing model runs benchmarked by RMSE for that station.  $CLI_{org}$  produces mean annual precipitation of 1827.5 mm.  $CLI_{adj}$  1674.3 mm.

For the present study non-precipitation parameters had to be added. Air temperature data were incomplete at BM so it was completed with data from Baiersbronn-Obertal (ID: 02752, 622 m ASL). The stations are almost in a line of sight and the height difference of 26 m between stations was neglected as our study site lies within the range of this difference. Mean dew point temperature was calculated with data from Freudenstadt WEWA (ID: 02751, 797 m ASL) as it was the only station with relative humidity data. The height difference between BM and Freudenstadt WEWA of 201m was compensated by the dew point lapse rate of 0.2K/100m (Jacobson 2005). Solar radiation was taken from the DWD station Freiburg (ID: 1443, 236 m ASL) as closest station in the region.

### Simulation of runoff and sediment measurements

The topography of the 50 m sections analyzed in the field campaign was entered into WEPP. Treatments A-C were modeled with the skid-trail management (SKID) in Disturbed WEPP. Treatment D with the insloped road with bare ditch management (RBAR) in WEPP:Road. All were modeled with weather input from  $CLI_{org}$  and  $CLI_{adj}$ . As we were unsure if these management options are the proper choices A-C were also modeled with the tall grass management (TALL) and D with the insloped road with vegetated ditch

management (RVEG). WEPP ran for 2 years for treatments A-C and 1 year for D. By definition FS WEPP output refers to the area which is afflicted by the disturbance, i.e., in our case 50 m section length times width of ruts or road.

In this modeling step the validity of the adjusted climate file and of our management choices are checked.

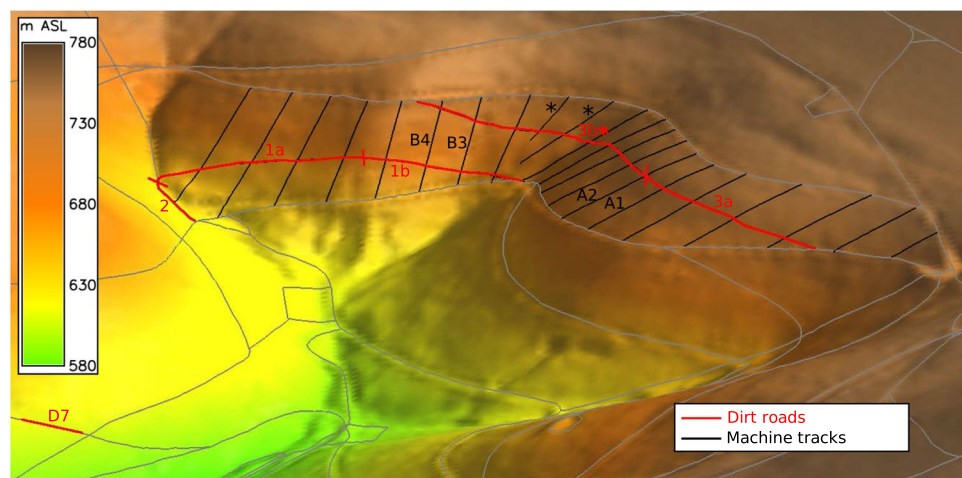
### Modeling of subcatchment

The studied stand is delimited by the surrounding paved roads. These hydraulically define the subcatchment we want to analyze here. We assume that all sediment and runoff reaches the paved roads and affect sediment retention capacities here. Beyond this the paved roads are not considered in this study.

As the site was completely harvested with what we defined as treatment A and B we know about the actual topography of infrastructure of fully mechanized logging operations. As we want to compare this practice with the practice of winch logging we had to know about the hypothetical topography of the dirt roads and cable tracks needed to harvest the entire subcatchment. Forest professionals of the state's forest authorities of Baden-Württemberg (ForstBW) outlined to us these hypothetical dirt roads and the cable tracks on map material and a digital elevation model (DEM). Both actual and hypothetical infrastructures were entered into a DEM with GrassGIS and their individual topography (length above ground and slope) was determined (Fig. 3).

In WEPP it is possible to define sophisticated rotation plans including different managements, like harvest, planting off crops, tillage cycles, or, in the case of forest operations, regeneration of the disturbed area. The simplified interface of FS WEPP does not directly offer these complex options. Instead Elliot et al (2000) suggest to model a sequence of treatments and vegetations, i.e., the management options, to represent an extended period of regeneration. With the

**Fig. 3** DEM of the subcatchment. Black lines: machine tracks in slope line established during harvesting operations with the fully mechanized logging practice. Red lines: hypothetical forest dirt roads that would need to be constructed for the cable winch logging practice. Cable tracks for this practice are not shown here because they are too numerous. Dirt road section D7 was also established for this campaign. Machine tracks and dirt roads with an asterisk (\*) are not included in modeling as they drain into forest buffer



help of the FS WEPP documentations we defined realistic 10-year and 5-year rotations for both harvesting practices (Fig. 4) to represent forest regeneration.

With the topographies of both practices we modeled the return periods of every possible treatment along the rotations. The value of a return period represents the magnitude of a certain extreme erosion event that very likely will occur in this time period.

Finally we modeled the sediment and runoff that is produced by the practices from the entire catchment within the 5 year and the 10 year rotations. To these ends every management being part of a rotation was modeled with a 100-year WEPP run. The long-term averages of these runs were then multiplied with the numbers of years they appear in the rotation and added to total sediment production.

Analogous to that we calculated dissolved organic carbon (DOC) discharge from the catchment with modeled runoff from the three rotations. As we are unsure about the development of DOC concentrations in runoff beyond our measurement campaign we only did this for the first and second year. Hence first year DOC discharge was derived by multiplying modeled mean annual runoff from the first year of a rotation, i.e., from FS WEPP management options SKID for r1 and RBAR and CSKID for r2 and r3 (compare Fig. 4), with the first year mean DOC concentration at treatment B, and C and D, respectively. Accordingly second year DOC discharge was calculated from TALL for r1, RVEG and CTALL for r2, and RTALL and CTALL for r3 multiplied with second year mean DOC concentrations.

As shown in Fig. 3 two machine tracks end in the middle of the hillslope. Those tracks are not included as sufficient forest buffer to retain sediment is below the tracks. Same applies to dirt road 3b. It is concave and runoff discharges

into sufficient forest buffer. For this reason cable tracks uphill from 3b were also not included reducing the size of the subcatchment for this practice to 9.3 ha and the total number of cable tracks to 264. As it would be too laborious to model each of those tracks individually the mean length and mean slope of all cable tracks was used in modeling.

One machine track drains into what is shown as dirt road number 2. This machine track is extended by this section of dirt road 2 as the machines had to exit via this section. Dirt road 1a discharges into dirt road 2 and they are treated as one road with changing slope.

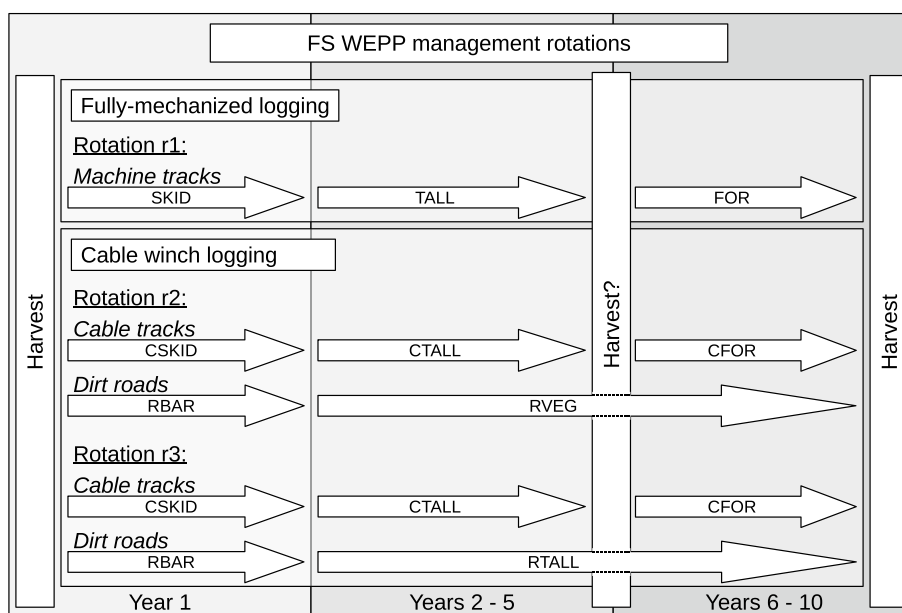
The hypothetical dirt roads are assumed to have no cross-drains. Possibly this assumption might be unrealistic. Runoff from the cable tracks was not added to the runoff on dirt roads as such complex topography would not be possible to model in FS WEPP. Possibly this assumption balances the missing crossdrains to some extent.

## Results

### Logging experiments

Mean rutting width of the different treatments varied significantly (Table 4). The widest ruts from fully mechanized logging surprisingly appeared on machine track B3 which was a track worked with traction supporting winches. But this track was also the steepest. Treatments C5 and C6 were done right next to treatments B3 and B4, respectively, so slope values are the same. Mean width of D7 was exactly 4 m which was the target width. The values from Table 4 will serve as input topography to the WEPP model. Unfortunately soil moisture

**Fig. 4** Rotations of FS WEPP management options used to model the two harvesting practices. The rotation is designed to estimate soil erosion in the 5-year or 10-year period between two harvests. Abbreviations are as described in Table 3

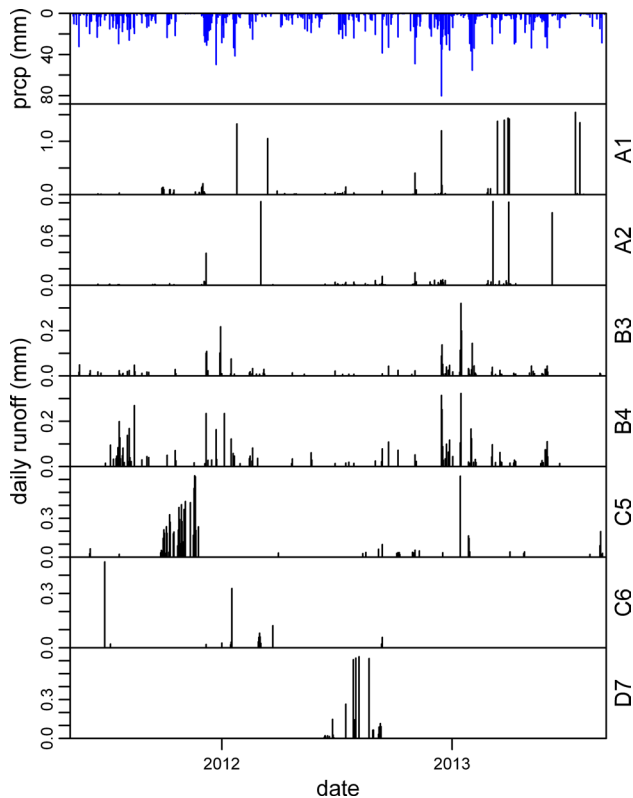




**Table 4** Properties of the tracks resulting from treatments

	A1	A2	B3	B4	C5	C6	D7
Width (m)	1.83	2.77	2.90	2.00	0.60	0.95	4.00
Disturbed area (ha)	0.009	0.014	0.015	0.01	0.003	0.005	0.02
Slope (%)	35.04	37.00	45.17	44.76	45.17	44.76	20.48
Soil moisture (vol%)	42.53	43.64	50.85	31.30	–	–	–

For A–C two repetitions were done, for D one repetition, indicated by numbers after letters. Track width is mean width from several points along the track. Widths for A and B result from adding left and right track. Area is width multiplied with the section length of 50 m. Slope was determined from a DEM. Soil moisture was monitored during logging

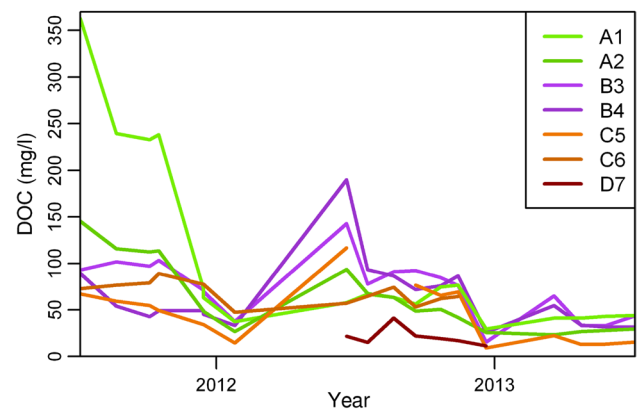


**Fig. 5** Daily precipitation (prcp) which occurred at our study site during the field measurements and daily runoff from plots of all 7 treatments normalized by afflicted area, i.e., the area of the 50 m sections of machine and cable tracks, and of the dirt road section (see Table 4). Mean annual precipitation during the campaign was 1738.0 mm. Note different scales on the axes for different treatments

data for C and D was lost. But initial soil moisture can not be altered in FS WEPP anyway.

### Runoff

Runoff response to precipitation was quick at all sites (Fig. 5). Unfortunately errors due to damage and loss were high, hence we are uncertain about the quality of the records. Nevertheless it is obvious that runoff at A1 and A2 was significantly higher than at B3 and B4 and runoff events were



**Fig. 6** DOC concentration in surface runoff from the different treatments

more extreme. At C5 there are extensive runoff events at the end of 2012. Possibly this is an error from rain entering the system directly or snow melting on the track. As we had no records of such a disturbance the events were included here. No separation of runoff from rain and snow melt was done in this study.

The sediment and runoff trap at D7 was destroyed multiple times by extreme events. The capacitive sensor went out in an early stage of the campaign.

While sediment and DOC samples could usually be saved, the runoff sums shown in Table 6 are not fit for model validation.

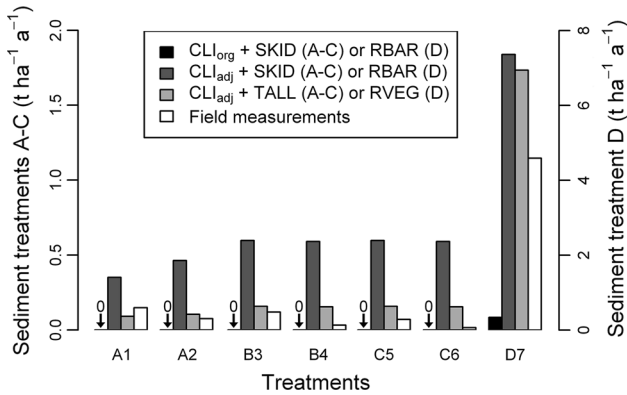
### Dissolved organic carbon in runoff

Fortunately in the phases of continuous surface runoff measurements we were able to collect a substantial amount of water samples for DOC measurements. The concentration of DOC decreased over the entire measurement period at all treatments (Fig. 6). This decrease was most pronounced at A1 and least at D7. In the measurement period occurred minimum values for every treatment in winter and maximum values in summer or fall. At D7 there is a pronounced peak in fall 2012. The decrease is also visible with average values for the first and second year (Table 5).

**Table 5** DOC concentration in mg/l in measured runoff

Conc. (mg/l)	A1	A2	B3	B4	C5	C6	D7
1st year mean (mg/l)	170.3	92.9	92.4	72.5	55.6	72.6	–
2nd year mean (mg/l)	52.3	37.6	59.5	55.4	35.7	63.6	–
1st year mean (mg/l)	131.6		82.4		64.1		–
2nd year mean (mg/l)	45.0		57.5		49.6		–
Mean (mg/l)	111.3	65.3	75.9	64.0	45.6	69.8	–
Mean (mg/l)	88.3		70.0		57.7		20.8

Shown are annual average values for the individual plots, annual averages for the treatments, and averages for the entire period. Measurements at D7 only continued for one year so there is just one value



**Fig. 7** Sediment delivery into the sediment traps from all 7 treatments normalized by disturbed area, i.e., the area of the 50 m sections of machine and cable tracks, and of the dirt road section (see Table 4). Also displayed are the corresponding WEPP results for different managements. Abbreviations are as presented in Table 3. For comparison all results are shown as rates per year. Note that treatment D7 has its own ordinate on the right

**Sediment yield**

Sediment yield from the machine and cable tracks were relatively homogeneous (Fig. 7 and Table 6). Not shown here is the fact that sediment rates constantly declined during the measurement campaign and almost dropped to 0 after the two years at treatments A, B and C. While there was also

some sediment lost due to damages on the sediment traps, especially due to freezing, we consider these values reliable.

**WEPP modeling results**

**Simulation of runoff and sediment measurements**

Model runs with CLI<sub>org</sub> underestimated annual sediment delivery compared to field measurements for all treatments, even resulting into 0 sediment from treatments A-C (Fig. 7 and Table 6). For comparison all results are normalized to disturbed area, i.e., the area of the 50 m sections of machine and cable tracks, and of the dirt road section shown in Table 4, as also is FS WEPP definition of model output. The integration of the adjusted climate file CLI<sub>adj</sub> delivered more reasonable results but overestimated sediment production by a factor of 2-4. As described above the FS WEPP management option skid-trail (SKID) would be the recommended management for the first year after harvest for treatments A-C. Insloped road with bare ditch (RBAR) for the dirt road D7. Tall grass (TALL) and insloped road with vegetated ditch (RVEG) for the second, or rather the third year and beyond, respectively. Nevertheless we realized during our modeling efforts that TALL and RVEG with CLI<sub>adj</sub> delivered estimates closer to our field measurements than SKID and RBAR in the observed period, especially for the 2-year

**Table 6** Supplementary data to Fig. 7. Sediment and runoff delivery from all 7 treatments normalized by disturbed area, i.e., the area of the 50 m sections of machine and cable tracks, and of the dirt road section (see Table 4). Also displayed are the corresponding WEPP results for different managements. For comparison all results are shown as sediment rates per year or mm runoff

	Manag.	A1	A2	B3	B4	C5	C6	Manag.	D7
<i>Sediment (t ha<sup>-1</sup> a<sup>-1</sup>)</i>									
Field measurements		0.15	0.08	0.12	0.03	0.07	0.02		4.59
CLI <sub>org</sub>	SKID	0	0	0	0	0	0	RBAR	0.34
CLI <sub>adj</sub>	SKID	0.35	0.46	0.6	0.59	0.6	0.59	RBAR	7.36
CLI <sub>adj</sub>	TALL	0.09	0.11	0.16	0.16	0.16	0.16	RVEG	6.94
<i>Runoff (mm a<sup>-1</sup>)</i>									
Field measurements		10.04	3.98	2.04	4.04	6.63	0.9		2.4
CLI <sub>org</sub>	SKID	9.24	11.37	16.07	16.09	16.07	16.09	RBAR	15.59
CLI <sub>adj</sub>	SKID	25.74	27.41	27.4	27.4	27.4	27.4	RBAR	96.38
CLI <sub>adj</sub>	TALL	30.38	30.39	30.35	30.36	30.35	30.36	RVEG	99.73

modeling period with treatments A-C, and hence included these results here.

According to the practice that dirt roads often remain unused until the next harvest dirt road D7 had no traffic during the field campaign and we observed some revegetation. To represent that revegetation we modeled the topography of the dirt road D7 in Disturbed WEPP with the FS WEPP management option for tall grass, here RTALL. For the observed one year period that resulted in  $0.105 \text{ t ha}^{-1} \text{ a}^{-1}$  of modeled erosion and is not listed here.

Runoff was overestimated for all treatments, regardless of the climate input file used.

**Modeling of subcatchment**

Table 7 shows the properties of the infrastructure used in modeling of the subcatchment. In parts this infrastructure is shown in Fig. 3. As mentioned before only tracks were considered that were in some fashion connected to the system of paved forest roads, whether directly or via a dirt road. Width of the machine and cable tracks was set to the same value for every track as width measurements at a couple of more tracks were included, yielding a more reliable value.

The impacts of harvesting operations to the entire subcatchment of 11.3 ha are to be evaluated with the results from return period calculation (Table 8) and 5-year and 10-year sediment delivery estimates (Table 9). Because of this they are in the first place shown in tons sediment (t) and cubic meter runoff ( $\text{m}^3$ ) instead of rates per area. The machine tracks included in rotation r1 have a total area of 0.574 ha. The cable tracks and dirt roads included in r2 and r3 have a total area of 1.317 ha and 0.217 ha, respectively, 1.534 ha together. This also means that the total area affected by fully mechanized logging is only around one third of the size of the total area affected by winch logging. As mentioned above we assume that erosion from undisturbed forest soils is negligible and sediment and runoff only originate from the areas affected by logging.

Concerning the use of  $\text{CLI}_{\text{org}}$  the tendency from Table 6 was repeated in (Table 8) and sediment delivery is low across all managements and return periods while  $\text{CLI}_{\text{adj}}$  seems to deliver reasonable results.

Focusing on  $\text{CLI}_{\text{adj}}$  in Table 8 it is remarkable that cable tracks contribute to total sediment delivery substantially more than the dirt roads, and even more so to total runoff.

Also interesting is that the two competing practices converge in terms of sediment delivery with increasing return periods at SKID and RBAR+CSKID, the FS WEPP management options which both represent the first year of rotation. In contrast to the machine and cable tracks the increase in sediment delivery with increasing return periods is less pronounced on the dirt roads.

Modeling a 5-year and a 10-year management rotation r2 delivers most sediment and runoff regardless of climate and harvest interval applied (Table 9). Focusing on  $\text{CLI}_{\text{adj}}$  r2 delivers about 5 times and r3 about 2 times more sediment than r1.

Remarkable is that r2 and r3 differ significantly in terms of sediment but not runoff. Note that r2 and r3 only differ in their configuration of the dirt roads, i.e., management RTALL instead of RVEG starting with year 2 of the rotation. The managements for the cable tracks which are part of r2 and r3 remain the same, i.e., CTALL starting with year 2 and CFOR with year 6 of the rotation.

As mentioned above, annual DOC discharge in Table 10 was derived by multiplying modeled mean annual runoff from a year of a rotation with the measured mean annual DOC concentration at the corresponding treatment from Table 5. While model runs with  $\text{CLI}_{\text{org}}$  produced little to no sediment they did produce runoff. Hence they were also included in calculations here.

DOC concentrations at treatment B were in general a little higher than at C and significantly higher than at D. This difference is also reflected in DOC discharge from r1 compared with r2 and r3. Particularly with  $\text{CLI}_{\text{adj}}$ , which we consider the more valid climate input, where modeled runoff in Table 6 was 3 to 4 times higher from both r2 and r3 than from r1. In contrast to that total DOC discharge after 2 years is only around twice as high. The contribution of the dirt road to this difference is, of course, significant.

**Discussion**

**FS WEPP validation and performance**

Erosion measurements were in the first place done to validate the choices of FS WEPP management options and climate input. Our model efforts clearly show that the adjusted CLIGEN input file is the better choice. In fact the original

**Table 7** Properties of infrastructure as modeled in WEPP for the entire catchment. Dirt road 1a empties into dirt road 2 and is treated as one road

	Machine tracks	Dirt roads			Cable tracks
	19 tracks	1a + 2	1b	3a	264 tracks
Length (m)	46.50 to 182.65	201.19 + 88.14	139.62	114.03	60.09
Slope (%)	31.50 to 48.02	14.41 + 13.22	5.76	5.94	41.30
Mean width (m)	2.36	4	4	4	0.83

**Table 8** Return periods in years for daily extreme events of all managements used in the WEPP model

Period	Prep. (mm)	Machine tracks			Dirt road			Cable tracks			Road and cable		
		SKID	TALL	FOR	RBAR	RVEG	RTALL	CSKID	CTALL	CFOR	RBAR + CSKID	RVEG + CTALL	
<i>CLL<sub>org</sub></i>													
		<i>sediment (t)</i>											
5	36.6	0.08	0.00	0.00	0.49	0.35	0.00	0.00	0.00	0.00	0.49	0.35	
10	45.5	0.17	0.00	0.00	0.77	0.61	0.00	0.00	0.00	0.00	0.77	0.61	
25	57.7	1.34	0.06	0.38	1.32	1.18	0.01	0.13	0.00	0.00	1.46	1.18	
50	67	7.76	0.16	0.63	1.64	1.27	0.02	0.40	0.00	0.00	2.04	1.28	
<i>CLL<sub>adj</sub></i>													
5	78.8	2.43	0.68	0.02	1.30	1.26	0.08	2.78	0.79	0.00	4.08	2.06	
10	97.2	4.02	0.83	0.04	1.54	1.55	0.10	4.76	0.93	0.00	6.3	2.48	
25	121.7	7.43	1.21	0.07	1.85	1.78	0.15	6.34	1.32	0.00	8.19	3.1	
50	127.8	9.93	2.68	0.13	1.98	1.92	0.22	8.06	1.98	0.13	10.04	3.91	
<i>CLL<sub>org</sub></i>													
		<i>runoff (m<sup>3</sup>)</i>											
5	36.6	102.81	61.54	76.70	31.31	33.52	18.24	239.18	126.86	170.47	270.5	160.38	
10	45.5	136.74	101.27	127.83	41.92	54.61	31.64	322.43	215.40	284.11	364.35	270.01	
25	57.7	180.29	152.31	183.56	62.95	60.84	55.08	418.90	326.40	416.26	481.85	387.24	
50	67	228.77	263.23	258.39	77.98	83.75	86.56	524.62	582.76	574.83	602.59	666.51	
<i>CLL<sub>adj</sub></i>													
5	78.8	205.44	123.08	187.62	79.36	78.82	38.82	473.08	273.54	414.94	552.44	352.36	
10	97.2	239.07	182.11	216.42	92.52	93.42	55.93	549.72	405.69	481.01	642.24	499.1	
25	121.7	339.87	245.27	306.20	104.21	107.85	70.83	765.12	544.44	680.55	869.33	652.29	
50	127.8	468.59	276.96	316.91	113.87	116.68	88.92	1098.13	623.72	704.33	1211.0	740.41	

Values are sums for sediment and runoff coming from machine tracks or cable tracks and dirt roads of the entire subcatchment. Abbreviations as in Table 3



**Table 9** Modeled sediment and runoff delivered from the entire subcatchment (in t and m<sup>3</sup>) and normalized by stand area of 11.3 ha (in t ha<sup>-1</sup>) after rotations described in Fig. 4 were finished

Rotation	5-years			10-years		
	r1	r2	r3	r1	r2	r3
	<i>Sediment (t)</i>					
CLI <sub>org</sub>	0.43	1.53	0.58	0.43	2.73	0.6
CLI <sub>adj</sub>	4.44	20.71	8.22	4.53	36.67	8.55
	<i>runoff (m<sup>3</sup>)</i>					
CLI <sub>org</sub>	206.2	734.29	546.93	463.41	1595.78	1174.21
CLI <sub>adj</sub>	761.21	2755.26	2144.77	1982.47	6506.81	5133.2
	<i>Sediment (t ha<sup>-1</sup>)</i>					
CLI <sub>org</sub>	0.04	0.14	0.05	0.04	0.24	0.05
CLI <sub>adj</sub>	0.39	1.83	0.73	0.4	3.25	0.76
	<i>runoff (mm)</i>					
CLI <sub>org</sub>	1.82	6.5	4.84	4.1	14.12	10.39
CLI <sub>adj</sub>	6.74	24.38	18.98	17.54	57.58	45.43

**Table 10** DOC discharge calculated from modeled runoff and measured concentrations (see Table 5) for the first 2 years of the three rotations. Results are normalized by subcatchment area to kg ha<sup>-1</sup>

	r1 (kg ha <sup>-1</sup> )	r2 (kg ha <sup>-1</sup> )	r3 (kg ha <sup>-1</sup> )
<i>1st year</i>			
CLI <sub>org</sub>	0.53	1.08	1.08
CLI <sub>adj</sub>	1.53	3.32	3.32
<i>2nd year</i>			
CLI <sub>org</sub>	0.17	0.43	1.51
CLI <sub>adj</sub>	0.7	1.75	1.47
<i>sum</i>			
CLI <sub>org</sub>	0.7	1.51	1.43
CLI <sub>adj</sub>	2.24	5.07	4.79

input file produced unrealistically low sediment values throughout all treatments.

Rather more cause for discussion are the choices for the FS WEPP management options we made. Sediment measurements at treatments A, B, and C showed comparable sediment rates. This indicates that we are rather correct with our assumption that machine and cable tracks are comparable in the disturbance they cause to soil, of course, considering the significant difference in disturbance width. Hence choosing same managements for same years in management rotation is justified. Possibly less justified is the choice of the skid-trail management (SKID/CSKID) for the first year. While the Disturbed WEPP documentation (Elliot et al 2000) is rather clear about SKID being the right choice for mechanically disturbed and compacted surfaces the FS WEPP documentation (Elliot 2004) is also rather clear in its recommendation to experiment with the management and cover options to meet individual observations. Our observations in the field were that in both machine and cable track parts of vegetation remained intact during harvest, and flow paths were

often interrupted by patches of rather rough surface. This made us try other managements with positive results for the tall grass management (TALL/CTALL). Elliot et al (2000) comment that FS WEPP results are at best +/- 50% correct. With TALL at treatments A1, A2, and B3 and both dirt road management options at D7 we met this margin. With all other combinations FS WEPP overestimated significantly. This is in contrast to Fernández and Vega (2018) who found that Disturbed WEPP underestimated erosion from burned forests in Spain. Some of this overestimation might also be related to the fact that the first year of erosion measurements at sites A-C was a year with observed precipitation well below long-term mean annual precipitation, hence also well below CLIGEN precipitation. As most erosion happens in the first year after disturbance (Phillips et al 2018) this weakens the overestimation with SKID to some extent. This and the fact that SKID is by definition the better choice for the first year in rotation let us stick with it as a sort of worst-case scenario in the modeling of return periods and subcatchment erosion. When comparing infrastructures of the entire subcatchment, in fact, the individual management options do not matter that much as proportions between machine tracks and cable tracks remain similar. Shifting management from SKID to TALL on machine and cable tracks in the first year would only put more emphasize on erosion from the dirt roads.

The above applies to some extent to the choice of RBAR as management for the first year of dirt roads. While here the differences between RBAR and RVEG in relation to field measurements were negligible RBAR represents both the worst-case scenario and the most realistic option in the first year. Questionable here is rather the choice if RVEG is the best option for years 2–10 in the rotations. Observations vary here. While on some dirt roads erosion is limited to the ditch, others show erosion across the entire dirt road, and again other dirt roads quickly regrow low vegetation. Here

again the combination of RBAR with RVEG can be considered the worst-case end of the spectrum while RBAR with RTALL would be the moderate end. To sum this up rotation r1 and r2 are rather worst-case scenarios, this even more with r2. r3 is designed as more moderate option in terms of dirt roads, but still delivers significantly more sediment than r1 due to the rotation of the cable tracks. According to our results from FS WEPP fully mechanized logging produces less sediment in its worst-case configuration than winch logging in its most moderate configuration.

The relevance of return period modeling is even more obvious when considering that the first year of our campaign was below average and that observed variations in revegetation likely depend on weather conditions after harvest. Particularly if erosion has sometimes finished after 1 year (Phillips et al 2018) or maybe 2 years, as our measurements on treatments A-C suggest, it is important to know about the possible magnitude of extreme events. As an example: a possible daily event with a return period of 10-years hitting a machine track in the first year after harvest can contribute to around 90% of total sediment in rotation r1. For good decision making erosion estimates from the entire subcatchment as well as risk estimates by return period analysis is necessary. By the model results presented in this study we consider FS WEPP an appropriate tool to produce both, given proper choices of management options and valid climate input.

### Ecological relevance of forest erosion in the region

Erosion from forested watersheds has generally shown to be less than  $0.01 \text{ ha}^{-1} \text{ a}^{-1}$  (Auerswald et al 2009). In comparison to this our measurements and model results are significantly higher, ranging up to  $0.37 \text{ t ha}^{-1} \text{ a}^{-1}$  in our worst-case scenario (5 year rotation of r2). Considering that forests cover approximately 32% of Germany and as climate change was a premise to this study our results are valuable in terms of ecologically comparing harvest practices.

Erosion from forested watersheds entails several ecological consequences that can be divided into on-site and off-site damages. On-site soil erosion can degrade stand and infrastructure stability (Schmid et al 2004), eroded material transports nutrients out of the stand, and additionally DOC loss triggers even more mobilization of nutrients which are lost to soil bacteria, fungi and vegetation (Missong et al 2018). After leaving the stand eroded soil material and DOC accumulate in retention structures or reaches surface water bodies like headwater streams or lakes. Off-site sediment affects permeability and habitat properties of stream beds (Fulton and West 2002), and nutrients transported with sediment play a major role in stream pollution (Basher et al 2011). Particularly DOC additionally affects transport and degradation of pollutants, proton and pH balance, mineral

reactions, and the depth of the photic zone in aquatic systems (Weishaar et al 2003).

While our erosion measurements best served to validate the choices of FS WEPP management options and climate input, our DOC measurements were a surprisingly good indicator for ecological consequences of harvesting practices. Studies have shown that the practices of clear cutting and final felling are the reason for elevated fluxes of nitrogen, phosphorus, base cations and DOC to surface water bodies (Loefgren et al 2014). Those fluxes can continue up to ten years after harvest (Kreutzweiser et al 2008) and are promoted by drainage measures and ditch maintenance (Ahtiainen and Huttunen 1999, Joensuu et al 2002). Practices like commercial thinning, comparable to harvest at our site, are considered to have significantly less impact on nutrient fluxes (Jerabkova et al 2011). However, our DOC measurements show that DOC discharge on plot scale probably depends on harvesting practices. The annual changes in DOC concentrations observed are presumably due to the annual changes in terrestrial production (Zheng et al 2018). Concentrations were highest in summer when biological activity is high due to warmth and lowest in winter when biological activity is lowest. Low concentrations in winter could also be from thinning by runoff from snowmelt or when topsoil was frozen and runoff did not interact much with topsoil. The peak at D7 probably occurred due to leaves falling on the dirt road section. Other sources for DOC are not available there as dirt roads are rather biologically inactive, especially directly after maintenance when topsoil has been removed to the fill slope. This also explains the overall very low concentrations of DOC at D7.

Compared to the relatively higher concentrations at treatments A-C on plot scale this would give the impression that the dirt roads, and hence cable winch logging, are the ecologically more reasonable infrastructure option. But on catchment scale with adequate rotations and including the larger area affected by cable winch logging, modeled DOC discharge showed that winch logging also promotes the loss of DOC more than fully mechanized logging. However, the difference between practices is less pronounced with DOC than it is with erosion.

### Practical considerations

The ongoing discussion in the literature and between forest professionals about harvest intervals is mainly driven by economic considerations (Neumann 2014). Regular harvests every 3 or 5 years of low-value timber guarantee better development conditions of high-value trees. This especially applies to broadleaf stands, whereas coniferous stands also profit in terms of stability against storms. Ecological arguments for short intervals between harvests are higher turnover of litter, and more precipitation and sunshine reaching

the ground improving bioturbation (Neumann 2014). Also more frequent harvests mean less passages per harvest and potentially less disturbance. Against those arguments stand that the concentration of harvest actions is more cost efficient (Neumann 2014) as machines have to be transported to the stand just once in 10 years and planning is more time efficient. This especially applies when machines have to be rented or a company has to be contracted with harvest. Also there is less frequent habitat disturbance for wildlife and longer regeneration periods for disturbed soils might compensate for more machine passages. Also long periods between harvests significantly boost carbon sequestration (Nunery and Keeton 2010). Our findings from modeling show that in terms of soil erosion long intervals between harvests are the better option. As most erosion happens in the time following harvest it is recommendable to reduce the number of “first years” and to reduce the risk of a highly erosive precipitation event coinciding with freshly disturbed tracks or dirt roads. For dirt roads this of course also means that no other traffic should be allowed and even the use of the roads for recreational purposes could be critical.

A desirable outcome from our erosion measurements would have been to see a difference between treatments A and B, i.e., a difference between working with a traction support winch or without. Erosion measurements at the two treatments were rather comparable and did not give a proper answer to that. Runoff was different from the treatments, with A having significantly more runoff than B. But runoff measurements were too incomplete to base a statement like this on them. Finally, in the model the difference was not considered or is, in fact, impossible to represent.

However, DOC concentration seems to be a parameter which serves to distinguish between treatments A and B. Initial DOC concentrations are significantly higher with treatment A. An explanation for this could be that treatment A cuts deeper into topsoil potentially including interflow where DOC concentrations tend to be higher than in surface runoff. During summer DOC concentrations are higher with treatment B. This again could mean that biological activity is higher due to initially lower grades of disturbance or better conditions for revegetation. Assuming DOC mobilization as an indicator for soil erosion the traction winch performs better in reducing both.

Rutting width seems to be controlled by slope as B produced wider ruts than A at a up to 10% steeper slope. Surprisingly sediment delivery was rather comparable. This also indicates that the traction winches possibly reduce mobilization of soil material or connectivity of flow paths in the track. In any case, additional traction measures like the traction supporting winches seem to be recommendable.

As a final remark: From the perspective of forest professionals there exist reasons to combine fully mechanized logging with the construction of more dirt roads. The first

to efficiently conduct harvest, the second to quickly react to storm damages, to facilitate pest control, or to easily harvest single high-value trees. In terms of erosion this is probably the worst alternative.

## Conclusions

From the above we conclude the following:

1. FS WEPP can be applied to model erosion measured after forest harvesting operations. Pre-parameterizations to WEPP available via FS WEPP are valid for disturbed forest infrastructure such as machine tracks, cable tracks, and dirt roads, given the correct choice of management options.
2. Quality of FS WEPP estimates can be significantly improved by using a regionally adjusted CLIGEN input file. Unadjusted climate input produces unrealistically low sediment delivery rates.
3. According to modeling results logging infrastructure used in fully mechanized logging is less prone to soil erosion than logging infrastructure used in cable winch logging. This conclusion holds even if worst-case assumptions of the former are compared with moderate assumptions of the latter.
4. Long intervals between harvests of, e.g., 10 years, instead of 3 or 5 years, are beneficial to erosion prevention as the risk of sediment production is greatest in the first 1 or 2 years after harvest.
5. DOC concentrations in surface runoff from logging infrastructure can help to distinguish between forms of disturbances caused by heavy machinery with or without a traction supporting winch. In combination with modeled runoff it can help to assess nutrient export caused by the two different logging practices.

**Acknowledgements** Open Access funding provided by Projekt DEAL.

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