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Using model simulation to evaluate soil loss potential in diversified agricultural landscapes

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Abstract

Agricultural production is facing a challenging transition through changing political framework conditions and climate change. Innovative field use and land management through temporal and spatial diversification measures support the political efforts to achieve the European Green Deal. However, increasing precipitation intensities through climate change are leading to an increased risk of soil erosion by water. To mitigate such risk, soil erosion should be taken into account when redesigning fields and landscapes. This paper aims to assess the present erosion risk situation in the innovative on-farm field experiment “patchCROP” with several implemented spatio-temporal crop diversification measures (field size, flower strips, crop rotation), using the physically-based Erosion 3D simulation model at the field scale. The modelling results showed that field reshaping from one large field into smaller field segments had the potential to reduce soil erosion. Flower strips reduced the sediment discharge to approximately half of that of small field segments without flower strips. However, as model results indicated, heterogeneous landscapes showed complex erosion and deposition patterns. To identify these, making use of physically based soil erosion models in new field arrangements is a critical future task.

Highlights:

- Evaluation of a physically based soil erosion model that can be integrated into field re-design.
- Patch crop systems promise to enable higher spatial field diversification.
- Equal consideration of minor site-specific topography and modified field design needed to prevent soil erosion.
- Physically based soil erosion models offer a powerful tool to optimise design of future cropping systems.

KEYWORDS
diversified cropping systems, erosion 3D, land management, patch cropping, soil erosion modelling

1 | INTRODUCTION

Agricultural management systems are in transition due to changing climate, policies, and new technologies (Edenhofer et al., 2012). As the largest land user of the European Union (EU), agriculture needs to contribute to Green Deal targets for climate resilience, biodiversity, and sustainable land use (Montanarella & Panagos, 2021). Furthermore, environmental and agricultural soil functions, as well as their effects on crop production, offer significant aspects to mitigate climate change (IPCC, 2022) through carbon storage, nutrient cycling, biodiversity conservation, as well as hydrological flow regulation (Adhikari & Hartemink, 2016; Olson et al., 2017). However, agricultural systems face many challenges through the already rising Earth's average temperature (IPCC, 2022) and an increasing intensity of precipitation, which is mainly due to globally increasing evapotranspiration (Prein et al., 2017). The changing intensity of precipitation is directly linked to an increase in rainfall erosivity (R factor), which is a major driver for soil erosion by water (Panagos et al., 2022). The anticipated increase in soil erosion on arable land poses a threat to food supply and human well-being (Panagos et al., 2016; Pimentel, 2006). Soil erosion can cause high ecological and economic costs (Frielinghaus & Grimme, 1999). Such ecological costs include, for example, the translocation of agricultural nutrients into surface water that can cause eutrophication and the loss of soil organic carbon, intensify global warming consequences (Nearing, 2001).

The current cropping systems of Central Europe are highly productive but have led to a series of environmental concerns due to loss of biodiversity, pollution of water bodies, or land degradation through soil erosion (Foley et al., 2011). There is an increasing interest in structural and temporal changes of agricultural fields combined with technical innovations to support their transformation towards more sustainable agricultural production (Raza et al., 2021). Consequently, innovative cropping systems like strip cropping, patch cropping, or spot farming are more often being investigated for agricultural landscapes (Wegener et al., 2019). However, innovative and digital technologies are also linked to high expectations in cropping system redesign to improve soil health, climate resilience, and ecosystem services (Wegener et al., 2019). Landscape experiments offer the possibility to foster multidisciplinary information on sustainable cropping systems´ potentials using digitalisation. The "patchCROP" landscape experiment at the Leibniz Centre for Agricultural Landscape Research (ZALF) has been established as such an innovative field infrastructure. It is an experimental approach of redesigning an agricultural landscape using multiple approaches of spatial and temporal crop diversification and thereby investigating the long-term applicability of precision farming and artificial intelligence in small-scale fields supported through digital tools (Grahmann et al., 2021).

The complex interactions between agricultural landscapes and soil properties characterise cropping systems. Cropping systems impact on soil properties (e.g. soil compaction, soil organic carbon) and such on the hydrological cycle mainly through effects on evapotranspiration, interception, infiltration, field capacity and, in consequence, runoff (Dyck & Peschke, 1995). Besides changing precipitation patterns and intensities which represent the major climate risks factors behind soil erosion, cropping systems and soil management decisions are the human risk factor for soil erosion (Panagos et al., 2016). Surface runoff occurs mainly when bare soil is exposed to precipitation. Dense crop stand or mulch cover reduce surface runoff substantially. Cover crops can extend the period of time during which crops protect the soil. The degree and duration of soil cover are important control variables for erosion process (Frielinghaus & Grimme, 1999). Row crops like maize and soybean with wide row distances result in large areas of uncovered soil during their early development stages and hence increased soil erosion risk. However, crop rotation management determines not only the degree of soil cover but also the mechanical stress on soil structure and the associated soil degradation (Brunnotte, 2002), thus also effecting the risk of soil erosion through soil compaction, and consequently soil function. For example, root crops are generally characterised by higher mechanical load inputs than cereal crops (Keller & Or, 2022).

Facing the challenges posed by soil erosion, stakeholders developed a range of practices and alternative cropping systems which have reduced soil erosion in the last decades (Frielinghaus et al., 2001; Lehmann, 2000). Some of the most important measures include the retirement and restoration of marginal lands (Kopittke et al., 2019), use of conservation tillage (Auerswald et al., 2006; Lal, 2003), use of terracing in steep slopes (Arnáez et al., 2015), adjusted tillage direction

(Brunnotte, 2002), extending the length of vegetation cover (e.g. through intercropping), wide crop rotations, and the implementation of diversified cropping systems (Tamburini et al., 2020).

To assess the erosion risk on arable land and thus obtain a basis for systematic soil erosion estimates, a variety of soil erosion models is available (Borrelli et al., 2021). Soil erosion models can be classified into empirical, physically based, or conceptual models, which describe and formalise the influence of soil, climate, land cover, topography, and vegetation parameters on soil erosion risk (Raza et al., 2021). Empirical models are based on statistical correlations without considering the physical rules and assumptions for the correlation (Wainwright & Mulligan, 2013). They have great predictive power but little understanding of the process itself. They are not generalisable and only apply to the conditions for which their data were collected (Hebel, 2003). On the contrary, physically based models attempt to describe the phases of the erosion process mathematically, taking into account the fundamental concepts of physics (Morgan & Nearing, 2011). Thus, the models consist of multiple algorithms and a large number of parameters to predict the dynamics of soil erosion (Raza et al., 2021). Physically based models have great explanatory power, but their predictive accuracy depends on the calibration of the input parameters (Wainwright & Mulligan, 2013). Conceptual models are hybrids of physical-based and empirical models (Raza et al., 2021). Since the 1960s, many models have been developed to analyse and understand the soil erosion process and thereby support political decision making to minimise its impact (de Roo, 1993). One of the oldest, best known, and most widely applied empirical models is the Universal Soil Loss Equation (USLE), which was developed for the Midwest of the USA (Wischmeier & Smith, 1978). Auerswald and Schwertmann adapted it for Bavaria/Germany as the so-called "Allgemeine Bodenabtragsgleichung" (ABAG) (Schwertmann et al., 1987). Today, the ABAG is used in administrations to implement the common agricultural policy (CAP) in Germany. Thereby, the ABAG serves as an indicator to justify direct payments and environmental requirements, for example, soil erosion risk classification in the landscape. Full reviews of the strengths and weaknesses of different soil erosion models and recommendations for the choice of a model are provided, for example, by Borrelli et al. (2021) and Raza et al. (2021).

Regarding soil erosion modelling, the influence of crop rotation, soil cover, and cropping systems on the erosion process is recognised in various parameters (e.g. the crop and management factor (C) and the support practice factor (P) in the USLE model) (Wischmeier & Smith, 1978). For practical applications, such as CAP, empirical models have found widespread use (e.g. ABAG in Germany). However, with an increasing shift in agriculture towards novel field arrangements such as patch cropping or strip cropping and associated small-scale field diversification, there is a need for a detailed temporal and structural decision support approach on the effects of soil erosion. In addition, there is a need for suitable soil erosion models that can be integrated into such field re-design approaches (Raza et al., 2021).

Thus, the objectives of this study were (1) to use a physically based soil erosion model as a tool to make a comparative assessment of soil erosion threat by water for a newly arranged arable field, and (2) to demonstrate how a physically based soil erosion model can aid agricultural decision making for environmentally sound field structures.

2 | MATERIALS AND METHODS

2.1 | Study site

The study area is located at the landscape experiment "patchCROP" in Tempelberg, Brandenburg, Germany (52° 26,827′N, 14° 8492′E), about 50 km east of the city of Berlin. The field elevation varies between 67 and 81 m.a.s.l. and the studied field has a size of 70 ha. This region is characterised by a mean annual temperature of 8.9°C, a mean annual rainfall of 533 mm, and a rain erosivity factor of 80 N/h (1981–2020 base period) (MUGV Brandenburg, 2022). The geological formation is based on young moraine landscapes. Loamy sand to sandy loam derived from glacial deposits are the dominant soil texture. The region is characterised by heterogeneous site conditions. Due to repeated advances and retreats of glaciation during the Pleistocene, a complex setting of unconsolidated sediments with high textural heterogeneity was developed. Soils that evolved from glacial till have shorter development depths than water-erosion prone loess locations and are more susceptible to a reduction in crop biomass production due to soil erosion and thus also yield loss (Öttl et al., 2021). The EU Cross Compliance rules based on the ABAG in Germany classify the field as a non-erosion prone field but nonetheless this side could be used for relative changes in management practice to be considered.

2.2 | Experimental setup of "patchCROP"

The "patchCROP" experiment was set up in March 2020. It studies the impact of increased landscape diversity

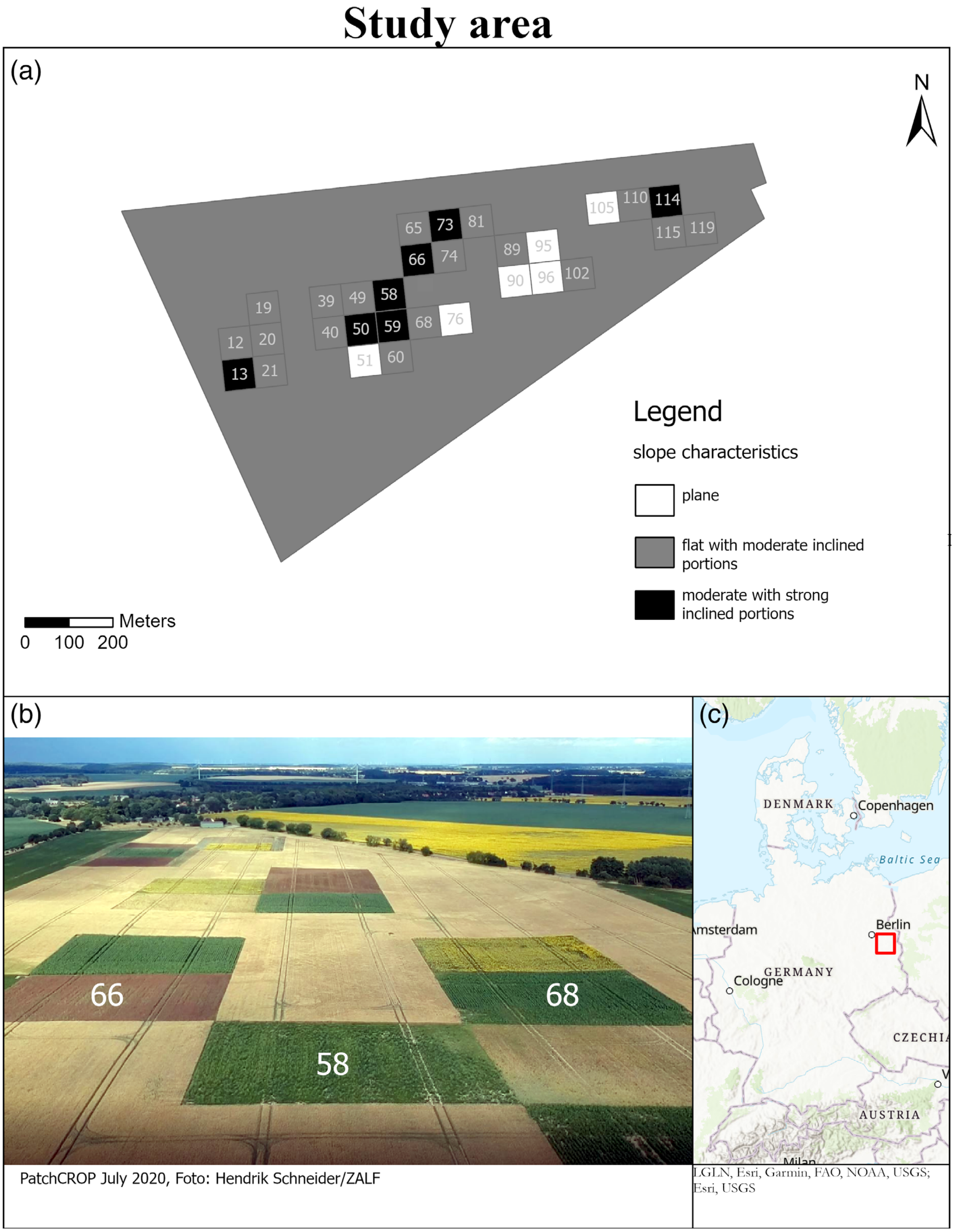

FIGURE 1 Study area: (a) slope characteristics according to Deumlich et al. (2021), numbers refer to patch-ID (b) patchCROP field (c) overview map

through smaller field sizes, site-specific crop rotations, the reduction of pesticides applying integrated plant protection strategies, and the use of new technologies (e.g., robotic applications) to develop designs of future cropping systems (Grahmann et al., 2021). To increase spatial diversification, new field arrangements were implemented. The site-specific new fields of 72 m × 72 m size (denominated as patch) are located within a 70 ha large field (Figure 1). Donat et al. (2022) used a fuzzy cluster analysis to examine historical crop yield maps of this particular field from the previous ten years when the site was managed uniformly and sole cropped. According to Grahmann et al. (2021), the new fields were organised in two different yield potential zones applying an automated cluster analysis and expert knowledge. A low yield potential zone and a high yield potential zone were defined. Each yield potential zone contains the same number of 15 new patch arrangements. Further, for each yield potential zone, a site-specific legume-supported crop rotation with five crops each was developed. The high yield potential crop rotation includes: rapeseed – winter barley - cover crops - soybean - cover crops - maize – winter wheat, while the low yield potential crop rotation is comprised by cover crops – sunflower – winter oats - cover crops – maize - lupin – winter rye. Each crop rotation was replicated three times. To test for landscape biodiversity, 10 patches (one crop rotation replicate) were either managed with business-as-usual pesticide application, with a reduced pesticide application, or a reduced pesticide application and additional 12 m perennial flower strips which surround the patches at the north and south side. However, the plant protection strategies were not relevant for this study and, therefore, excluded as treatment factor. The remaining field area (~55 ha) was cultivated in common farming practices; in 2021, winter rye was sown (Grahmann et al., 2021). Detailed information on the approach and design of the ZALF experiment can be found in Grahmann et al. (2021), and (www.landschaftslabor-patchcrop.de).

2.3 | Model description

Erosion 3D is a physically-based, event-related simulation model to describe water erosion, the sediment transport caused by it and the possible discharge into water bodies (Schmidt et al., 1996; von Werner, 1995). The theoretical principles of Erosion 3D are adapted from the main sub-processes of soil erosion by water: infiltration, flow routing, runoff generation, detachment, transport and deposition of soil particles (von Werner, 1995).

Thereby, Erosion 3D is divided into an infiltration- and erosion-model. The infiltration model is based on a modified Green & Ampt approach (Green & Ampt, 1911), and the infiltration rate is calculated with the Darcy equation (Schmidt et al., 1996), which is defined as:

$$i = -k\frac{\Delta\left(\Psi_m + \Psi_g\right)}{x_f(t)} \quad (1)$$

where i is the infiltration rate (m/s); k is the hydraulic conductivity (kg*s/m^3); Ψ_m is the matrix potential (J/kg); Ψ_g is the gravitation potential (J/kg); and x_f (t) is the depth of penetration (m) on dependence of time.

Due to the event related simulation by Erosion 3D, a dynamic calculation of the infiltration process with a temporal resolution of 10 min or less can be performed (Schob et al., 2006).

Erosion 3D calculates the detachment of soil particles by rainfall and runoff and the transport of soil particles by flowing surface runoff, which is defined by the equation:

$$\mathrm{E} = \frac{\varphi_q + \varphi_r}{\varphi_{crit}} \quad (2)$$

where E is the soil erosion ratio; φ_q is the momentum of the flux exerted by overland flow (N/m^2); φ_r is the momentum of flux exerted by droplet impact (N/m^2); and φ_{crit} is the critical momentum flux of the soil specific resistance.

Based on a momentum flux model approach, the detachment of soil particles occurs when the combined momentum flux of surface runoff and droplet impact exceeds soil specific resistance to erosion_the power of cohesion and gravity. Manning's equation of surface roughness is used in the calculation of the momentum flux of surface runoff (Schmidt et al., 1996). After the detachment process, soil particles are transported by the runoff water. The deposition is calculated by the hydraulic conductivity and Stokes law, respectively. A detailed description of the modelling algorithm and main equations implemented in the model can be found in Schmidt et al. (1996). Erosion 3D was originally calibrated and validated within 116 rainfall simulation studies on agricultural fields in Saxony, Germany, from 1992 to 1996 (Michael, 2000) and is used in official soil erosion assessments and soil conservation programs of the Federal state of Saxony (Schmidt & Schindewolf, 2010). It was also internationally validated (Hebel, 2003; Jetten et al., 1999; Németová et al., 2020) and was utilised in numerous international soil erosion studies (Beitlerová et al., 2020; Németová et al., 2020; Singh et al., 2022). Due to its calibration and validation for typical soil types and agricultural management in eastern Germany, as well as its good documentation, Erosion 3D was chosen for this study.

2.4 | Data

Erosion 3D is characterised by its requirement for fewer input parameters in comparison with other physically-based erosion models (Schob et al., 2006). Data on relief (x,y,z), precipitation (duration and intensity), soil, and land use are included in the modelling approach.

Since the parameters that influence the processes vary spatially and temporally, the model equations are only

TABLE 1 Input parameter for Erosion 3D

Input parameter	Unit	Data source
Altitude DEM	(m)	Digital elevation model with a resolution of 1 m, derived from laser scan (https://geobasis-bb.de/lgb/de/geodaten/3d-produkte/laserscandaten/)
Soil Cover	%	Soil data from existing, publicly available datasets on soil properties (German soil appraisal "Bodenschätzung") field measurements and the parameter catalogue provided within the Erosion 3D software package (Michael, 2000).
Bulk density	kg/m^3	
Soil organic carbon content	%	
Grain size distribution	%	
Skin factor	-	Parameters can be found in Tables S1 and S2
Surface roughness	s/m$^{1/3}$	
Initial soil moisture	%	
Erosion resistance	N/m^2	
Rainfall intensity	mm/min	German Meteorological Service (DWD)

applied to small spatial (grid) segments and are event-based. Thereby, Erosion 3D requires a raster-based representation of the study area and data. Hence, a digital elevation model (DEM) with a 1 × 1 m spatial resolution was used as data basis for the erosion model. All spatial input data were pre-processed using a geoformation system (ESRI, 2011) and then imported into Erosion 3D, following Vogel et al. (2016).

Reference precipitation data were provided within the Erosion 3D software package and are based on the analyses of extreme value statistics of interpolated precipitation data for the 30 year period 1951–1980 from 50 meteorological stations in a climatologically comparable region in Saxony (Michael, 2000). The data from the meteorological station Torgau were used since this station represents also the lowland climate of Tempelberg (Krumbiegel & Schwinge, 1991)

Table 1 summarised standard soil parameters which are required and used in the model approach (Schmidt et al., 1996). The specific soil parameters can be derived from the Erosion 3D parameter catalogue (Schmidt et al., 1996), which was experimentally determined during the field calibration of Erosion 3D. The parameter catalogue contains empirical values for resistance to erosion, surface roughness, and skin factor. These empirical values can be adapted on soil type, time since the last soil management measure, growth stage of a particular crop, soil texture, and soil moisture.

2.5 | Simulated scenarios

Deumlich (1999) examined rain gauge data from 16 regional ombrographs of the German Meteorological Service (DWD) with records lengths up to 34 years to calculate the rain erosivity, their monthly distribution, and their probability in Northeastern Germany. The highest rain erosivity occurs from May to August. Based on typical agricultural practices in Germany, various scenarios were simulated that represent typical high-risk conditions within the year. Risks scenarios are assumed at the end of April/beginning of May and early August (called May and August throughout this manuscript). On the one hand, the absence of soil cover, especially for root crops and late sown summer crops is critical in May. In August, on the other hand, the soil is usually covered by summer crops, but most winter crops have already been harvested. The maximal erosion hazard is presented by a "worst-case-scenario". This focus on the identification of danger areas in the field: (S1) worst-case scenario: heavy rain directly after conventional tillage (CT) of the whole field (70 ha) and seeding of Maize in May; (S2) status-quo scenario of the current "patchy" field arrangement, including perennial flower strips in May (most winter crops are full vegetative crops, summer crops have recently been planted); and (S3) status-quo scenario of the current patchy field arrangement, including perennial flower strips in August (most winter crops and lupin have been harvested, soil is mostly covered by straw/crop stubble, summer crops in their full vegetative growth). In order to identify effects of relief, crop rotation and the patchy design of the field, the whole five-year crop rotation was simulated for the S2 and S3 scenario.

Precipitation data for each scenario are based on a statistically derived rainfall event assigned to a 5-year, 50-year, and 100-year expected return period (Table 2).

Each scenario and rainfall event requires a separate data set. Soil parameters of the perennial flower strips surrounding the patches were altered concerning soil cover, skin factor, erosion resistance, and surface roughness. As the perennial flower strips were established in 2020, bulk density and soil organic carbon were assumed to be similar as in the corresponding patch.

To compare erosion and deposition areas on site and from each patch, the sediment budget per grid cell (SB) [kg m^2] was calculated for each scenario. SB determines whether erosion or deposition occurred in a specific cell and is calculated as the difference between sediment transport out of and sediment inflow into the

TABLE 2 Precipitation parameters for simulated rainfall events

Return period of precipitation [a]	Max. Intensity, 1-min interval [mm/min]	Duration [min]	Precipitation amount [mm]	Rain erosivity [N/h]
5	1.48	200	26.9	27.0
50	2.28	60	44.3	80.2
100	2.51	160	60.8	146.6

TABLE 3 Sediment budget classes for a single event according to von Werner (1995)

Erosion	E4	<−25 [kg m^2]
	E3	−25 to −2.5 [kg m^2]
	E2	−2.5 to −0.25 [kg m^2]
	E1	−0.25 to −0.001 [kg m^2]
Balanced	0	−0.001–0.001 [kg m^2]
Deposition	D1	0.001–0.25 [kg m^2]
	D2	0.25–2.5 [kg m^2]
	D3	2.5–25 [kg m^2]
	D4	>25 [kg m^2]

cell, divided by the area of the grid cell. The following sediment budget classes were distinguished according to von Werner (1995) (Table 3).

3 | RESULTS

The spatial distribution and histogram of SB simulated for the S1 scenario (monoculture maize) and three simulated precipitation events (Table 2) are shown in Figure 2. Approximately, 42% of the cells were affected by erosion [E1 - E4] at a 5 year event, compared to 51% of cells at a 50 year and 52% at a 100 year precipitation event. An increase in precipitation intensity also resulted in an increase in deposition, approximately 31% at a 5 year event, 34% at a 50 year event and 35% at a 100 year event. However, this increase was smaller than the increase in erosion.

The strongest erosion values were reached in flow accumulation zones and in areas that appear to form a branched network. Deposition most often occurred at the edges to this network. An increase in precipitation intensity caused a known shift towards higher erosion values and a greater percentage of erosion-affected pixel cells. However, the affected areas follow the same topography influenced network pattern throughout all precipitation intensities (Figure 2).

The mean SB for the S1 scenario for the different precipitation events were −0.3, −1.1, and −1.8 kg m^2 for a 5-, 50-, and 100-year event, respectively. The implementation of the patchy field structure with and without flower strips reveals that the flower strips reduced the sediment discharge to approximately half of that of the patches without flower strips (Table 4). However, because of the very high standard deviation, these effects cannot be statistically proven (Table 4).

Figure 3 reveals the reason behind the high standard deviations exemplarily for the experimental year 2021. Whilst winter crops like, for example, winter rape, winter wheat, and winter barley reduce the sediment discharge in May (S2) especially for 5 year events (Figure 3a), it can be seen that spring crops like, for example, maize, sunflower, and lupin have the highest sediment discharge (Figure 3a). In an eventual precipitation event in August (S3), the latter crops will have a reduced sediment discharge (Figure 3b) due to their soil cover.

For all 30 Patches, the mean sediment discharge for the S2 scenario (full crop rotation) for the different precipitation events were 0.04, 0.6, and 1.0 kg m^2 for a 5-, 50-, and 100-year event, respectively. The mean sediment discharge for the S3 scenario (full crop rotation) for the different precipitation events were 0.06, 0.4, and 0.7 kg m^2 for a 5-, 50-, and 100-year event, respectively. Furthermore, the patches showed a decrease in erosion affected cells and an increase in cells with a sediment budget close to zero for the 5-year precipitation event (exemplary for 2021, Figure 3). For the 50- and 100-year precipitation event, shifts from lower to higher erosion values were observed. However, it can be seen that the most affected areas are located in the flow accumulation zone and not in the steepest parts of particular slopes (Figure 1a).

In Figure 4, the influence of the spatial heterogeneity is exemplarily shown for patches 60 and 68, both in the low yielding part of the experiment, subject to the same crop rotation, and classified as flat with moderate inclined portions according to Deumlich et al. (2021). During the S2 scenario, the average soil loss for a 50 year event varies substantially with 1.9 kg m^2 (patch 60) and 0.5 kg m^2 (patch 68). In both patches, summer crops like lupin, maize, and sunflower are most prone to erosion, which were mostly in final seedbed preparation. Winter oats and winter rye, both narrow-row crops, covered the soil well during this time period, which resulted in less soil loss. In scenario S3, erosion at a 50 year precipitation event

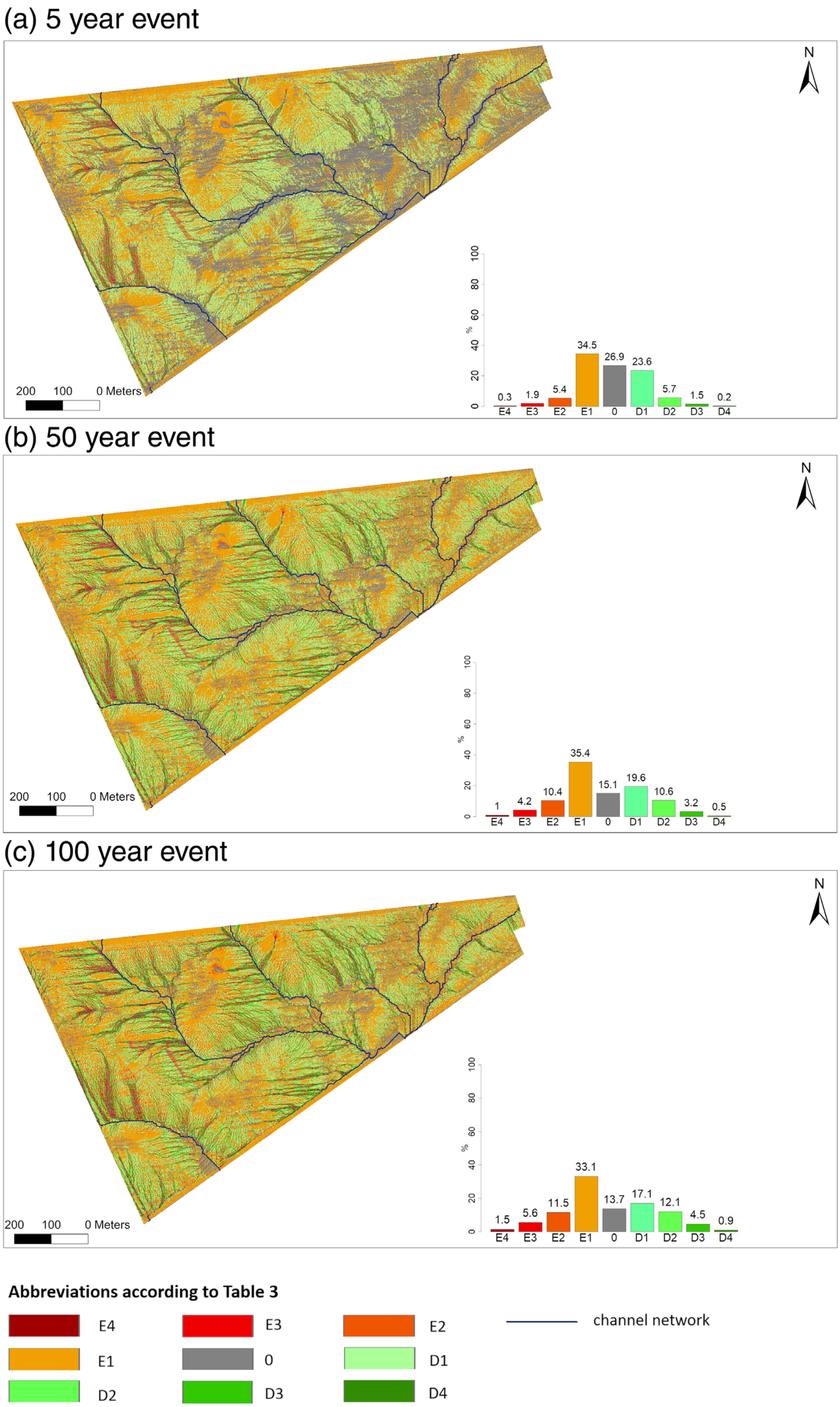

FIGURE 2 Sediment budget per pixel cell [kg m^2] as simulated for the "S1 –pre PatchCROP" scenario May and (a) 5 year, (b) 50 year and (c) 100 year precipitation event. The histogram shows the percentage area for each budget class according to Table 3 (E = erosion; D = deposition)

occurred mainly in patches cropped with maize, winter oats, and sunflower. Average soil loss range from 1.2 kg m^2 to 0.3 kg m^2 for patch 60 and 68, respectively. However, winter sown crops showed a good soil protection due stubble and residues. In contrast, larger losses were calculated in wide-row crops such as maize or sunflower.

TABLE 4 Effect of flower strips on potential sediment discharge [kg m^2] of patches during precipitation events either in May (S2) or August (S3) in dependence of the expected return period of the precipitation events (5, 50, or 100 years). Sediment discharge was calculated as mean of a full crop rotation (5 years). Presented are mean, standard deviation (SD), and analysis of variance (ANOVA) with $p < 0.05$ and $n = 10$

Scenario	Precipitation: expected return period	Sediment discharge of patches with reduced pesticide application [kg m^2]				ANOVA $p^{\#}$
		Without flower strip		With flower strip		
		Mean	SD	Mean	SD	
S2	5	0.05	0.047	0.02	0.020	n.s. $_{0.1157}$
	50	0.70	0.623	0.37	0.493	n.s. $_{0.2101}$
	100	1.21	1.062	0.64	0.845	n.s. $_{0.2056}$
S3	5	0.09	0.082	0.05	0.061	n.s. $_{0.3299}$
	50	0.52	0.474	0.30	0.391	n.s. $_{0.2654}$
	100	0.91	0.814	0.52	0.666	n.s. $_{0.2525}$

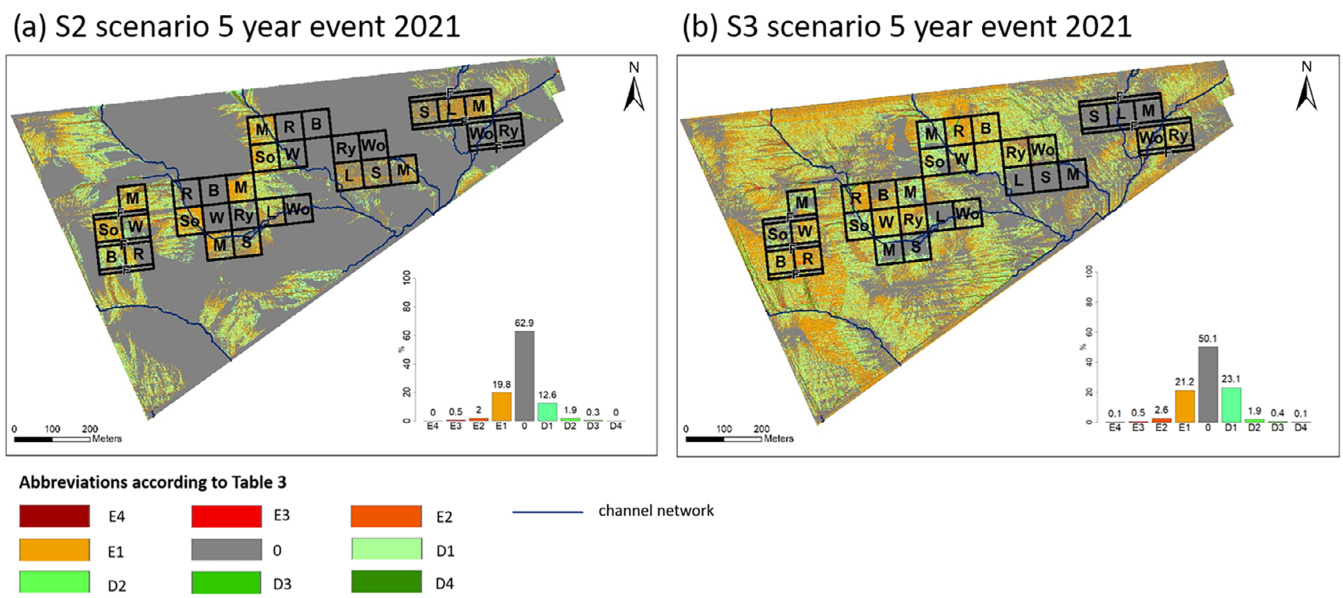

FIGURE 3 Sediment budget per pixel cell (SB) [kg m^2] as simulated for the "S2" scenario May (a), and for the "S3" scenario August (b) for a 5 year event 2021. M = maize; so = soybean; B = winter barley; R = winter rape; W = winter wheat; Ry = winter Rye; L = lupin; S = sunflower; wo = winter oats; F = flower strip; histograms refer to patch area

4 | DISCUSSION

A field classified by cross-compliance rules as non-erosion-prone was investigated by applying a new field design to estimate the potential water erosion hazards using the physical-based erosion model Erosion 3D. The unique aspect of this 70 ha field was an experimental redesign for a multifunctional and sustainable cropping system of small-scale management, while taking into account site heterogeneity (Grahmann et al., 2021). As soil erosion by water can be high on sites in young moraine areas, even if they were classified as weakly to moderately erosion-prone (Deumlich et al., 2018), assessments of the spatial distribution of soil erosion after a redesign of the field proved to be useful. The Erosion 3D model was already successfully applied and validated in Eastern Germany (Michael, 2000; Vogel et al., 2016). However, the input parameters were not determined experimentally, but estimated via the parameter catalogue and publicly available datasets; therefore, the results are more qualitative than quantitative.

The different computed scenarios confirmed that soil erosion increased with more intense precipitation (5-, 50- and 100-year rainfall event) and reinforced the importance of soil cover by plants to reduce soil loss. Evaluating the 30 patches demonstrated the sufficient soil cover

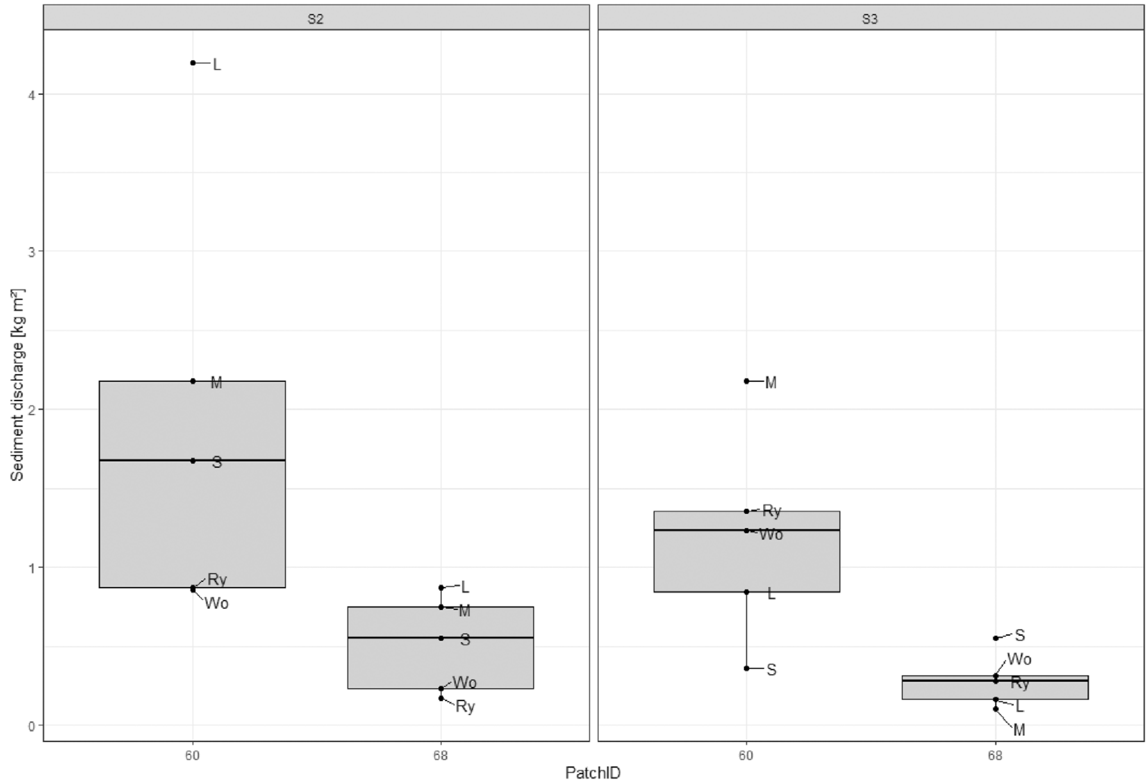

FIGURE 4 Effect of topography on sediment discharge. Exemplarily shown for patch 60 and 68 both in the low yielding part of the experiment, subject to the same crop rotation, and classified as flat with moderate inclined portions according to Deumlich et al. (2021). Mean of sediment discharge [kg m^2] of one crop rotation (5 years) for simulated precipitation (50 year event) in May (S2) and August (S3). M = maize; Ry = winter Rye; L = lupin; S = sunflower; wo = winter oats

by winter rape, winter rye, winter barley, and winter wheat to prevent soil loss in May (S2). In the August scenario (S3), most cereals and winter rape were harvested but before soil cultivation stubble provided good erosion protection as can be seen on the mean sediment discharge for S3 in comparison to S2. Contrasting, spring-sown crops were at high erosion risks during the simulated S2 scenarios in May, due to the final soil cultivation during seedbed preparation. Therefore, patches sown with sunflower or maize recorded a high soil loss in scenario S2 (Figure 4) whilst in August (S3), a lower soil loss was simulated, due to the full vegetative crops.

The presented results are, therefore, consistent with results of other studies, showing that, for example, small grains, the use of perennial sod crops or parcelling of the field can reduce soil erosion (Vogel et al., 2016). Yuan et al. (2022) implemented The Water Erosion Prediction Project (WEPP) model to study a rotational cropping system under changing climate conditions and demonstrated that crop rotations including perennial crops like alfalfa were the most effective soil conservation methods. New field arrangements or crop rotations that introduce permanent soil cover should be seen as optimised option for patch cropping to reduce soil erosion. Vogel et al. (2016) discussed the optimal arrangement of crops in the field and described the trade-off between converting areas with the highest erosion rates into, for example, winter cereal crop areas with low row spacing and sufficient cover during heavy rainfall in spring or snowmelt, and ensuring that the design is still manageable. However, patch crop systems promise to enable higher spatial diversification with adjusted yield designs (Donat et al., 2022).

Interesting observations were made regarding the slope characteristics of the patches. It could be assumed that a steeper characterisation of patches leads to simulated potential higher soil erosion. However, this simulation study demonstrated that patches with steeper parts did not show a higher sediment discharge than patches classified as plane. As depicted in Figure 2, strongest erosion values were reached in flow accumulation zones and branched networks. These flow accumulation zones and branched networks are mainly formed in Erosion 3D due to the Horton overland flow (Horton, 1945) and encourage higher erosion rates when the combined momentum flux of surface runoff and droplet impact exceeds soil specific resistance to erosion (Equation 2). However, these effects confirmed that common slope evaluation schemes as described by Deumlich et al. (2021) can only be used as indicators but were not able to assess small-scale soil erosion in the field. Introducing the patchy field structure resulted in both reduction and promotion of erosion effects. These were primarily related to the convex and concave relief shapes. As shown in Figure 4, patches with the same crop rotation and the same slope classification according to Deumlich et al. (2021), resulted in rather different sediment discharge, which can only be caused by different topography conditions. In summary, the slope is a significant factor of soil erosion by water as described in numerous studies (de Roo, 1993). Complex interaction between different curve forms (hollow forms: depressions; solid forms: crests, projections) and cultivation on the field are decisive for soil erosion and can only be simulated by physical soil erosion models. Nonetheless, their ability to reflect natural processes depends strongly on the spatial and temporal resolution of model input parameters (Jetten et al., 2003) and the quality of the digital elevation model and even 1×1 m grids are not able to fully represent natural topographic features.

Perennial flower strips have been widely recognised as erosion control measures (DWA, 2012; Fiener & Auerswald, 2003; López-Vicente et al., 2013). However, the perennial flower strips in the "PatchCrop" project were not established as an erosion control measure but implemented to increase structural diversity and biodiversity. Nevertheless, when designing the experimental patch area, it was assumed that establishing perennial flower strips at the north–south side of the patches would also lead to a lower sediment discharge. This assumption turned out to be true as patches with flower strips reduced the sediment discharge to approximately half of that of the patches without flowering strips (Table 4). Although runoff was reduced by flower strips, erosion still occurred for more severe precipitation events. This is in line with Vogel et al. (2016) who observed erosion reduction during low-intensity precipitation events but not for high precipitation events for permanent grass strips in agricultural fields. Contrasting to strip or patch designs, Schob et al. (2006) employed Erosion 3D to establish buffer zones and vegetated waterways beyond a predicted value of event based soil loss larger than 2 kg m^2. Establishing flower strips along the flow path rather than along the patches would have the advantage of increasing the retention time and thus infiltration of surface runoff as reported by Fiener and Auerswald (2003). Moreover, this would reduce the risk of runoff of nutrients and pesticides into adjacent surface waters (Nearing, 2001) and prevents harmful redistribution of fertilisers or pesticides within the field due to the targeted diversification. However, the layout of vegetated waterways is critical to their success and should, therefore, be carefully addressed (Vogel et al., 2016). Fiener and Auerswald (2005) have reported a reduction of runoff between 10% and 90%, depending on different layouts of vegetated waterways. Simulations of different layouts of flower strips along waterways' locations varying in width and design provide the opportunity to determine the optimal set-up to reduce sediment discharge while at the same time, minimising the loss of cropping area in agricultural fields with high spatial heterogeneity.

Because of the many factors effecting soil erosion processes, expert knowledge is required to develop mitigation strategies. Additionally, attention needs to be paid to interactions of these factors resulting into site-specific management decisions to improve crop production by the reduction of negative side effects. Marchamalo et al. (2016) presented a method to identify hotspots of sediment pathways by repeatedly field mapping after rainfall events. Keesstra et al. (2009) combined field surveys, site specific expert knowledge, and a sediment delivery model to predict erosion patterns. However, these approaches are accompanied by intensive field work. Physically based soil erosion models, such as Erosion 3D based on complex high resolution geo-relief will reduce such labour intensive field work to analyse environmental functional interrelationships (Raza et al., 2021). New cropping strategies like patch crop systems will also benefit from future developments of agricultural robots, predestined for field work at higher spatial diversification due to their smaller working width and thus also bring further advantages in terms of soil erosion, such as reduced soil compaction.

5 | CONCLUSION

Innovative cropping systems, which achieve increased soil health and climate resilience, require optimal soil protection and field diversity. Exemplarily for innovative cropping systems, a patch crop design was used to evaluate the usefulness of physically based erosion models during the development stages of such designs. This study showed that minor site-specific topography conditions and modified field design approaches need to be considered equally to achieve the best outcome in regards to sustainable soil use and water protection. For this purpose, a physically based soil erosion model offered a powerful tool to optimise land use and management practise in agriculture and should be used, among other things, during the design of future cropping systems.

AUTHOR CONTRIBUTIONS

Tobias Koch: Conceptualization; writing – original draft; methodology; software; investigation. **Detlef Deumlich:** Conceptualization; methodology. **Peter Chifflard:** Supervision. **Kerstin Panten:** Supervision;

conceptualization. **Kathrin Grahmann:** Conceptualization; project administration; resources.

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DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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