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Suitability of Strip-Tillage and Undersowing in Maize Crops to Control Runoff, Soil Erosion and Herbicide Loss: Field Trials and Modelling

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ABSTRACT

In Western Europe, the silt loam belt is highly vulnerable to erosion, especially in spring on fields cultivated with spring crops such as maize. Identifying conservation farming practices that reconcile agricultural production with soil and water protection is therefore critical. To this end, we evaluated the suitability of red fescue or white clover undersowing as well as strip-tillage to control runoff, soil loss, and herbicide surface loss in maize under natural rainfall conditions. Results were compared to a sole-maize control. The treatments were implemented in triplicate across six trial sites, distributed over three cropping seasons from 2021 to 2023. Weed control in the undersowing treatment proved particularly challenging due to herbicide constraints. Furthermore, no mitigation effect was observed on water, sediment, and herbicide surface flows, while maize yields were reduced by 11% on average compared to the control treatment. Although strip-tillage also resulted in an 11% loss in maize yields on average, it significantly decreased runoff (−31%) and soil loss (−60%) compared to the control. Based on the measured runoff and soil losses for the control and strip-tillage treatments, the process-based CREHDYS model was calibrated using a parsimonious approach. It was then used to conduct scenario analyses across a range of soil, rainfall and slope conditions found across the Belgian loess belt. On average across all scenarios, pluvial flood hazard was reduced by about half. Modelling of soil losses in strip-tillage proved insufficiently reliable, highlighting the need for improved characterisation of sediment fluxes in such systems. In spite of the disappointing results of undersowing in terms of yields and reduction in surface flows, future research could focus on other environmental benefits of this technique. For strip-tillage, strategies should be investigated to promote its adoption by farmers as a stepping stone towards no-till systems.

1 | Introduction

In cultivated farmlands across Western Europe, bare (non-vegetated) soils, typically around sowing time, are vulnerable to surface sealing and splash detachment, especially those with high silt and low organic carbon content (Morgan 2005; Blanco-Canqui and Lal 2010). Under such conditions, high-intensity rainstorms are likely to trigger sediment-laden Hortonian runoff, leading to muddy floods in downstream areas, while also enhancing diffuse pollution of surface water bodies (Van

Dijk and Kwaad 1996; Boardman et al. 1994; Evrard, Bielders, et al. 2007; Bach et al. 2001; Liess et al. 2021). Furthermore, in the long term, the imbalance between soil erosion and soil formation rates threatens the soil resource, particularly on steeply sloping fields (Montgomery 2007; Panagos et al. 2015). Maize-cropped fields are of particular concern because maize is sown in widely spaced rows, its sowing period around April–May coincides with an increased occurrence of stormy rainfall events (Ballabio et al. 2017), and it is commonly grown on steep slopes where it has replaced grassland as a source of fodder for cattle (Peeters 2009).

In order to prevent water and sediment surface flows and their adverse impacts, runoff generation and sediment detachment in the fields must be addressed (Verstraeten and Poesen 1999; Evrard, Persoons, et al. 2007). Conservation agriculture has been developed to this end, based on three pillars: minimising tillage, maximising vegetation cover and promoting crop diversification (FAO 2008). These basic principles have been translated into farming practices of various forms (e.g., cover crops or conservation tillage; Morgan 2005; Osman 2014). Strong evidence shows that these techniques provide various ecosystem services, particularly improvements in soil structure and the control of overland flows of water and sediments (Chabert and Sarthou 2020; Du et al. 2022; Palm et al. 2014). Some of these cultivation techniques have been adopted by farmers, although context-specific barriers still hinder their full implementation. In the context of intensive agriculture in Western Europe, the following limitations were identified: difficulties with pest and weed management, lower and/or fluctuating crop yields, the need for specific equipment, or the farmer's attitude (Heller et al. 2024; Van den Putte et al. 2010; Lahmar 2010; Wauters et al. 2010; Casagrande et al. 2016). Furthermore, there is significant variability in the effectiveness of conservation agriculture techniques in mitigating surface flows (Maetens et al. 2012; Clement et al. 2024). It is therefore essential to continue searching for and testing conservation practices that best reconcile agricultural production with soil and water conservation. The undersowing technique and strip tillage are two such techniques whose suitability for controlling surface flows has only been investigated to a very limited extent under western European conditions.

Undersowing is a type of intercropping technique. Intercropping involves the simultaneous cultivation of several (at least two) species on the same field. Given that maize (*Zea mays*) is cultivated in widely spaced rows, it is particularly suited for intercropping. The intercrop planted in the maize inter-row areas can potentially provide better soil protection through increased vegetation cover during critical erosion periods (Seran and Brintha 2010). When an associated crop is not intended for harvest and is grown beneath the canopy of a main crop, the intercropping can be specifically referred to as 'undersowing' or 'underseeding' (Ramseier and Crismaru 2014; Conrad and Fohrer 2016).

Several undersowing strategies have been investigated for their potential to mitigate overland flows in maize. When undersowing maize with fast-growing species such as ryegrass or red clover, it is recommended to delay sowing in order to limit competition with maize, a practice known as 'relay (inter)cropping' (Anil et al. 1998; Conrad and Fohrer 2016; Wall et al. 1991). In Germany, Goeck and Geisler (1988) reported a 62% reduction in soil loss following relay intercropping of white clover in maize, with greater effectiveness when rainfall erosivity in May and June was low. In a study in the Czech Republic, relay intercropping maize with cereals, clovers, grasses or mixtures decreased soil losses by 18% to 80% depending on the species and the timing of rainfall simulations (Kincl et al. 2022). In Canada, relay intercropping of Italian ryegrass in maize reduced the mean annual runoff and suspended sediment load by 53% and 74%, respectively (van Vliet et al. 2002). In these studies, runoff and erosion were mitigated mainly during late-season or even post maize harvest rainfall events and therefore had little effect in the early season, which is nevertheless a critical period for muddy floods in the Western European context (see above).

To prevent overland flows during the early stages of maize growth, one can consider sowing the intercrop simultaneously with maize yet still using slow-growing species to limit competition with maize. In New York state (USA), maize simultaneously undersown with perennial ryegrass, alfalfa, or red clover mitigated suspended solid loads by 77% on average, but the effect was statistically significant for only one of the two monitored spring seasons (Kleinman et al. 2005). Of these three undersown species, only red clover did not cause a significant reduction in maize yield compared to the sole maize control. In Germany, Goeck and Geisler (1988) reported a 23% maize yield loss when white clover was undersown simultaneously with maize, whereas in Denmark, undersowing red fescue did not lead to any significant maize yield loss (Manevski et al. 2015). However, there is overall very limited research on the mitigation effects of simultaneous undersowing in maize crops on runoff and erosion—and no research on pesticides—under temperate climate conditions. Specifically, the mitigation potential of different undersown species during spring storm events and the impact on maize yields remain unclear.

Strip-tillage, also known as 'zone-tillage', is another soil conservation practice. It involves tilling only the crop row using a knife, chisel, or coulter, while leaving the inter-row area untilled. It is suitable for preparing the seedbed of row crops such as sunflower, sugar beet and maize (Morrison 2002). Strip-tillage offers a trade-off between the benefits of conventional and reduced tillage systems. On the one hand, soil tillage in the crop row ensures successful crop emergence through crop residue clearing, proper soil-seed contact, and better soil warming. On the other hand, the inter-row soil remains undisturbed, preserving its structure and retaining crop residues on the surface (Morrison 2002; Laufer and Koch 2017; Morris et al. 2007). This can be beneficial for controlling soil erosion. Under simulated rainfall in Belgium, Ryken et al. (2018) measured a soil loss of 2.4 t/ha under conventional tillage, but only 0.02 t/ha under strip-tillage in a maize crop. In Poland, erosion monitoring during one maize cropping season by Jaskulska, Romaneckas, Jaskulski, and Wojewódzki (2020) showed an 82% cut in soil loss with strip-tillage compared to conventional (plough) tillage, which produced 3.14 t sediments/ha. Additionally, Achankeng and Cornelis (2023) reported an average 5% increase in crop yields in Europe following strip-tillage compared to conventional tillage.

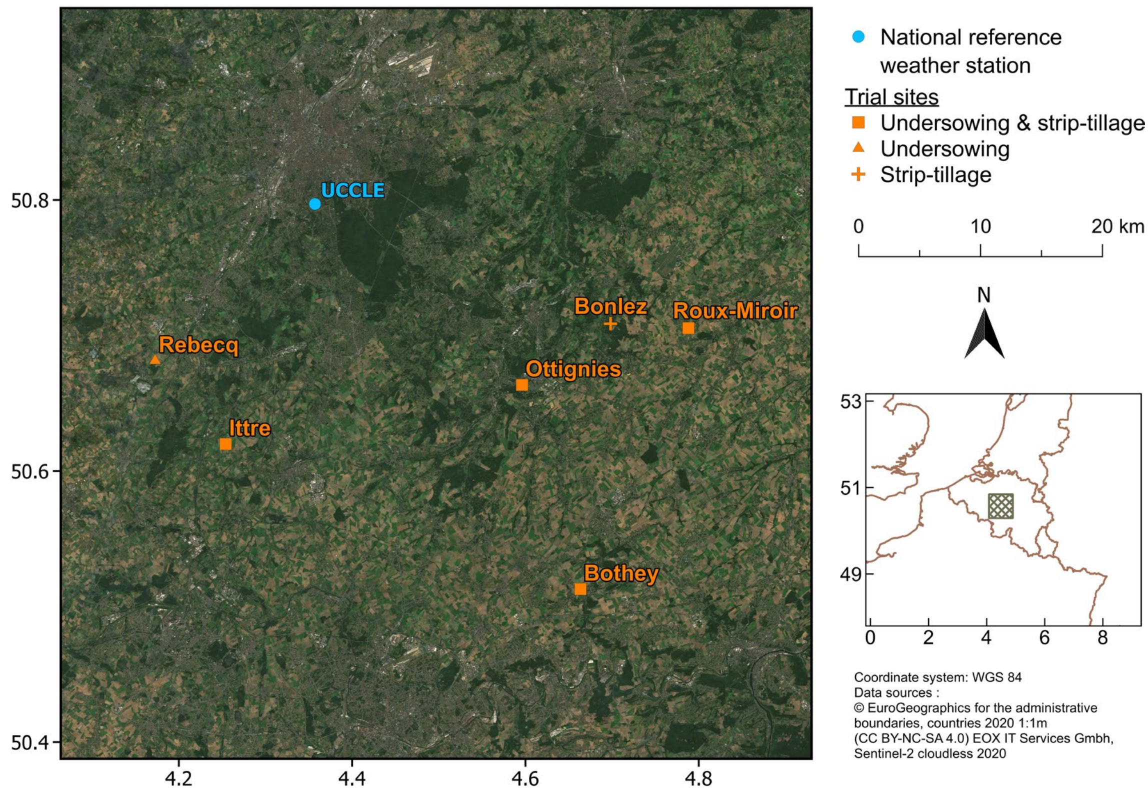

FIGURE 1 | Location of trial sites and national reference weather station used for scenario analyses (see Section 2.3.4).

Strip-tillage in maize crops thus holds great potential, although published studies assessing its effect on mitigating surface flows, in Western Europe but also elsewhere, remain scarce.

Considering the above, our study aimed at evaluating under field conditions the suitability of (1) undersowing red fescue or white clover, and (2) strip tillage, for controlling runoff, soil loss and herbicide loss in maize crops. Since surface flows measured in field experiments are highly specific to trial conditions, modelling is often used to generalise the outcomes of crop management practices on runoff and soil loss across a broader range of situations, within the limits of the calibration dataset (Wang et al. 2008; Mikołaj et al. 2023; Sittig et al. 2022; Laloy and Bielders 2009b). An additional objective was therefore to calibrate a physically based model to assess the potential of strip tillage in reducing surface flows across a wider range of conditions. For reasons explained in Section 2.3, only the control and strip tillage treatments were considered for the modelling.

2 | Materials and Methods

2.1 | Field Trials and Measurements

2.1.1 | Experimental Design and Treatments

Undersowing and strip-tillage trials were conducted in farmer fields of central Belgium during the maize cropping seasons 2021, 2022 and 2023 (Figure 1 and Table 1). Maize was grown for silage, which is the predominant use of maize in this region (Taube et al. 2020). Both techniques were evaluated at five sites each. At each site, monitoring was limited to a single year, as maize was part of a crop rotation, except in Ottignies, where monitoring was conducted on the same field for two successive years. The trial sites were selected to represent a range of soil textures: sandy-loam, loam and silt-loam. The slopes ranged from 4% to 18%. Detailed information about the field experiments is provided in Table 1.

The four treatments considered in the trials are as follows:

1. *Control*: Sole silage maize crop, sown at 75-cm row spacing and 14-cm intra-row spacing. Primary tillage (decompaction or moldboard plough) was performed if needed, followed by secondary tillage (powered rotary harrow or vibrating tine cultivator) for seedbed preparation.
2. *Undersowing red fescue*: Same as the control, with red fescue (*Festuca rubra*) undersown in the maize inter-rows at 10 kg/ha, simultaneous to maize sowing. Harrows mounted on the rear of the seeding unit lightly covered the broadcast fescue seeds with soil to enhance germination (Figure S1e).
3. *Undersowing white clover*: Same as (2), but with white clover (*Trifolium repens*) undersown at 5 kg/ha.
4. *Strip-tillage* (*ST*): No primary tillage. A single pass with a Zebra strip-tiller (Maschio Gaspardo) to a depth of approximately 15 cm in the residues of the previous winter cover crop, followed by maize sowing with a conventional disc seeder.

TABLE 1 | Characteristics of the field trials: Year, site name (municipality), GPS coordinates (WGS 84), slope steepness [%], texture class according to the USDA soil texture triangle and fractions of sand–silt–clay respectively [%], soil organic carbon content [%], treatments implemented (in triplicates), preceding main crop, preceding winter cover crop and total aboveground dry biomass produced at the end of the winter [t/ha], destruction mode of the winter cover crop, primary and secondary tillage operations performed on control and undersowing plots**, maize and undersowing sowing date, erosion plots monitoring period, cumulative rainfall [mm] during the monitoring period, maximum rainfall intensity measured at 10 min resolution [mm/h], number of 'meaningful' (mean runoff in any treatment > 0.5 mm) runoff events, herbicide sprayed for weed control in cropping season (application date and rate), additional remarks and observations specific to the trial.

Year	**2021**			**2022**		**2023**	
Site	**Rebecq**	**Bonlez**	**Ottignies**		**Ittre**	**Bothey**	**Roux-Miroir**
Coordinates	50.682 N, 4.171 E	50.709 N, 4.700 E	50.664 N, 4.597 E		50.620 N, 4.253 E	50.513 N, 4.664 E	50.705 N, 4.791 E
Abbreviation	Reb21	Bonl21	Ott21	Ott22	Itt22	Both23	RM23
Slope [%]*	7.4 ± 0.2	17.6 ± 0.6	16.5 ± 1.6		13.9 ± 0.9	4.2 ± 0.9	10.3 ± 0.8
Texture (sand–silt–clay fraction [%])	Silt loam (14–70–16)	Silt loam (31–54–15)	Silt loam (8–72–20)		Sandy loam (55–36–9)	Silt loam (4–74–22)	Loam (42–43–15)
SOC content [%]*	1.04 ± 0.03	1.22 ± 0.21	1.13 ± 0.11		0.95 ± 0.12	1.27 ± 0.06	1.10 ± 0.10
Treatments	Control Undersowing	Control ST	Control Undersowing ST		Control Undersowing ST	Control Undersowing ST	Control Undersowing ST
Preceding crop	Winter wheat	Winter wheat	Maize		Winter wheat	Winter wheat	Winter barley
Preceding winter cover crop (aboveground dry biomass)*	Mustard-clover (~1.7 t/ha)	Mustard-phacelia-clover (~1.7 t/ha)	No winter cover crop	Control: no winter cover crop	Oats-phacelia (1.7 ± 0.1 t/ha)	Control: no cover crop sown but widespread regrowth of preceding wheat (1.4 ± 0.3 t/ha)	Control: oats-pea-clover (mowed on 26/10) then bare soil
				Undersowing fescue and clover: preceding undersown fescue (1.0 ± 0.5 t/ha) and clover (0.3 ± 0.1 t/ha), respectively		Undersowing fescue and clover: fescue (1.3 ± 0.2 t/ha) and clover (1.0 ± 0.02 t/ha), respectively	Undersowing fescue and clover: fescue (1.5 ± 0.6 t/ha) and clover (1.7 ± 0.3 t/ha), respectively
				ST: rye-oats-mustard (0.5 ± 0.1 t/ha)		ST: mustard-pea-sunflower-phacelia (2.0 ± 0.6 t/ha)	ST: oats-pea-clover (3.4 ± 1.0 t/ha)

(Continues)

TABLE 1 | (Continued)

Year	2021			2022		2023	
Site	Rebecq	Bonlez	Ottignies	Ottignies	Ittre	Bothey	Roux-Miroir
Destruction of the winter cover crop	Winter mouldboard plough	Winter frost	/	29/3: glyphosate 1440 g/ha	29/3: glyphosate 1440 g/ha	5/4: glyphosate 1080 g/ha	31/10: rototiller on control 5/4: glyphosate 1080 g/ha
Primary tillage (control and undersowing)**	Winter mouldboard plough	Fall ripping	Spring ripping	Spring ripping	Spring mouldboard plough	Control: spring mouldboard plough. Undersowing: no primary tillage	No primary tillage
Secondary tillage (control and undersowing)**	2 × rotary harrow + 1 × seeding unit***	2 × vibrating cultivator 1 × disc seed drill	2 × rotary harrow + 1 × seeding unit***	1 × rotary harrow + 1 × seeding unit	1 × rotary harrow + 1 × seeding unit***	1 × vibrating tine cultivator + 2 × rotary harrow + 1 × seeding unit***	1 × vibrating tine cultivator + 2 × rotary harrow + 1 × seeding unit***
Sowing date	20/4	28/4	28/4	15/4	21/4	20/4	21/4
Monitoring period	23/4–20/9	4/5–15/9	10/5–15/9	22/4–25/8	27/4–24/8	27/4–11/9	26/4–8/9
Rainfall [mm]	443	546	538	171	156	315	282
Max. rainfall intensity [mm/h]	73.2	52.9	62.4	56.4	50.4	38.4	47.4
# meaningful runoff events	11	5	8	2	3	0	1
Herbicide for weed control	2/6: sulcotrione 300 g/ha	7/6: sulcotrione 225 g/ha (+prosulfuron, flufenacet, terbuthylazine)	8/6: sulcotrione 150 g/ha	9/6: sulcotrione 150 g/ha (+pyridate)	16/6: sulcotrione 225 g/ha (+pyridate)	5/6: sulcotrione 150 g/ha (+pyridate) 28/6: 300 g/ha sulcotrione	5/6: sulcotrione 150 g/ha (+pyridate) 28/6: 300 g/ha sulcotrione

(Continues)

TABLE 1 | (Continued)

Year	2021			2022		2023	
Site	**Rebecq**	**Bonlez**	**Ottignies**	**Ottignies**	**Ittre**	**Bothey**	**Roux-Miroir**
Remark	Undersown clover destroyed by herbicide		High weed pressure, manual weed control	High weed pressure, specific herbicide application on control & strip-tilled plots (3/6: tembotrione, isoxadifen-ethyl, flufenacet, terbuthylazine, nicosulfuron). Winter monitoring of control and undersowing treatments		High weed pressure	High weed pressure
			Rill erosion observed in strip-tilled maize rows. Winter monitoring of all treatments				

*Mean ± standard deviation.
**ST plots were prepared by 1 pass of strip-tiller followed by maize sowing with a disc seed drill, in all trials.
***Seeding unit: rotary harrow + roller + disc seed drill.

At each trial site, treatments were applied to 30 m long × 6 m wide plots cultivated along the slope. The experimental layout followed a randomised complete block design with three blocks.

2.1.2 | Trial Management

For soil conservation purposes, weed control was performed chemically across all trials, as mechanical weeding would have destroyed the undersown crops and disturbed the inter-row topsoil in strip-tilled plots. Based on previous undersowing field trials in Belgium, sulcotrione was identified as the herbicide with the lowest impact on the growth of both undersown red fescue and white clover (CIPF, n.d.), and it was therefore used in all trials. At Bonlez (2021) and Ottignies (2022), the control and ST treatments were additionally sprayed with broader-spectrum active compounds to achieve more effective weed control (Table 1). At Ottignies, manual weeding was also carried out in late June 2021 to remove remaining weeds.

All treatments received identical fertilisation, with NPK compound or liquid mineral fertiliser applied in spring at a rate of 140 kg N/ha. On the 2023 trials, farmers also applied 20 t/ha of cattle manure during winter. When the preceding crop was a cereal, the straw was exported, except at Rebecq (2021) where it was chopped and retained in the field. Additional details on trial management are provided in Table 1.

2.1.3 | Monitoring of Surface Flows

Within each plot, a 20 m × 3 m sub-plot was delineated using rigid plastic sheets buried into the soil to ensure surface hydrological isolation (further referred to as 'erosion plot'). Each erosion plot was equipped downstream with a steel funnel connected to a 500-L capacity tank for collecting runoff and sediment (Figure S1a). Adjacent to each erosion plot, a 3-m-wide 'duplicated sub-plot' of the same treatment was reserved for destructive interventions, that is, tractor tramlines for herbicide spraying and destructive measurements (see below).

On-site rainfall was continuously measured using WatchDog 1120 tipping bucket rain gauges, with a time resolution of 10 min. After significant rain events (> 5 mm rainfall) during the maize cropping season, runoff volumes were assessed either by measuring the water height in the collection tank for larger runoff volumes or by means of beakers for smaller volumes. Water samples were collected after thorough mixing of the tank's content using a closed-circuit pump. A 1 L sample was taken for sediment concentration analysis, which involved decanting, removing the supernatant, and oven drying the sediment at 45°C for a minimum of 3 days.

For all 'meaningful' runoff events occurring after herbicide spraying—a 'meaningful' event is here defined as an event for which the mean runoff in any treatment exceeds 0.5 mm—an additional 1 L sample was collected in an amber glass bottle to measure sulcotrione concentrations in runoff water. These samples were stored in a fridge at 4°C and subsequently analysed by the 'Protection, control products and residues unit' of the Walloon Agricultural Research Centre (CRA-W) in Gembloux, Belgium. There, samples were centrifuged and filtered at 0.2 μm to remove sediments, and the solution was extracted with acetonitrile before being analysed using liquid chromatography (Nexera X2Shimadzu, USA) coupled with a Time-of-Flight Mass Spectrometer (Q-TOF) (X500R ABSciex, Singapore). Only the dissolved phase of sulcotrione was measured, based on evidence from sediment analyses in 2021 as well as cost considerations. The sediment analyses, together with PRZM model scenario simulations (Young and Fry 2020), indicated that over 90% of the total seasonal transfer of sulcotrione (dissolved + adsorbed) occurred in the dissolved phase. The predominance in the dissolved phase can be attributed to the low mean Freundlich adsorption coefficient (K_{OC} = 36 mL/g; ECHA 2011) and high water solubility (> 130 mg/L; EFSA 2008).

Percentage vegetation cover was assessed every 2–3 weeks during the maize growth phase using orthogonal pictures taken from a height of 3 m. The proportion of green pixels was quantified with the 'Colour Threshold' tool in imageJ software (version 1.53e). Except for Bonlez and Rebecq in 2021, the total aboveground dry biomass produced by winter cover crops prior to the maize crop was measured at the end of winter (late March), just before chemical destruction. Aboveground biomass was harvested from a 1 m^2 representative area in each plot, then dried at 90°C for 2 days before being weighed. For Bonlez and Rebecq in 2021, biomass was estimated using sowing dates and temperature data, applying the cover crop growth function from Laloy and Bielders (2009a). Maize dry biomass yields were also evaluated at the end of the cropping season. The two central maize rows in each plot were harvested over a length of 1.5 m, and the biomass was dried at 90°C for 2 days before weighing.

Soil physico-chemical analyses (Table 1) were performed on one composite sample (0–20 cm) per experimental block, by the 'Centre provincial de l'agriculture et de la ruralité' laboratory in Belgium. Soil texture (fraction < 2 mm) was determined by sieving (fraction > 50 μm) and sedimentation (fraction < 50 μm), while organic carbon content was measured using dry combustion.

All previously described measurements were performed during the maize cropping season. Additionally, in Ottignies, runoff, soil loss and vegetation cover were also monitored during the winter periods of 2021–2022 (4/11/21–11/4/22) and 2022–2023 (6/10/22–29/3/23) for the control and undersowing treatments. The erosion plots were re-installed after maize harvest but were limited to the width of a single inter-row (0.75 m wide × 20 m long). After the maize harvest in 2021 (19/10), the control plots were stubble-tilled using a vibrating tine cultivator while the undersown plots were left undisturbed. The same operations were performed on control and undersown plots following the maize harvest in 2022. Biomass of undersown crops was also measured at the end of the winter (late March).

2.2 | Experimental Data Analysis

Before data analysis, some measurements were invalidated due to failure of the water collection device. In total, across all trials, such issues occurred for 7 out of 30 meaningful runoff events, resulting in 18 missing event-plot data out of 288. In these instances, missing data were replaced by the (mean of the) measurement(s) from the remaining valid plot(s) for the same treatment and event. Additionally, four tank overflows were recorded during two events in 2021. In these cases, the runoff volume was capped at the maximum tank capacity. At Ottignies in 2022, one replicate of the control treatment was entirely invalidated due to a sowing failure, which was not noticed on time. This resulted in a delayed soil cover and an outlier in the measured runoff and soil loss.

Cumulative measured surface flows—that is, total seasonal (spring–summer) runoff, soil loss, and sulcotrione loss—as well as maize biomass yield were analysed by fitting a generalised linear model (GLM) with two factors. The model included a 'trial' (site-year pair) effect, a 'treatment' effect (control vs. either undersowing of clover, or undersowing of fescue, or strip tillage), and the 'trial × treatment' interaction. To ensure normality of the residuals, the natural logarithms of cumulative flows and the square of yield data were used as the response variables. Normality of residuals was visually checked using a Q-Q plot, and homoscedasticity was assessed by plotting the residuals against the fitted values. For each linear model (i.e., for each outcome and each conservation treatment), a relative difference was calculated between the (back-transformed) estimated overall (across all trials and replicates) marginal mean outcome from the conservation treatment and the one from the control (Equation 1):

$$\text{relative difference } [\,\%\,] = \left(\frac{\widehat{Y_{\text{cons}}} - \widehat{Y_{\text{cont}}}}{\widehat{Y_{\text{cont}}}} \right) \times 100 \tag{1}$$

where $\widehat{Y_{\text{cons}}}$ and $\widehat{Y_{\text{cont}}}$ are the (back-transformed) estimated marginal mean outcome from the GLM for the conservation practice and the control treatment, respectively.

Significant differences between the estimated marginal mean outcomes from each conservation treatment and the control were assessed by marginal contrasts. When the p value of the marginal contrast for a treatment was statistically significant (p value < 0.05), the 'treatment × trial' interaction contrasts were also tested. Statistical analyses were performed using the 'emmeans' package (Lenth et al. 2024) in Rstudio 2022.12.0. For each outcome (runoff, soil loss, sulcotrione loss and yield), the 'raw' p values from all tested contrasts were adjusted using the Benjamini–Hochberg method (Benjamini and Hochberg 1995; 5% false discovery rate) to assess the significance of the effects of the conservation treatments on the outcome while correcting for multiple treatment comparisons.

2.3 | Modelling and Scenario Analyses

Given the lack of effect of the undersowing technique on all three surface flows and the challenges encountered with weed control (see Sections 3.2 and 4.1.1), only the control and ST treatments were considered for modelling.

2.3.1 | Model Description

In order to quantify the effectiveness of ST in mitigating runoff and soil loss across a broader range of conditions, the CREHDYS physically based hydrological model was calibrated using our field data (Laloy and Bielders 2009a). In view of the characteristics of our surface flow data, that is, event based measurements of water and sediment over entire cropping seasons, across multiple trial sites with sometimes few observed events per site, we sought to use a model that is applicable at the plot scale, time continuous, with limited parameterization requirements and proven applicability in the agropedological context of our study. Among popular mechanistic runoff and sediment transport models (e.g., EUROSEM, WEPP, LISEM), CREHDYS is the only one that meets all these criteria. Both EUROSEM and LISEM are event based models (Morgan et al. 1998; De Roo et al. 1996), while WEPP has very high parameterization requirements (Flanagan et al. 2001). CREHDYS is also spatially distributed, which was deemed valuable for representing the effect of zone tillage (see Section 2.3.2) (Bonell and Bruijnzeel 2005). Furthermore, CREHDYS has been successfully used to model the impact of winter cover crops on runoff and soil loss in maize cropping systems under similar agropedological conditions to those of the present study (Laloy and Bielders 2009b). The CREHDYS model includes a simple, temperature driven crop growth module. Rainfall interception, depressional storage, evapotranspiration and percolation to the subsoil (of undefined depth) are calculated using empirical equations. Infiltration is computed using the one layer Green–Ampt method modified for unsteady rainfall (Chu 1978). The erosion module simulates splash detachment as a function of rainfall kinetic energy, flow detachment based on flow shear stress, and transport and deposition determined by flow transport capacity. The hydraulic module solves the continuity equation and Manning's equation using a kinematic wave approach. Crop growth and soil water balance (evapotranspiration and percolation) are calculated on a daily time step, while overland flow processes (interception, infiltration, soil detachment and deposition, overland flow) are calculated at a smaller time step, set to 1 min in the present study. The spatial resolution was set at 25 cm. For the soil water balance, CREHDYS operates as a simple bucket model assuming a single homogeneous topsoil layer, the depth of which was set to 20 cm because this corresponds to the zone with the highest root density (Sha et al. 2024). Consistent with our trial sites, plots were modelled with a uniform slope. Further details on the hydrological and sediment modelling components of CREHDYS can be found in Laloy and Bielders (2008, 2009a).

2.3.2 | Model Calibration and Parameterization

The modelling period for calibration and validation of each trial spans from maize sowing to the end of the experimental monitoring (see Table 1; except for Ott21, see below). Winter seasons were excluded from simulations due to insufficient data for parametrisation and calibration. Because trial sites changed each year due to crop rotation (except at Ottignies), each site requires specific parameter values for soil physical properties. Given the limited number of meaningful runoff events in some trials as a result of unfavourable rainfall conditions for runoff and erosion during the early part of the maize growing season, and to avoid equifinality issues, a parsimonious approach was necessary in selecting the site-specific parameters for calibration.

The saturated hydraulic conductivity (*Ksat*) and the Manning's *n* roughness coefficient were selected for optimization for the runoff and soil loss outcomes, respectively. These parameters were chosen for calibration because: (1) they are highly sensitive, as demonstrated by the sensitivity analyses of Laloy and Bielders (2008, 2009a); (2) unlike other parameters of the model, they are difficult to estimate from measurements, the literature or pedotransfer functions (Weynants et al. 2009; Shen et al. 2023) (see Table S1 for detailed parameterization); and (3) it is physically reasonable to assume that ST affects hydraulic conductivity (by increasing macroporosity through preceding crop roots and biological activity; Wahl et al. 2004) and hydraulic roughness (by increasing crop residues; Panachuki et al. 2015).

Calibration was performed separately for each trial. First, the *Ksat* for the control treatment ($Ksat_{\mathrm{cal,control},i}$) was calibrated for each trial i using inverse modelling. This involved minimising the Nash–Sutcliffe model efficiency coefficient (NSE, Equation 2; Jain and Sudheer 2008) for the runoff outcome of the control treatment ($NSE_{\mathrm{runoff,control},i}$), while Manning's n roughness coefficient was initially set to $0.03\,\mathrm{s\,m}^{-1/3}$ (Laloy and Bielders 2008). In a second step, Manning's n for the control treatment ($n_{\mathrm{cal,control},i}$) was calibrated by minimising the NSE for the soil loss outcome ($NSE_{\mathrm{erosion,control},i}$). For the ST treatment (again, separately for each trial), we attempted to calibrate the parameters specifically for the untilled inter-row area, assuming the parameter values of the 40-cm wide tilled row were the same as those for the control treatment.

For each calibration step (control runoff, control soil loss, ST runoff, ST soil loss), the parameter space was first explored through a global screening, with *Ksat* ranging from 0.1 to 10 mm/h and Manning's n from 0.01 to $0.1\,\mathrm{s\,m}^{-1/3}$. Subsequently, the Nelder–Mead algorithm was employed to locally converge to the optimal parameter value using the python package scipy.optimize (Virtanen et al. 2020).

$$NSE = 1 - \frac{\sum_{j=1}^{n} (\hat{y}_j - y_j)2}{(y_j - \overline{y_j})2} \tag{2}$$

where NSE is the Nash–Sutcliffe model efficiency coefficient, $\hat{y}_j$ is the simulated event flow (runoff or soil loss) at event j, y_j is the measured event flow at event j, $\overline{y_j}$ is the mean measured event flow across all events j. Note that due to the periodic flow collection methodology (see Section 2.1.3), j may occasionally correspond to a period with multiple runoff events. Strictly speaking, y_j and $\hat{y}_j$ correspond to the cumulative flows (measured or simulated, respectively) produced during the period between two visits ($j-1$ and j) at a given site. In addition to trial-specific NSE values, an overall NSE (across all trials) was calculated as a global indicator of model fit.

Additionally, simulations for the Ott21 trial were restricted to the period before June 28, when a manual weeding was performed on the plots which significantly altered soil surface conditions (see Section 2.1). Furthermore, a particularly extreme rainfall event with a return period of up to 200 years occurred in Belgium in mid-July 2021 (Journée et al. 2023). On July 15, 80 mm of rain fell within 24 h at Bonlez, while 41 mm had already fallen during the preceding 2 days. Within a reasonable range of *Ksat* values, the simulated runoff for this event greatly exceeded the measured runoff. We concluded that such a high-volume and prolonged event fell outside the scope of the one-layer Green–Ampt infiltration model as implemented in CREHYDS. This model neglects percolation to the subsoil during the rain event. As a result, the topsoil layer quickly reaches—and remains at—saturation under these extreme conditions, which likely led to the underestimation of infiltration. Therefore, we excluded this event from the model calibration for the Bonl21 trial. Finally, failures with on-site rain gauges occurred in some trials, requiring the use of hourly rainfall records from nearby weather stations (CRA-W 2024) to fill in data gaps. This applied to the first 42, 10 and 8 days of the monitoring period at Reb21, Bonl21 and Ott21, respectively. Fortunately, no 'meaningful' runoff event was recorded during those periods (Table 1).

2.3.3 | Model Validation

Given the limited runoff and sediment loss data available for each site and year, we conducted a leave-one-out cross-validation of the model (Wan Jaafar et al. 2011; Arsenault and Brissette 2014). As is well established in the literature (Flanagan et al. 2001; Jarvis et al. 2002; Weynants et al. 2009), we found a positive relationship between the optimised *Ksat* values and the sand fraction of the trial sites. For each treatment (control or ST) and for each cross-validation subset i (all n trials except trial i), we computed the linear regression between the calibrated *Ksat* and the sand content for the $n-1$ trials. The $Ksat_{\mathrm{cross-val,treatment},i}$ of the trial i was then predicted using this regression equation. For Manning's n, as it could not be predicted from static soil properties, we calculated the $n_{\mathrm{cross-val,treatment},i}$ for each trial i as the average of the calibrated Manning's n values from the other $(n-1)$ trials. Each trial was simulated using its respective cross-validation parameters values, and overall NSE values were calculated as indicators of model fit.

2.3.4 | Scenario Analysis

The scenario analysis aimed to estimate the mitigation effect of strip-tillage on runoff and soil losses in the loess belt of central Belgium. This analysis involves a comprehensive set of simulations that consider all levels of different factors, as outlined in Table 2, including the tillage treatment through specific values for the *Ksat* and Manning's n parameters. We simulated 30 cropping seasons, from April 15 to October 1st, using weather data (daily solar radiation, temperature and 10-min rainfall intensity) recorded at Uccle's national reference weather station between 1991 and 2020 (Figure 1; Royal Meteorological Institute 2024). Two levels of slope steepness (5% and 10%) and slope length (50 and 100 m) were assessed. In Wallonia in 2021, 32% of the cultivated area under silage maize was located on slopes exceeding 5%, and 6% of the maize cropped area was on slopes steeper than 10% (SPW 2022; Farr et al. 2007). The median size of a silage maize field was 1.7 ha (SPW, 2022), which corresponds to 130 m in length assuming square plots. However, as the model has been calibrated for much smaller slope lengths (20 m), and given that maize fields are unlikely to have such high slope gradients (5% or 10%) continuously over a long distance, slope lengths of 50

TABLE 2 | Cross-simulated factors for the scenario analysis, and (number of) levels.

Factor	Levels
Year (weather and rainfall sequence)	30 cropping seasons (15/4–1/10), from 1991 to 2020
Slope steepness	5% and 10%
Slope length	50 and 100 m
Soil texture of the topsoil (0–20 cm)	Silt loam 1: 10%–75%–15% sand–silt–clay ($\psi = 523$mm; $\theta_{sat} = 0.435$; $d50 = 22\mu$m) Silt loam 2: 27.5%–60%–12.5% sand–silt–clay ($\psi = 338$mm; $\theta_{sat} = 0.427$; $d50 = 30\mu$m) Loam: 45%–45%–10% sand-silt-clay ($\psi = 199$mm; $\theta_{sat} = 0.420$; $d50 = 43\mu$m)
Treatment	Control or ST
Ksat	20 values sampled according to the normal distribution around the confidence interval resulting from the regression $Ksat_{\text{cal.,treatment}} = f(sand)$. The sampling is therefore specific to each treatment and soil texture
Manning's *n*	5 values evenly distributed between the minimum and maximum value of the Manning's $n_{\text{cal,treatment}}$, that is: Between 0.016 and 0.082 s m$^{-1/3}$ for the control treatment Between 0.016 and 0.100 s m$^{-1/3}$ for the ST treatment
Total	$30 \times 2 \times 2 \times 3 \times 2 \times 20 \times 5 = 72\,000$ simulations

and 100 m were chosen for the scenario analysis. For soil texture, three textural classes were considered to represent the spectrum of textures found in the topsoil of soils from the Belgian loess belt (D'Or 2018; Table 2). Finally, inter-site variability in calibrated parameters was accounted for by sampling multiple values within their ranges, as identified during the calibration process. For each soil texture level and treatment, 20 values of *Ksat* were thus randomly sampled from the normal distribution within the confidence interval derived from the regression $Ksat_{cal,treatment} = f(sand)$ (Figure 4). For Manning's *n*, five values were considered for each treatment, evenly distributed between the minimum and maximum value of Manning's $n_{\text{cal,treatment}}$. All other parameter values were set according to the scenario, that is, $\theta_{sat}, \theta_{FC}, \theta_{WP}, \psi, d50$ were estimated from pedotransfer functions (PTF from Table S1; estimated values in Table 2) with the remaining parameters set at the same values used during calibration.

3 | Results

3.1 | Maize Yield, Biomass of Undersown Crops and Total Vegetation Cover

Measured maize dry biomass yield was found to strongly depend on the trial (Figure 2; p value $< 10^{-3}$), but the GLM revealed no significant trial-by-treatment interaction. Compared to the control, the three conservation practices significantly reduced mean maize yields by 8% to 14%, depending on the treatment (Table 3).

Overall, the total vegetation cover exhibited similar temporal dynamics across all treatments during the cropping season (Figure S2a). On average, undersown clover showed a marginally higher total cover compared to the control, with the difference peaking 60–75 days after maize sowing (84% ± 8% mean cover for undersown clover vs. 70% ± 11% for the control). This difference was not observed with undersown fescue (65% ± 14%). Consistent with this observation, undersown clover developed greater biomass than fescue during the cropping season (Figure S1b,c).

During the winter monitoring at Ottignies (2021–2022 and 2022–2023), mean cover in undersown clover plots decreased from 37% ± 13% after maize harvest to 19% ± 13% by the end of winter (Figure S2b), whereas undersown fescue maintained approximately 60% ± 10% cover throughout the winter. End-of-winter biomass, averaged across the two winter seasons, reached 1.6 ± 0.8 t/ha for fescue but only 0.4 ± 0.3 t/ha for clover.

3.2 | Runoff, Soil and Pesticide Losses

Figure 3 presents the measured cumulative surface flows for each trial and treatment. At Itt22, the three 'meaningful' runoff events (> 0.5 mm mean runoff) all occurred before herbicide spraying, while no meaningful event occurred at Both23. This explains the absence of measured sulcotrione loss for these two trials (Figure 3c).

Unsurprisingly, the 'trial' effect was highly significant (p values $< 10^{-3}$). Undersowing maize with red fescue or white clover did not result in any statistically significant mitigation effect on runoff, soil or sulcotrione losses (Table 3). It is worth noting that the lower flows measured in the fescue undersowing treatment at Reb21 compared to the control (Figure 3) likely result from high

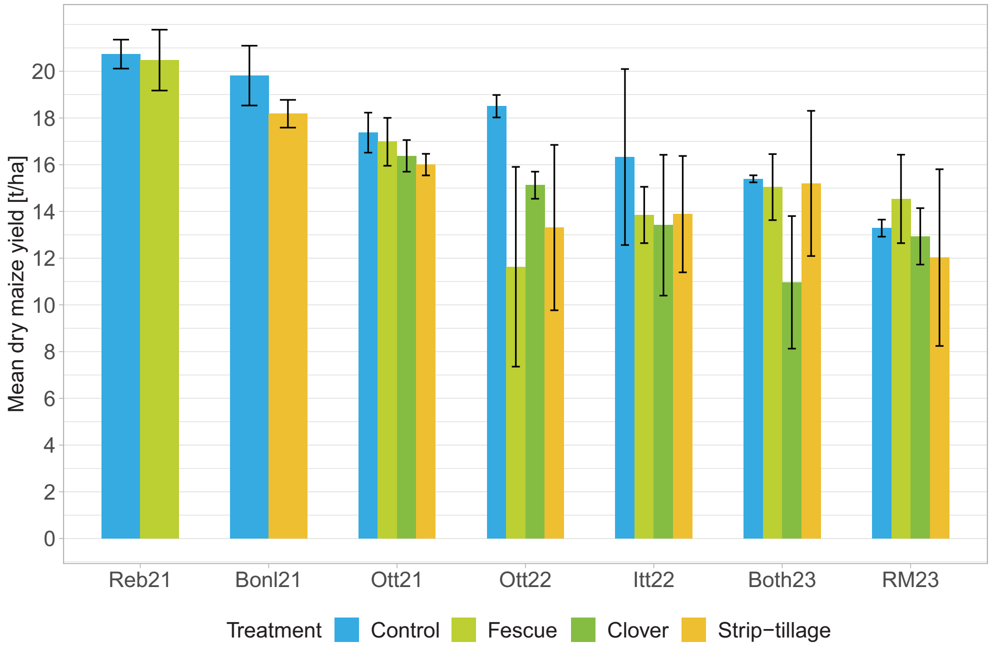

FIGURE 2 | Mean above-ground dry biomass maize yield for each treatment in each trial. Error bars are standard deviations. Not all treatments were implemented at each site-year. See Table 1 for trial abbreviations.

TABLE 3 | Relative difference in back-transformed overall (across all trials and replicates) marginal mean estimated from linear models between each conservation treatment and the control (Equation 1), with 95% confidence intervals.

		Treatment		
Response variable	**Effect measure**	**Undersowing fescue**	**Undersowing clover**	**Strip-tillage**
Maize yield	Relative difference [%] vs. control	**−8%** [−15%; −2%]	**−14%** [−23%; −7%]	**−11%** [−20%; −4%]
	Adjusted *p* value	**0.017**	**0.0036**	**0.011**
Runoff	Relative difference in geometric* mean [%] vs. control	+3% [−15%; +26%]	+26% [−6%; +70%]	**−31%** [−46%; −11%]
	Adjusted *p* value	0.75	0.31	**0.041**
Soil loss	Relative difference in geometric* mean [%] vs. control	−19% [−42%; +13%]	+11% [−47%; +133%]	**−60%** [−74%; −40%]
	Adjusted *p* value	0.47	1	**0.0009**
Sulcotrione loss	Relative difference in geometric* mean [%] vs. control	+2% [−28%; +44%]	−12% [−39%; +26%]	−3% [−32%; +39%]
	Adjusted *p* value	1	1	1

Note: Response variables are maize dry yields, and seasonal cumulative runoff, soil loss and sulcotrione loss. Adjusted *p* values of marginal contrasts (see Section 2.2) assess the significance of the differences between (log- or square-transformed) estimated marginal mean from each conservation and the control treatment, bolded when p value < 0.05.
*Geometric mean, because of the log-transformation of the response variable and the subsequent back-transformation (see Section 2.2).

weed pressure rather than the fescue itself. By chance, two of the three fescue plots were densely covered with weeds, whereas only one control plot was strongly affected.

Compared with conventional tillage (control), ST significantly reduced runoff and soil loss (Table 3). Because the trial × treatment interaction effect in the GLM's was statistically significant (p value = 3×10^{-6} for both runoff and erosion outcomes), contrasts were applied to investigate ST versus control differences by trial. Results showed that the difference was statistically significant only for the Itt22 trial, for both runoff (corrected p value = 2×10^{-7}) and soil loss (corrected p value = 4×10^{-8}).

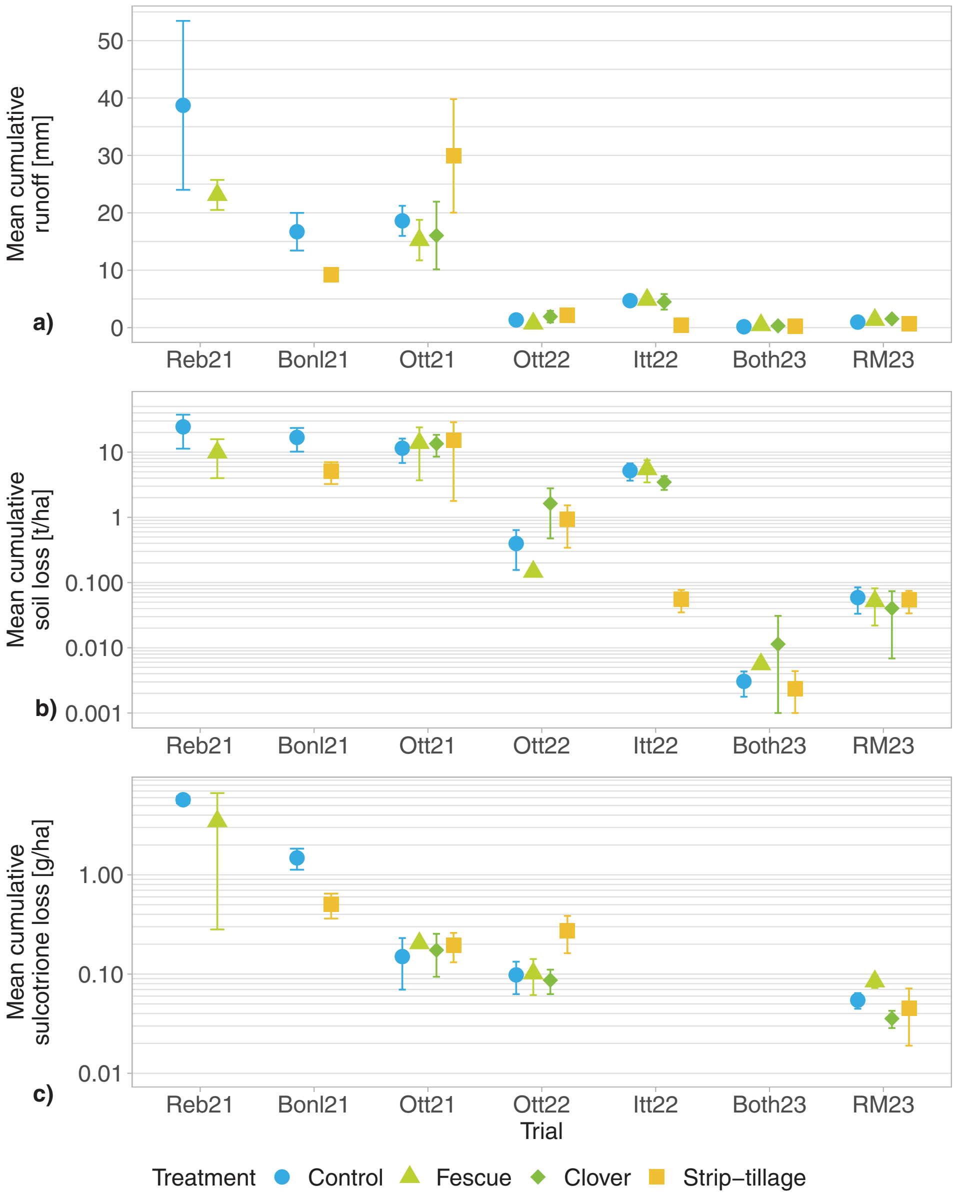

FIGURE 3 | Mean cumulative seasonal runoff (a), soil loss (b) and sulcotrione surface loss (c) for each treatment on each trial. Error bars are standard deviations. See Table 1 for trial abbreviations. Not all treatments were implemented at each site-year. No sulcotrione loss was measured at Itt22 and Both23.

Surface flows measured during the two winter seasons at Ottignies were low across all treatments. Across the winters 2021–2022 (total rainfall: 332 mm) and 2022–2023 (total rainfall: 405 mm), the average cumulative winter runoff was 1.5 ± 0.4 mm for the control, 2.2 ± 1.1 mm for the undersown fescue and 4.6 ± 5.3 mm for the undersown clover treatment (data not shown). Mean soil loss amounted to only 0.06 ± 0.04, 0.06 ± 0.04 and 0.12 ± 0.14 t/ha, respectively, for these treatments.

3.3 | Modelling of Strip-Tillage and Scenario Analysis

Given the lack of effect of the undersowing technique on surface flows and the challenges encountered with weed control, this section focusses exclusively on the control and strip tillage treatments. Figure 4 presents the calibrated values of *Ksat* and Manning's *n* for the control treatment. A linear relationship was found between *Ksat* and sand content. Fortunately, no correlation was found between *Ksat* and Manning's ***n***. CREHDYS did not simulate any flow detachment for the Both23 trial because the simulated flow shear stress did not reach the critical value required to trigger flow detachment. Consequently, no Manning's *n* could be calibrated for this trial.

According to criteria defined by Yilmaz and Onoz (2020) for NSE values, the CREHDYS model yielded good fits ($NSE_{cal,control} > 0.65$) for both runoff and soil loss with the control treatment (Figure 5a,b). When parameter (*Ksat* and Manning's *n*) values were estimated for each trial through cross-validation from the other trials, the model still delivered 'satisfactory' fits for event-scale surface flows ($NSE_{cross-val,control} = 0.29$ and 0.38 for runoff and soil loss

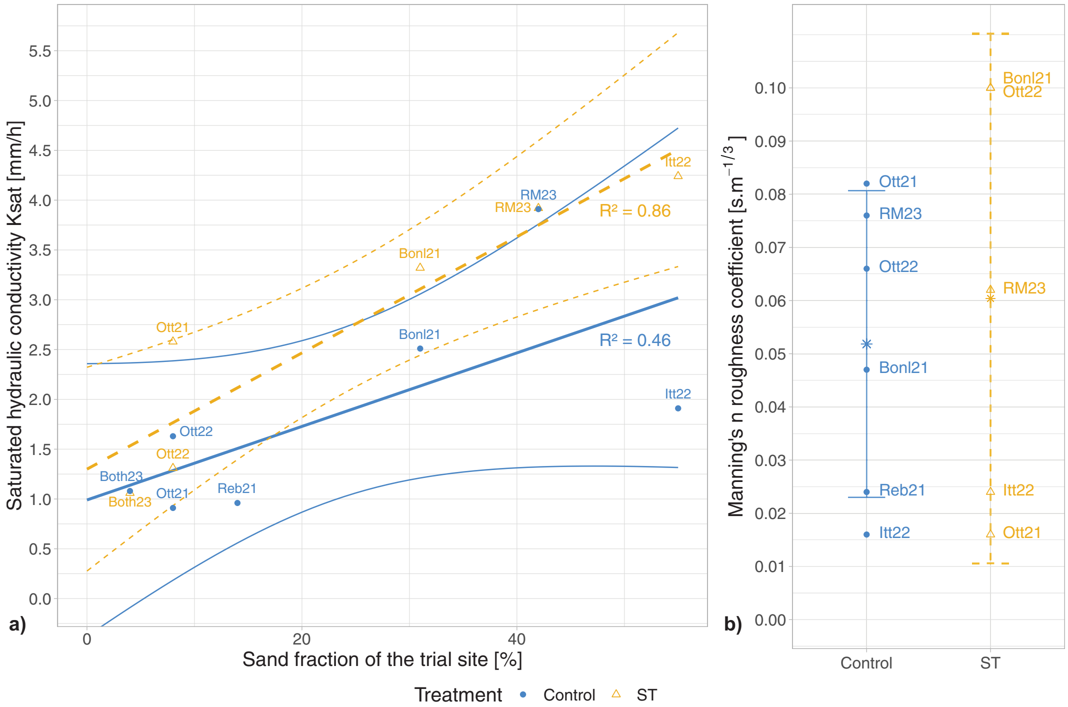

FIGURE 4 | Optimised parameters values following calibration of the CREHDYS model, per trial and treatment (control or strip-tillage (ST)). (a) for *Ksat*, with linear regression against trial sand content, and corresponding confidence intervals. (b) For Manning's *n*, with the mean value and confidence intervals.

respectively; Figure 5c,d), notwithstanding the high sensitivity to these two parameters.

For the ST treatment, calibrating *Ksat* and Manning's *n* for the untilled inter-row area while assuming the properties (*Ksat* and *n*) of the tilled row to be the same as the control failed to accurately reproduce observed runoff and soil loss. Specifically, trials where strip-tillage strongly mitigated surface flows (e.g., Itt22; Figure 3) were poorly modelled using this strategy because excessive flows were simulated from the row alone. This suggests that *Ksat* for the rows under ST treatment differs from that of the control treatment. However, attempting to calibrate separate Manning's *n* and *Ksat* values for the row and interrow for each trial would have led to equifinality issues. Therefore, for each trial i, a single 'effective' $Ksat_{cal,ST,i}$ was calibrated based on runoff measurements, and a single effective $n_{cal,ST,i}$ was calibrated using the soil loss data. Figure 4 shows the calibrated *Ksat* and Manning's *n* values for ST, along with the linear regression of *Ksat* versus sand content. For Bonl21 and Ott22 trials, $n_{\mathrm{cal,ST}}$ reached the upper limit of the predefined range ($0.1\,\mathrm{s\,m^{-1/3}}$) and Manning's *n* was therefore set at this value. The simulated event runoff under ST matched observed runoff well following calibration (Figure 5a; $NSE = 0.56$), and the fit remained acceptable after cross-validation (Figure 5c; $NSE = 0.38$) (Yilmaz and Onoz 2020). While soil loss modelling was nearly satisfactory following calibration (Figure 5b; $NSE = 0.29$), it was unsatisfactory following cross-validation (Figure 5d; $NSE = 0.07$). Even so, the positive NSE indicates that the model's predictions of event soil loss still outperform the average measured event soil loss.

The outcomes from the scenario analysis are presented as cumulative probabilities of flows (runoff and soil loss) per treatment for combined factors (Figure 6), and as boxplots depicting flow value distributions by scenario factor (Figure S3). Soil texture and slope length actually had little influence on total seasonal or maximum daily runoff and soil loss (Figure S3i–p). In contrast, inter-annual variability in climatic conditions (rainfall) (Figure S3a–d), variability in *Ksat* values, and treatment had a much greater impact on surface flows. As expected, variability in Manning's *n* values and slope steepness had additional influence on soil losses, but very little effect on runoff (Figure S3e–h). Averaged across all factors except treatment, control scenarios resulted in cumulative seasonal runoff and soil loss of 6.5 ± 8.8 mm and 6.2 ± 11.6 t/ha, compared to 3.7 ± 6.7 mm and 3.4 ± 8.4 t/ha under ST simulations.

4 | Discussion

4.1 | Field Experiments

4.1.1 | Undersowing

In contrast to the few previous studies in the literature that report successful runoff and erosion control through crop associations in maize, our undersowing trials demonstrated no mitigation effect on surface flows, in addition to challenges related to weed control (Figure S1f) and reduced maize yields. We attribute the weed control issues to the narrow action spectrum of sulcotrione (and pyridate), which is nevertheless required to avoid damaging the undersown crops (red fescue and white clover). Additionally, the response of both weeds and undersown crops to theses herbicides appeared highly variable, depending on moisture conditions (even at a constant application rate). Further research is needed to develop undersowing techniques that are agronomically operational.

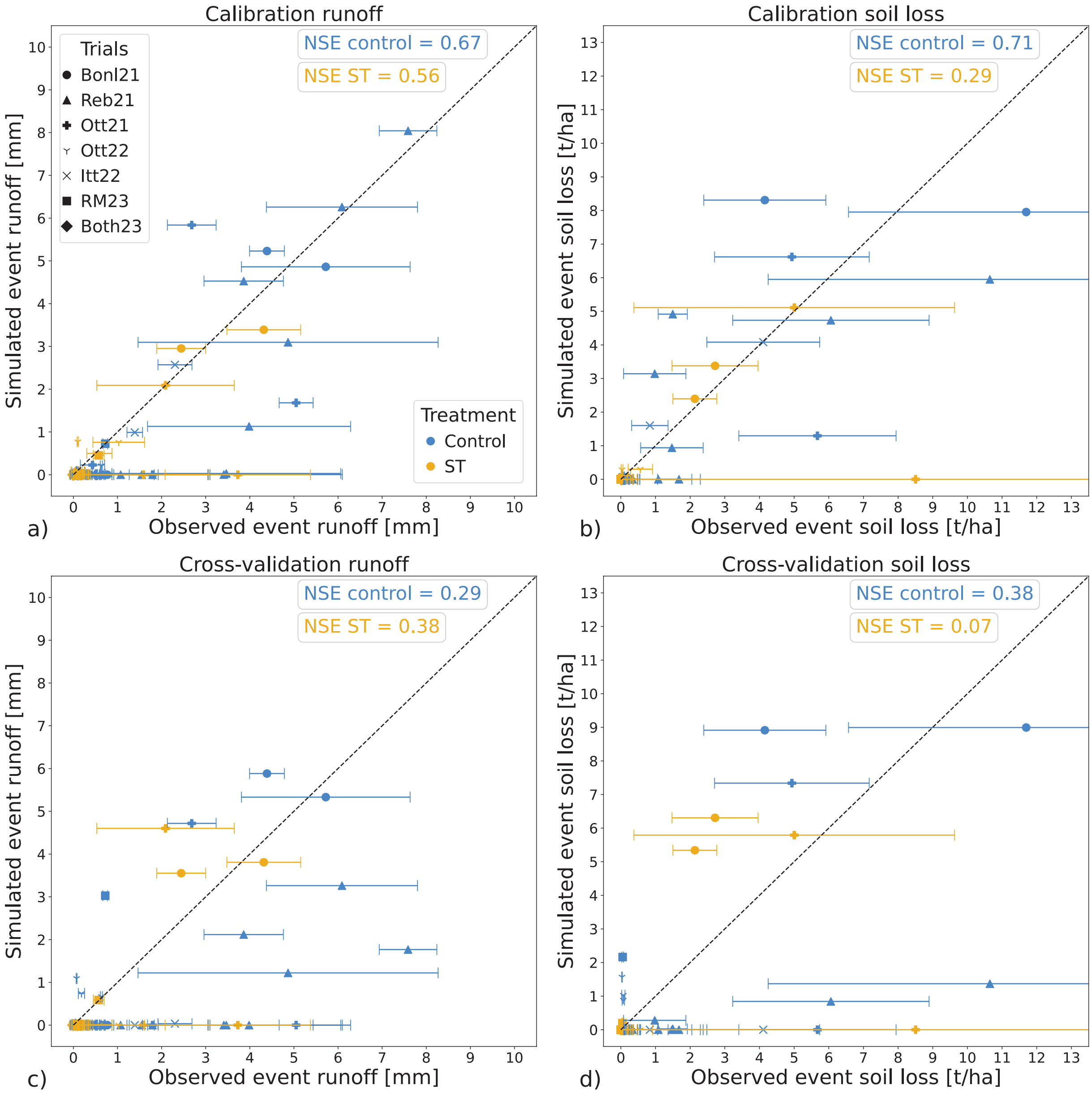

FIGURE 5 | Simulated versus measured event runoff and soil loss, per trial (see Table 1 for trial abbreviations) and treatment (control or strip-tillage [ST]). Overall (all trials together) Nash–Sutcliffe efficiency coefficients NSE are reported as indicators of model fit. (a) Runoff fit, with calibrated *Ksat* (and nominal Manning's $n = 0.03\,0.1\,\mathrm{s\,m^{-1/3}}$, see Section 2.3.2). (b) Soil loss fit, with calibrated *Ksat* and Manning's *n*. (c) Runoff fit, with cross-validated *Ksat* and Manning's *n*. (d) Soil loss fit, with cross-validated *Ksat* and Manning's *n*.

The lack of mitigation effect of undersowing on surface flows is primarily explained by the slow growth of fescue and clover, which resulted in similar total vegetation cover dynamics between control and undersown plots (see Section 3.1 and Figure S2a). Red fescue and white clover did not significantly cover the soil until mid-June, by which time maize plants already provided extensive inter-row cover. While weed control proved challenging in many trials, it does not appear to explain the lack of mitigation effect. For instance, on the Itt22 trial, where weeds were well controlled and the three 'meaningful' runoff events occurred during the early maize growth period (between 29 and 49 days after sowing), neither runoff nor soil loss was significantly reduced in the undersowing treatment compared to the control treatment (Figure 3). This contrasts with the limited studies in the literature under similar agro-climatic conditions, which report significant reductions in runoff and erosion achieved by undersowing practices, whether sown simultaneously or as relay intercrops (see Section 1).

The maize yield loss of approximately 11% due to undersowing (Table 3) aligns with findings in the literature. Some studies have reported maize yield reductions of 15% to 50% following undersowing (Kleinman et al. 2005; Goeck and Geisler 1988), while others observed equivalent yields compared to sole maize crop (Wall et al. 1991; Conrad and Fohrer 2016; Alonso-Ayuso et al. 2020). The more pronounced yield loss observed with clover undersowing compared to fescue is consistent with the

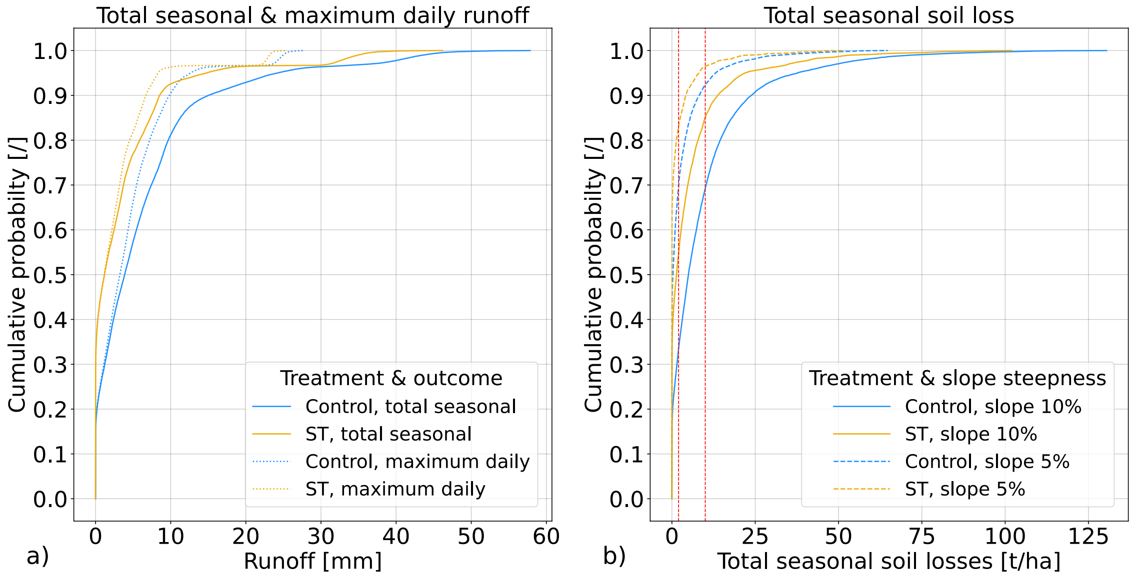

FIGURE 6 | Cumulative probability distribution for all simulations of the scenario analysis for (a) total seasonal and maximum daily runoff by treatment, and (b) total seasonal soil loss by treatment and by level of slope steepness. The two vertical red dashed lines in (b) refer to the critical thresholds for 'sustainable' erosion rate of 2 t/ha/year (Panagos et al. 2020) and 10 t/ha/year (Morgan 2005).

higher vegetation cover and biomass of clover during the maize cropping season (Figure S2a). This suggests that undersown clover competed more strongly with maize for resources (water, nutrients) compared to fescue.

During the winter season (Figure S2b), fescue maintained its biomass and vegetation cover, while clover declined due to frost damage and consumption by overwintering Canada geese. Furthermore, traffic during maize harvest operations in 2021 and 2022 damaged both undersown crops, leaving prominent wheel tracks and resulting in uneven vegetation cover. As a result, approximately half of the undersown plot area was almost bare due to wheel tracks (see Figure S1g,h). Because end-of-winter biomass of fescue (1.6 t/ha) and clover (0.4 t/ha) had been measured on track-free sub-plots, the overall biomass for the entire undersown plot area can thus be estimated at 0.8 ± 0.4 t/ha for fescue and 0.2 ± 0.15 t/ha for clover, averaged across the late winter periods of 2022 and 2023. Such values are low. In comparison, Laloy and Bielders (2010) measured an average end-of-winter aboveground biomass of 1.2 t/ha for 'standard' rye or ryegrass winter cover crops sown after maize harvest, across two sites monitored over three winter seasons in Belgium. However, we wish to emphasise the need for caution in interpreting our winter season results, as the monitoring was conducted at a single site (Ottignies) over only two winter periods.

Although runoff during these winter seasons was low across all treatments, it was lowest on the control plots. Despite the soil being bare (Figure S2b), the stubble tillage performed on the control treatment after maize harvest created a rough surface that effectively limited overland flow during the winter (Clement et al. 2024). Given the two main issues encountered with the undersowing technique as tested in this study—poor weed control and the lack of flow mitigation effect—it cannot be recommended for erosion control as it stands.

4.1.2 | Strip-Tillage

We demonstrated that strip-tillage in maize significantly mitigates runoff and soil loss, reducing these by 31% and 60%, respectively, compared to conventional tillage (Table 3). These results align well with the meta-analysis by Clement et al. (2024), which reported that a conservation tillage scheme including a single pre-sowing tillage operation—such as strip-tillage—when implemented for the first time in a spring row crop (e.g., maize) grown on a silt loam soil, reduces runoff by an average of 37% and erosion by 58%, compared with conventional tillage. However, other studies focusing specifically on strip-tillage in maize have reported even greater reductions. For instance, Ryken et al. (2018) observed a decrease from 2.4 t/ha under conventional tillage to 0.02 t/ha under strip-tillage in Belgium, while Jaskulska, Romaneckas, Jaskulski, and Wojewódzki (2020) reported reductions from 3.14 to 0.57 t/ha in Poland. One explanation for these differences could lie in the level of soil protection against crusting and detachment offered by crop residues. Ryken et al. (2018) measured a 14% soil cover by crop residues from the preceding grain maize crop under strip-tillage, compared to only 2.3% in conventional tillage. Jaskulska, Romaneckas, Jaskulski, and Wojewódzki (2020) tested various preceding crops (winter and spring cereals, soybean, sunflower, rapeseed, maize) and observed residue cover reaching up to 80% under strip-tillage (4–13 t/ha of residues on the surface), compared to just 4% under conventional tillage (0.2–0.8 t/ha of residues). In our trials, residue cover was considerably lower. At Itt22, ground cover by residues was highest, with rough estimates from our orthogonal pictures showing approximately 10% cover in strip-tillage plots compared to almost 0% in control plots. In contrast, at Bonl21, despite good biomass development of the winter cover crop in autumn, residue cover in spring (post-tillage and sowing) was similarly low in both treatments (1%–2%) due to early frost damage and subsequent decay of the winter cover crop. Nevertheless, despite the limited residue level at Bonl21, strip-tillage still reduced runoff and soil loss (Figure 3).

During the field trials at Ott21, a specific rill erosion process was observed in the strip-tilled maize rows (Figure S1k), resulting in increased runoff and soil losses (Figure 3), which were not observed in the control plots. This phenomenon may be attributed to the combination of repeated erosive events, erodible silt loam soil, absence of preceding winter cover crop (i.e., no protective residues), and a slightly elevated inter-row relative to the row, which concentrated runoff towards the latter. Although the strip-tiller used in this study is equipped with two discs surrounding the tine (Figure S1i) to limit soil transfer from the row to the inter-rows, the elevated inter-row relative to the row was frequently, though not always (e.g., Ott22 and Itt22), observed.

Despite the substantial reduction in runoff and soil loss, the relative mean difference in sulcotrione losses between the strip-tillage and control treatments was only 3%. This apparent discrepancy is primarily due to the absence of herbicide loss data for the Itt22 trial, where strip-tillage had an outstanding mitigation effect on runoff and soil loss, but where the three meaningful runoff events occurred before herbicide application, which prevented the high flow mitigation potential of this trial from being reflected in the sulcotrione loss mitigation.

Regarding maize yields, we found a statistically significant average decrease of 11% under strip-tillage compared to the control treatment. From an economic perspective, this yield loss may be partially offset by reduced tillage costs. In their meta-analysis covering Europe, Achankeng and Cornelis (2023) also reported an average crop yield loss under strip-tillage on silt loam soils, though the decrease (3%) was less than that observed in the present study. Apart from the inclusion of crops other than maize in their review, the discrepancy may in part stem from the timing of the strip-tillage operation in our experiments, which was performed immediately prior to maize sowing—either on the same day or the day before. As has been shown for conservation (no or reduced) tillage practices in general, in humid climates like Belgium's, soil temperature is a key limiting factor for crop development, especially in the early season. Soils with minimal or no tillage tend to remain wet and cold for a longer time, delaying crop germination (Van den Putte et al. 2010; Achankeng and Cornelis 2023). In temperate European climates, performing strip-tillage 1–2 weeks before sowing may enhance soil warming in the row, thereby minimising crop yield losses (Luna and Staben 2003; Adee et al. 2016). It may be that a significant number of the primary studies collected by Achankeng and Cornelis (2023) implemented such anticipated strip-tillage.

4.2 | Modelling and Scenario Analysis

Based on the field experiments, two highly sensitive parameters of the CREHDYS model, *Ksat* and Manning's n, were calibrated for each treatment (control and strip-tillage) and each trial. According to this methodology and for the sake of parsimony, we assumed that other parameters—including *RR*, θ_{sat}, *As* and *Coh* (Table S1)—do not depend on treatment. For random roughness (*RR*), this assumption appears justified based on in situ soil surface observations during the maize growing season as well as the literature (Paz-Ferreiro et al. 2008; Panachuki et al. 2015). For the other three parameters, the assumption is more tenuous, as tillage (or its absence) is known to affect total porosity, soil stability, and cohesion (Tangyuan et al. 2009; Casamitjana et al. 2009). Nevertheless, these parameters are less sensitive compared to *Ksat* or Manning's n (Laloy and Bielders 2009a; De Roo and Offermans 1995). In ascending order, the model is also sensitive to the soil moisture content at field capacity (θ_{FC}), to the soil matric potential (ψ) at the wetting front, and to the median particle diameter ($d50$) (Laloy and Bielders 2009a). However, as these parameters are primarily related to soil granulometry, adjusting their values based on cropping practices seems of little relevance, at least when studying short-term impacts. Furthermore, these key parameters could be estimated from measured textural fractions, though such an approach does not fully capture the specific soil structural conditions of each trial. This may partly explain the limited quality of model fits (see below).

Moreover, Laloy and Bielders (2009b) demonstrated that, as with many (complex) models and due to structural inadequacies (Efstratiadis and Koutsoyiannis 2010), there is a space of Pareto-optimal solutions—multiple sets of parameters that balance the two objectives of the CREHDYS model: accurately simulating runoff on the one hand, and soil loss on the other. In other words, the *Ksat* value that optimises runoff prediction is likely not the same as the one that optimises soil loss prediction, and vice-versa for Manning's n. Given the methodology used in this study, it is not guaranteed that the calibrated parameter set falls within this Pareto-optimal space. Since *Ksat* is the most sensitive parameter, our calibration prioritises runoff prediction over soil loss.

Notwithstanding these methodological concerns, the calibrated values of *Ksat*—ranging from 0.9 to 4.2 mm/h—align with those reported in other studies on silt loam soils with low organic carbon content, which are highly prone to crusting (Cerdan et al. 2002; Laloy and Bielders 2009b; Elhakeem et al. 2018). Similarly, the calibrated Manning's n values are generally consistent with the literature (Kwaad et al. 1998; Laloy and Bielders 2009b), though they cover a broad range (Figure 4b), skewed towards the higher end.

The application of the CREHDYS model to simulate flows observed in our trials yielded good or satisfactory fits for runoff and soil loss prediction on the control treatment, and for runoff on strip-tillage, in both the calibration and cross-validation steps (see Section 3.3 and Figure 5). However, the simulation of soil loss under strip-tillage was unsatisfactory, particularly after cross-validation (see Section 3.3 and Figure 5b,d). While three major soil loss events were well predicted by the model (Figure 5b), the highest soil loss event under strip-tillage (Ott21 trial) was not predicted at all. Although rill erosion was observed in the strip-tilled maize rows (see Figure S1k), no runoff—hence no erosion—was simulated. This case is illustrative of a parameter set that prioritises the runoff prediction objective over the soil loss one. Additionally, for two trials (Bonl21 and Ott22), the upper limit for Manning's n during calibration (max $n = 0.1\,\mathrm{s\,m^{-1/3}}$) was reached for the strip-tillage treatment, suggesting that changes in (*Ksat* and) hydraulic roughness alone cannot explain the soil loss mitigation under strip-tillage. For the reasons outlined above, calibrating additional parameters was deemed inappropriate. A similar parsimonious calibration approach with the WEPP model by Zhang et al. (1996), using event plot data from diverse sites and conditions, showed comparable fit performances ($R^2_{\text{runoff}} = 0.77$ and $R^2_{\text{erosion}} = 0.36$), even with a much larger dataset (556 plot-years).

The scenario analysis results, focusing on treatment effect, show that the average seasonal runoff and soil loss rate simulated in the conventional tillage scenario (6.5 mm and 6.2 t/ha) are nearly double that of strip-tillage (3.7 mm and 3.4 t/ha). From a soil conservation perspective, the total seasonal soil loss is the most relevant flow outcome. For the control treatment, 19.2% of all control treatment simulations yield a seasonal soil loss rate above the 10 t/ha threshold for a whole year (Morgan 2005; Bielders et al. 2013). Under strip-tillage, only 9.2% of the simulations exceed this threshold. However, this 10 t/ha/year threshold is relatively high, as a more recent critical tolerable value of 2 t/ha/year has been recommended for Europe, based on soil formation rates (Panagos et al. 2020). The probability of exceeding this 2 t/ha/year threshold is 48.5% for the control treatment and 31.1% under strip-tillage. The situation becomes even more critical when focusing specifically on the more vulnerable 10% slope steepness scenario (Figure 6b). Overall, the soil loss mitigation achieved by strip-tillage appears comparable to other conservation farming practices, such as cover crops or deep tillage (Maetens et al. 2012), and is even more effective than intensive reduced tillage systems (no ploughing but repeated powered shallow tillage operations; Clement et al. 2024).

From the perspective of mitigating the risk of extreme pluvial flood events, maximum daily runoff is likely the most relevant flow outcome to look at. We are preferring it to maximum daily soil loss because, in our case, runoff is modelled more accurately than soil loss (Figure 5). In the control treatment, half of the simulations show maximum daily runoff values below 3.2 mm, whereas under strip-tillage, 50% of simulated max. daily runoff values are below 1.1 mm (Figure 6a). Over the 30 simulated years, the average maximum daily runoff from a maize field exceeds 7 mm under conventional tillage in 1 year out of five (6/30 years). In contrast, this same runoff amount is only reached in 1 year out of 10 (3/30 years) when ST is applied (Figure S3c). In other words, strip-tillage management could halve the pluvial flood risk from maize fields.

Although already satisfactory, the overall mitigation effects of strip-tillage on runoff and soil loss are likely underestimated in this study. The technique could further improve soil structure when applied over successive years (Han et al. 2024; Jaskulska, Romaneckas, Jaskulski, Gałęzewski, et al. 2020). This effect may also extend to strip-tillage within a crop rotation, provided that other (winter) crops are cultivated using conservation tillage practices (Packer et al. 1992; Clement et al. 2024). In most of our trials, however, conservation tillage was implemented as a one-time intervention (during a single season) in a previously conventional system. The slow processes enhancing soil structure following conservation management—such as increased organic matter concentration in the topsoil and biological activity—were not captured in our field experiments and, therefore, are not reflected in the model calibration or scenario analysis.

5 | Conclusions

We evaluated undersowing (fescue or clover) and strip-tillage through field experiments, focusing on their impact on runoff, soil loss and herbicide surface loss in a maize crop. The undersowing technique showed serious failures in weed control, had no mitigation effect on surface flows, and reduced maize yields. Even with adequate weed management, undersowing as implemented in this study seems ineffective for controlling erosion and muddy floods, as it did not substantially increase total vegetation cover during the critical stages of the maize growing season. Additionally, after maize harvest, undersown crops did not provide any clear advantage over standard winter cover crops (sown after maize harvest).

As opposed to undersowing, strip-tillage reduced all measured surface flows on average, with statistically significant reductions in runoff and soil loss according to field experiments data. A 30-year scenario analysis for the Belgian context using the CREDHYS model showed that strip-tillage could approximately halve the risk of storm-induced pluvial floods. The model's prediction of soil loss was unsatisfactory, highlighting the need for improved characterisation of sediment fluxes in such a spatially heterogeneous tillage system. Despite its suitability for different row crops, strip-tillage remains less adopted than other conservation tillage practices in Europe (Heller et al. 2024). Future research should investigate the underlying causes for this adoption gap and explore ways to promote the practice among farmers.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available in the Supporting Information of this article. The full datasets and codes are available from the corresponding author upon reasonable request.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section.