IMPACTS OF SOIL MOISTURE AND TILLAGE ON SHORT-TERM EROSION IN AGRICULTURAL LANDS OF NORTH CENTRAL MEXICO †

[IMPACTO DE LA HUMEDAD DEL SUELO Y LABRANZA EN LA EROSION A CORTO PLAZO EN TIERRAS AGRICOLAS DEL NORTE CENTRO DE MÉXICO]

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SUMMARY

Background: Soil erosion is a natural process accelerated by anthropogenic activities such as agriculture, leading to increased runoff and erosion, resulting in global environmental and economic losses. Addressing this issue through conservation agriculture is critical, particularly in arid regions where soil degradation is prevalent. This study adds value by evaluating the combined effects of tillage practices and antecedent soil moisture conditions (AMC) on runoff and soil erosion under controlled rainfall simulation. **Objective**: To assess the effects of tillage practices and AMC on runoff and soil erosion, hypothesizing that conservation-oriented practices would reduce erosion and runoff. **Methodology**: A randomized complete block design experiment was conducted in an arid zone of North-central Mexico. Four tillage treatments were evaluated: 1) no crop (NC), 2) maize with conventional tillage and crop residues (CTR), 3) maize with conventional tillage (CT), and 4) maize sown by handspike (HS). Each treatment was tested under two AMC scenarios: dry and wet. Runoff and soil erosion were measured, and results were analyzed using ANOVA. **Results**: Dry AMC significantly reduced erosion in HS ($p \leq 0.01$) and CTR ($p \leq 0.05$) compared to wet AMC. CT and CTR produced the lowest erosion under wet AMC ($p \leq 0.05$). For total runoff, CTR and HS produced the lowest values under dry AMC. These findings highlight the effectiveness of crop residue cover in CTR and no-tillage cropping (HS) in reducing both erosion and runoff. **Implications**: The study demonstrates the importance of soil moisture conditions and tillage practices in managing erosion. Limitations include the use of simulated rainfall, which may not fully capture natural variability. However, the findings provide valuable insights for conservation agriculture in arid regions. **Conclusion**: Crop residue cover and no-tillage cropping are effective in reducing soil erosion and runoff, especially under dry AMC. These practices are crucial for sustainable soil management in arid agroecosystems.
Key words: conservation agriculture; runoff; corn; arid lands; simulated rainfall.

RESUMEN

Antecedentes: La erosión del suelo es un proceso natural acelerado por actividades antropogénicas como la agricultura, lo que genera un aumento del escurrimiento y la erosión, y con ello, pérdidas económicas a nivel global. Abordar este problema mediante prácticas de agricultura de conservación es fundamental, especialmente en regiones áridas donde la degradación del suelo es un problema importante. Este estudio aporta valor al evaluar los efectos combinados de las prácticas de labranza y el contenido antecedente de humedad del suelo (CAHS) sobre el escurrimiento y la erosión del suelo bajo condiciones de lluvia simulada. **Objetivo**: Evaluar los efectos de las prácticas de labranza y el CAHS en el escurrimiento y la erosión del suelo, con la hipótesis de que las prácticas de conservación reducirían la erosión y el

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escurrimiento. **Metodología**: Se realizó un experimento con un diseño de bloques completos al azar con cuatro repeticiones en una zona árida del norte centro de México. Los tratamientos evaluados fueron: 1) sin cultivo (SC), 2) maíz con labranza convencional y residuos de cultivo sobre el suelo (LCR), 3) maíz con labranza convencional (LC) y 4) maíz sembrado a espeque (EP). Cada tratamiento fue llevado a cabo en dos CAHS: seco y húmeda. Se midieron el escurrimiento y la erosión del suelo, y los resultados se analizaron mediante un ANVA. **Resultados**: El CAHS seco redujo significativamente la erosión en EP ($p \leq 0.01$) y LCR ($p \leq 0.05$) en comparación con el CAHS húmedo. Los tratamientos LC y LCR produjeron la menor erosión bajo el CAHS húmedo ($p \leq 0.05$). Para el escurrimiento total, los tratamientos LCR y EP presentaron los valores más bajos bajo el CAHS seco. Estos resultados destacan la efectividad de la cobertura del suelo con residuos de cultivo en el tratamiento LCR y la siembra sin laboreo del suelo (EP) para reducir tanto la erosión como el escurrimiento. **Implicaciones**: El estudio demuestra la importancia del CAHS y las prácticas de labranza en el manejo de la erosión. Entre las limitaciones se incluye el uso de lluvia simulada, que no captura su variabilidad natural. No obstante, los hallazgos aportan información valiosa para la agricultura de conservación en regiones áridas. **Conclusión**: Las prácticas orientadas a la conservación, particularmente la cobertura del suelo con residuos de cultivo y la siembra directa, son efectivas para reducir la erosión del suelo y el escurrimiento, específicamente bajo el CAHS seco. Estas prácticas son fundamentales para el manejo sostenible del suelo en agroecosistemas áridos.
Palabras clave: agricultura de conservación; escurrimiento; maíz; zonas áridas; simulación de lluvia.

INTRODUCTION

Soil erosion imposes significant economic and environmental burdens, reducing corn yield by up to 65%, soil nitrogen by over 50%, organic matter by 39%, water retention by 7% to 44%, and infiltration by as much as 93%. Economically, replenishing lost water and nutrients in US agricultural lands costs about $27 billion annually, while in India, soil replacement costs $245 million (Pimentel *et al.*, 1995; Nkonya, Mirzabaev and von Braun, 2016).

While soil erosion is a natural process, human activities like agriculture, construction, and mining accelerate it. Agricultural practices, especially converting native vegetation to farmland and using conventional tillage, worsen erosion. Conventional tillage leads to 56% to 60% more soil loss compared to no-tillage methods. Excessive agrochemical use degrades soil health and pollutes water, while heavy machinery compacts soil, reducing water absorption and increasing runoff. These activities highlight the urgent need for sustainable land management practices (Swaminathan, 2006; Patil, 2018; López-García *et al.*, 2020).

Conventional agriculture in arid and semi-arid regions involves intensive tillage that disrupts soil structure and reduces organic matter, making the soil vulnerable to erosion. This issue is prevalent in regions like the Sahel, the Middle East, South Asia, the southwestern United States, Australia, and southern Europe (FAO and ITPS, 2015; World Bank, 2019). Poor soil management and lack of vegetation cover exacerbate erosion and runoff, diminishing soil productivity and impacting water quality. Conservation agriculture practices, such as no-tillage and crop residues, can improve soil structure, increase water infiltration, and reduce erosion, promoting sustainable agriculture.

Conservation agriculture mitigates the adverse effects of conventional farming by altering tillage methods and adding crop residues. No-tillage farming enhances water infiltration and reduces runoff, minimizing soil erosion. Crop residues act as protective barriers against raindrop impact, regulate soil temperature and moisture, and create a stable environment for crops. This sustainable approach promotes long-term productivity and environmental conservation (Lal, 1995; Baker and Saxton, 2007).

In Mexico, conservation agriculture covers only 41,000 hectares, but practices like crop rotation, organic matter addition, intercropping, and terracing help mitigate soil erosion, enhance fertility, and improve water retention. Expanding these practices could boost agricultural resilience and productivity (Friedrich, Derpsch and Kassam, 2017; Cotler and Cuevas, 2019). Currently, 52% to 76% of Mexico's land suffers from water erosion, affecting agricultural productivity and food security, especially in states like Chihuahua, Zacatecas, Durango, San Luis Potosí, Tamaulipas, Aguascalientes, Sonora, and Coahuila. Addressing soil erosion through terracing, contour plowing, and cover crops, and promoting no-tillage is crucial for sustainable farming in these regions (Bolaños-González *et al.*, 2016; Cotler, Corona and Galeana-Pizaña, 2020).

The objective of this research was to study the effect of agricultural management practices and antecedent soil moisture on soil erosion by water and runoff in an arid zone using simulated rainfall.

MATERIALS AND METHODS

Study site

Seasonal maize was planted on September 11 and 12, 2015, in the Northern Mexican settlement of Santo Domingo, at an altitude of 1750 masl (Figure 1). The climate of the zone is arid, and the average annual temperature ranges from 14 to 22 °C. The annual rainfall ranges from about 200 to 400 mm. The Reference Soil Group is Leptosol, with a sandy clay loam texture and soil organic carbon content of 0.76%.

Experimental design

The evaluated treatments of antecedent soil moisture conditions (AMC) were dry and wet. Separately, four tillage systems were evaluated too: 1) No Crop (NC), with no soil and vegetation movement; 2) Conventional Tillage (CT), with moldboard plow followed by harrowing, furrowing, and corn planting; 3) Conventional Tillage + Residues (CTR), which was the same as CT, but with crop residues on the soil surface; and 4) Handspike (HS), which consisted of no soil movement and corn planting using only a wooden stick. The treatments were replicated four times and arranged in a randomized complete block design. The scheme of the experiment is shown in Figure 2.

Rainfall simulator

The design of the rainfall simulator was adapted from the Miller (Miller, 1987) experiment (Figure 3). It consisted of a water supply tank, a pump with connection to three sprinklers, and three electric solenoid valves. The opening was controlled by a PLC (programmable logic controller) and three 360° spray nozzles. To regulate the flow of water to the valves, pressure was monitored by three manometers. Power was supplied by the spray nozzle of a 5500-watt portable generator producing 110 VAC.

At each experimental unit, the simulator operated within a rainfall intensity range of 69 to 172 mm/h and exhibited high spatial variability, as indicated by Christiansen's uniformity coefficient of 38.4% (Figure 4).

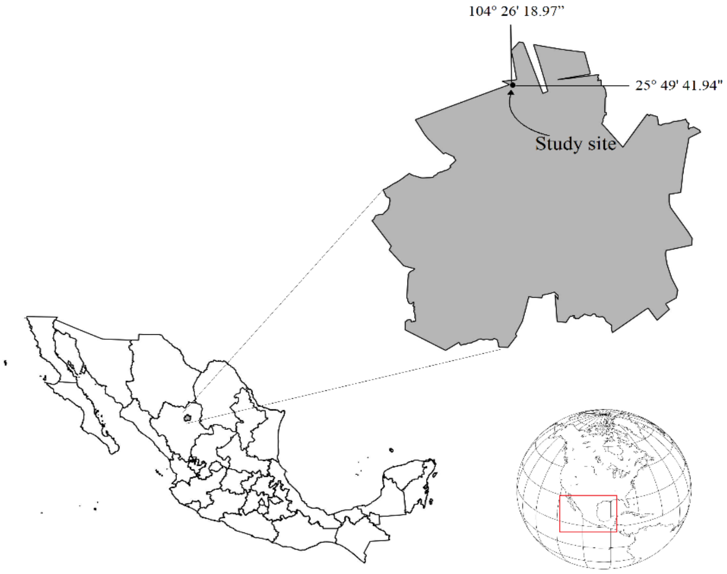

Figure 1. Location of the study in the state of Durango, Mexico. Source: Created by the authors.

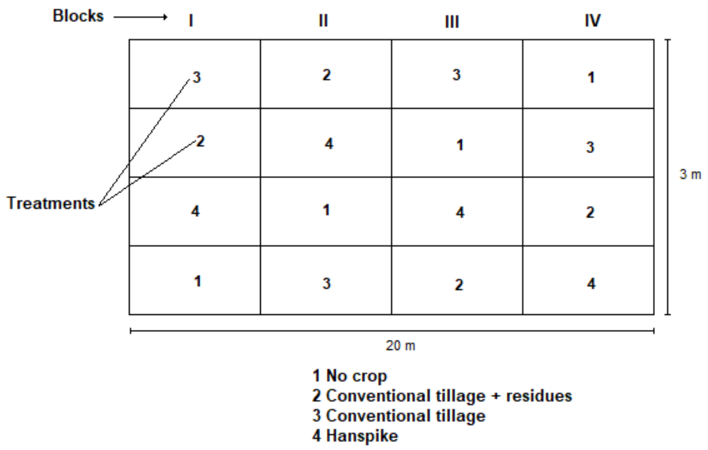

Figure 2. Treatment distribution and experimental plot dimensions.

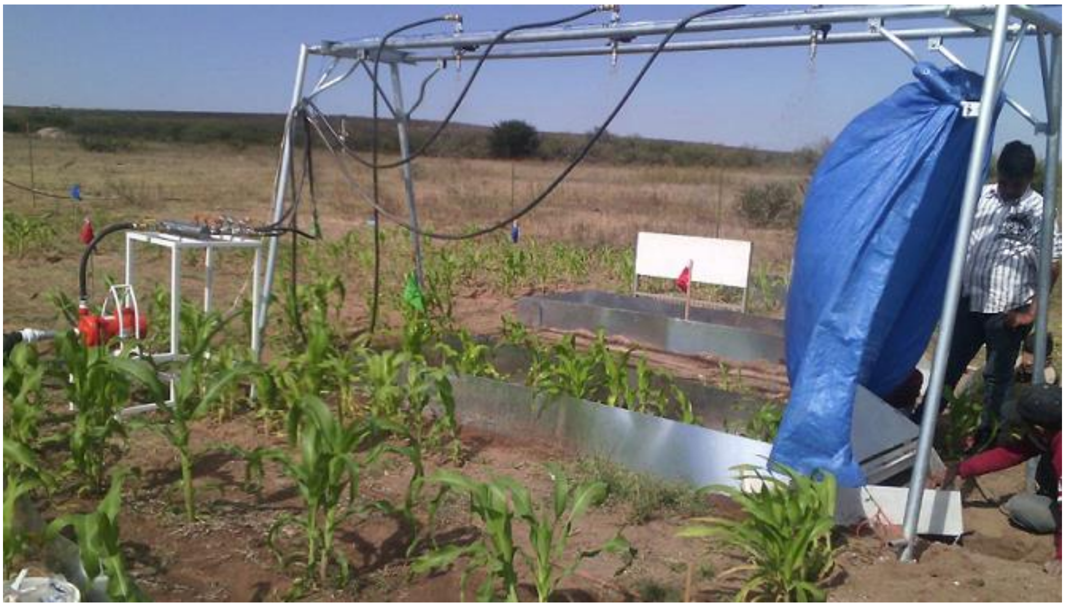

Figure 3. Rainfall simulator on a simulation plot.

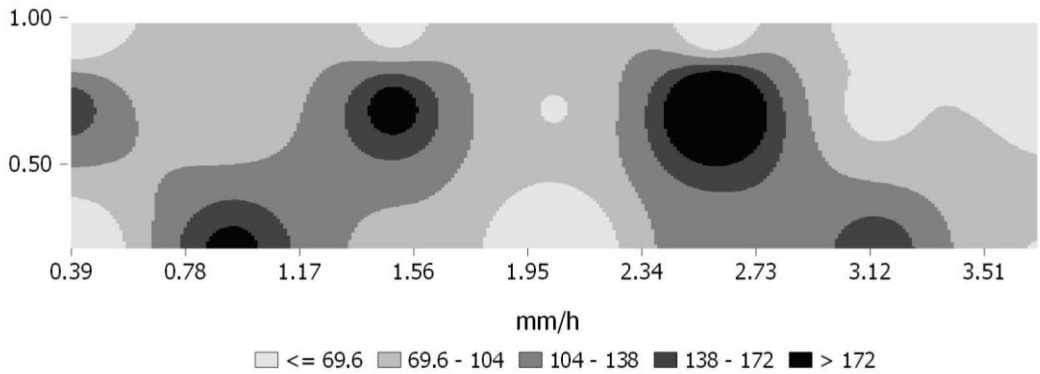

Figure 4. Spatial distribution (m) of rainfall intensity induced by rainfall simulator

Rainfall simulation and sampling

Rainfall simulations took place on 1-meter-wide by 3-meter-long plots, surrounded by smooth galvanized sheet barriers and equipped with metal structures to gather surface runoff, from November 11th to 16th, 2015. Each simulation ran for 45 minutes, under varying soil moisture levels, specifically between 16-19% for dry antecedent moisture content (AMC) and 23-25% for wet AMC (see Table 1), obtained by the gravimetric method. The runoff was captured in 19-liter plastic containers, and its volume was calculated by measuring the water's height and then multiplying this by the container's bottom surface area. To ensure the samples were representative, the collected runoff was stirred every 5 minutes, from which 1-liter samples were then taken. These samples were subsequently filtered and oven-dried at 105°C before their weight was recorded.

Table 1. Soil moisture of each treatment and replication.

Treatment	Replication	Soil moisture (%)	
		Dry AMC	Wet AMC
No crop	I	16.19	---
	II	16.85	23.32
	III	17.4	24.39
	IV	19.08	24.36
Conventional tillage + residues	I	16.19	24.28
	II	17.56	25.33
	III	18.52	24.24
	IV	18.48	24.32
Conventional tillage	I	---	---
	II	17.21	24.32
	III	18.99	24.37
	IV	18.98	24.36
Handspike	I	16.19	---
	II	17.21	24.80
	III	16.28	24.33
	IV	19.38	24.35

Erosion estimation

The experiment should yield 9 samples of soil concentration and several water height measurements (depending on the number of water samples collected). However, some sediment samples were lost, and only water height measurements were collected. The runoff and sediment concentration measured during rainfall simulation are detailed in Table 2.

To estimate sediment concentration at points where concentration data could not be collected, we fitted the following equation to data points for each treatment (Table 3):

$C_s = A + Be^{-Ct}$ (Eq. 1)

Where:
A, B and C are parameters to be fitted using the least square method, t is the time step, and e is the natural exponential base; Once A, B and C are estimated for each treatment, the missing concentrations are estimated using the above equation and used to calculate total erosion inside the time step.

Statistical analysis

We conducted ANOVA tests (at significance levels of $p \leq 0.05$ or $p \leq 0.01$) to detect differences in cumulative soil erosion, erosion rate, total runoff and runoff rate resulting from variations in tillage practices and AMC. Post-hoc analysis using Tukey test was performed when necessary, utilizing R Studio for data analysis. In instances of completely missing data, such as runoff in NC replication 1 under wet AMC, and sediments in CT replication 1 under both dry and wet AMC, the Yates (Yates, 1933) equation was employed to estimate these values. Subsequently, the corresponding ANOVA was adjusted to account for the reduction in necessary degrees of freedom.

RESULTS AND DISCUSSION

Runoff

Tillage treatments had a statistically significant impact on total runoff, but these differences were observed only under DAMC and not under WAMC. Under DAMC, the NC treatment produced the maximum mean runoff per plot at 518.83 L, indicating poor infiltration. The CTR and HS treatments induced the lowest mean runoff, with 432.64 L and 429.42 L, respectively, suggesting that the presence of crop residues in addition to a conventional tillage and cropping on a soil with no-tillage improved soil structure and increased infiltration. The treatment CT did not show statistically significant difference from these three treatments (Figure 5), highlighting the complex interactions between soil management practices and runoff dynamics.

The finding that the CTR treatment resulted in less runoff compared to the NC treatment is consistent with other research, which has shown that surface litter significantly reduces runoff by enhancing water infiltration and minimizing soil crusting. For example, similar studies have demonstrated that surface litter can reduce runoff by 29.5% and 31.3% compared to bare soil plots (Li, Niu and Xie, 2014). Additionally, our data revealing no statistical differences between CT with or without residues and the HS treatment contrasts with results from Wang, Ma and Wu, 2017) and Nyamadzawo *et al.* (2012). These studies found that wheat stubble cover plots produced less runoff than traditional plowing, and that conventional tillage increased runoff compared to conservation agriculture.

Under wet antecedent moisture conditions (WAMC), the highest runoff was recorded in the CTR treatment (569.38 L) and the lowest in the CT treatment (482.12 L). However, these differences were not statistically significant, likely due to the soil being near saturation (23 to 25% of moisture), which reduces the capacity of crop residues to enhance infiltration. When the soil is saturated, additional rainfall is more likely to produce surface runoff regardless of tillage treatment. This suggests that crop residues are more effective in reducing runoff under dry conditions, where they can improve infiltration substantially, than under wet conditions.

Regarding the effects of AMC on runoff, we observed that only the CTR treatment exhibited the highest runoff under wet AMC induced the highest runoff under wet AMC (Figure 5). This behaviour is consistent with findings from Zhao *et al.* (2015), in agricultural lands with rainfall simulation and Meyles *et al.* (2003), in a small catchment, they observed similar patterns as the current research. Although soil moisture variability is widely reported as a critical factor in runoff production (Bronstert and Bardossy, 1999), our research found that only one of the four tillage treatments (CTR) was significantly influenced by AMC. This suggests that the presence of crop residues in agricultural lands plays a crucial role in modulating runoff, particularly under varying moisture conditions. In other studies, conducted in semiarid shrub-steppe landscapes, bare soil surfaces exhibited higher runoff compared to other landscape types, but these differences were only relevant under dry soil conditions (Mayor, Bautista and Bellot, 2009), that suggests the crop residues can mitigate runoff more effectively in dry conditions by enhancing soil infiltration and reducing surface sealing.

Table 2. Runoff volume and sediment concentration (Cs) measured during rainfall simulation

Treat. & time step		Rep.	Dry AMC Vol. (L)	Dry AMC Cs (g/L)	Wet AMC Vol. (L)	Wet AMC Cs (g/L)
NC	5	1	14.48	16.79	nd*	3.07
NC	10	1	62.44	nd	nd	2.08
NC	15	1	68.59	1.08	nd	1.94
NC	20	1	68.53	0.71	nd	1.76
NC	25	1	70.46	0.70	nd	1.58
NC	30	1	71.77	1.20	nd	3.52
NC	35	1	73.82	0.50	nd	2.93
NC	40	1	68.37	nd	nd	3.27
NC	45	1	81.56	0.46	nd	2.36
NC	5	2	12.48	2.32	46.20	1.80
NC	10	2	54.32	0.78	68.39	1.23
NC	15	2	53.93	0.59	65.37	1.07
NC	20	2	55.19	0.22	73.79	0.58
NC	25	2	56.31	0.46	70.44	0.50
NC	30	2	61.18	0.35	71.09	0.50
NC	35	2	53.29	0.50	57.95	0.42
NC	40	2	61.70	nd	82.93	0.36
NC	45	2	66.23	0.13	64.73	0.36
NC	5	3	17.25	4.00	12.48	2.13
NC	10	3	51.96	1.02	87.72	0.61
NC	15	3	57.64	0.78	64.42	0.23
NC	20	3	60.77	nd	61.22	0.54
NC	25	3	54.91	0.54	68.74	0.55
NC	30	3	53.71	0.45	69.79	0.53
NC	35	3	61.16	0.44	72.16	0.46
NC	40	3	56.83	0.50	62.08	0.13
NC	45	3	70.99	0.49	62.08	0.25
NC	5	4	27.62	nd	50.62	5.83
NC	10	4	50.19	0.41	65.74	5.49
NC	15	4	59.30	nd	68.05	2.23
NC	20	4	62.12	2.34	69.73	1.08
NC	25	4	63.39	0.50	71.07	2.95
NC	30	4	58.61	1.16	70.75	1.39
NC	35	4	66.48	nd	67.05	1.09
NC	40	4	67.37	1.59	69.39	1.13
NC	45	4	80.35	1.60	62.22	1.37
CTR	5	1	3.86	3.84	66.42	0.19

Treat. & time step		Rep.	Dry AMC Vol. (L)	Dry AMC Cs (g/L)	Wet AMC Vol. (L)	Wet AMC Cs (g/L)
CTR	10	1	36.22	1.56	65.04	0.94
CTR	15	1	55.26	0.33	71.10	0.53
CTR	20	1	54.61	0.53	74.97	0.54
CTR	25	1	70.42	0.50	71.37	0.92
CTR	30	1	65.71	nd	59.26	1.05
CTR	35	1	75.25	0.50	74.31	1.01
CTR	40	1	68.42	0.44	76.18	0.90
CTR	45	1	73.13	0.33	81.10	1.06
CTR	5	2	6.50	2.91	36.68	1.26
CTR	10	2	46.33	1.16	68.50	0.72
CTR	15	2	36.45	0.85	61.00	0.85
CTR	20	2	50.64	0.69	70.50	0.74
CTR	25	2	53.81	0.68	75.87	0.37
CTR	30	2	57.90	0.56	63.64	0.16
CTR	35	2	50.97	0.68	78.69	0.15
CTR	40	2	59.84	0.66	64.46	0.12
CTR	45	2	62.72	0.35	96.71	0.12
CTR	5	3	0.00	0.00	11.82	2.43
CTR	10	3	34.96	1.14	62.44	1.34
CTR	15	3	47.46	nd	65.43	1.01
CTR	20	3	40.19	0.46	67.16	0.58
CTR	25	3	42.88	0.63	66.57	0.37
CTR	30	3	48.61	0.32	68.10	0.37
CTR	35	3	54.29	0.01	61.90	0.31
CTR	40	3	55.61	0.27	67.09	0.42
CTR	45	3	57.92	0.25	83.23	0.93
CTR	5	4	1.07	4.76	2.73	1.04
CTR	10	4	35.46	nd	51.28	3.57
CTR	15	4	64.41	0.65	54.56	1.50
CTR	20	4	52.58	nd	59.64	0.41
CTR	25	4	50.62	0.57	58.02	0.69
CTR	30	4	47.30	nd	61.02	nd
CTR	35	4	57.87	0.50	59.98	0.57
CTR	40	4	53.34	0.50	57.00	0.37
CTR	45	4	57.94	nd	63.77	0.32
CT	5	1	28.64	nd	nd	nd
CT	10	1	68.40	nd	nd	nd

Treat. & time step		Rep.	Dry AMC Vol. (L)	Dry AMC Cs (g/L)	Wet AMC Vol. (L)	Wet AMC Cs (g/L)
CT	15	1	39.49	nd	nd	nd
CT	20	1	nd	nd	nd	nd
CT	25	1	nd	nd	nd	nd
CT	30	1	nd	nd	nd	nd
CT	35	1	nd	nd	nd	nd
CT	40	1	nd	nd	nd	nd
CT	45	1	nd	nd	nd	nd
CT	5	2	0.80	nd	2.45	10.80
CT	10	2	27.95	1.05	44.56	0.40
CT	15	2	49.07	0.60	67.06	0.23
CT	20	2	55.30	0.07	57.25	0.08
CT	25	2	55.00	0.15	56.98	0.30
CT	30	2	58.92	0.31	74.84	nd
CT	35	2	59.19	0.14	55.66	0.28
CT	40	2	54.85	0.07	51.00	0.00
CT	45	2	71.42	nd	56.54	0.12
CT	5	3	6.80	0.50	15.85	2.92
CT	10	3	49.26	1.08	58.17	0.81
CT	15	3	54.47	0.70	67.72	1.05
CT	20	3	54.26	0.70	76.88	0.48
CT	25	3	49.30	0.54	61.12	0.27
CT	30	3	54.33	0.58	69.73	0.71
CT	35	3	57.48	0.19	68.05	0.50
CT	40	3	59.18	0.28	67.45	0.36
CT	45	3	59.44	nd	71.07	0.42
CT	5	4	20.13	6.40	31.16	nd
CT	10	4	59.77	1.61	64.38	1.82
CT	15	4	56.36	nd	64.45	0.62
CT	20	4	48.95	nd	65.51	0.58
CT	25	4	117.70	0.72	68.38	0.49
CT	30	4	23.87	0.52	66.71	0.89
CT	35	4	46.18	nd	68.37	0.44
CT	40	4	68.68	0.47	64.76	nd
CT	45	4	81.22	nd	75.05	0.37
HS	5	1	9.89	6.80	34.78	6.82
HS	10	1	47.94	nd	44.35	1.63
HS	15	1	60.69	nd	53.93	3.03

Treat. & time step		Rep.	Dry AMC Vol. (L)	Dry AMC Cs (g/L)	Wet AMC Vol. (L)	Wet AMC Cs (g/L)
HS	20	1	58.35	nd	44.61	2.11
HS	25	1	58.62	nd	23.32	9.68
HS	30	1	60.41	0.50	nd	0.09
HS	35	1	65.57	0.38	nd	nd
HS	40	1	61.23	nd		nd
HS	45	1	74.94	nd		nd
HS	5	2	0.53	6.80	14.65	2.44
HS	10	2	38.76	nd	81.25	0.55
HS	15	2	42.87	nd	77.28	2.97
HS	20	2	52.02	nd	67.23	3.25
HS	25	2	52.39	nd	77.59	0.24
HS	30	2	43.18	0.50	87.97	0.27
HS	35	2	56.95	0.38	83.16	0.12
HS	40	2	54.90	0.33	84.88	0.37
HS	45	2	40.94	nd	101.64	0.35
HS	5	3	0.00	0.00	7.71	nd
HS	10	3	19.41	0.74	62.40	4.46
HS	15	3	34.89	1.89	68.00	0.27
HS	20	3	51.55	0.50	70.00	0.75
HS	25	3	51.28	0.36	67.25	0.24
HS	30	3	51.67	0.34	66.07	nd
HS	35	3	50.28	0.16	71.52	0.07
HS	40	3	60.68	nd	69.08	nd
HS	45	3	60.43	1.70	79.63	nd
HS	5	4	39.90	5.67	47.24	2.77
HS	10	4	40.53	nd	63.35	1.87
HS	15	4	71.01	1.98	63.21	1.84
HS	20	4	125.35	1.96	63.25	1.69
HS	25	4	75.74	nd	61.30	1.42
HS	30	4	0.00	1.15	74.97	3.41
HS	35	4	0.00	1.00	67.05	2.73
HS	40	4	49.53	nd	59.88	3.17
HS	45	4	55.25	nd	52.14	2.32

*nd = no data

Table 3. Exponential models for estimating missing sediment concentration, where "y" is the sediment concentration and "x" is the time

Treat.	Rep.	Dry AMC	RMSE	Wet AMC	RMSE
NC	1	y=0.4+50exp(-0.22x)	0.54	No missing data	---
NC	2	y= 0.3+6exp(-0.22x)	0.14	No missing data	---
NC	3	y= 0.46+14exp(-0.27x)	0.14	No missing data	---
NC	4	y= 1.15+8exp(-0.19x)	0.97	No missing data	---
CTR	1	y=0.32+10.5exp(-0.22x)	0.16	No missing data	---
CTR	2	No missing data		No missing data	---
CTR	3	y= 0.2+1.5exp(-0.11x)	0.43	No missing data	---
CTR	4	y=0.5+16.5exp(-0.27x)	0.06	y= 0.4+8exp(-0.17x)	1.17
CT	1	No records		No records	---
CT	2	y= 0.14+5.5exp(-0.18x)	0.11	y= 0.1+65exp(-0.36x)	0.53
CT	3	y= 0.4+1.7exp(-0.18x)	0.30	No missing data	---
CT	4	y= 0.5+20exp(-0.24x)	0.33	y=0.3+15exp(-0.36x)	0.50
HS	1	Y= 0.37+14.5exp(-0.16x)	0.05	y= 0.7+15exp(-0.15x)	3.71
HS	2	y=0.3+13exp(-0.14x)	0.02	No missing data	---
HS	3	y= 0.2+5exp(-0.20x)	1.03	y= 0.09+15exp(-0.15x)	1.03
HS	4	y=1+11exp(-0.17x)	0.27	No missing data	---

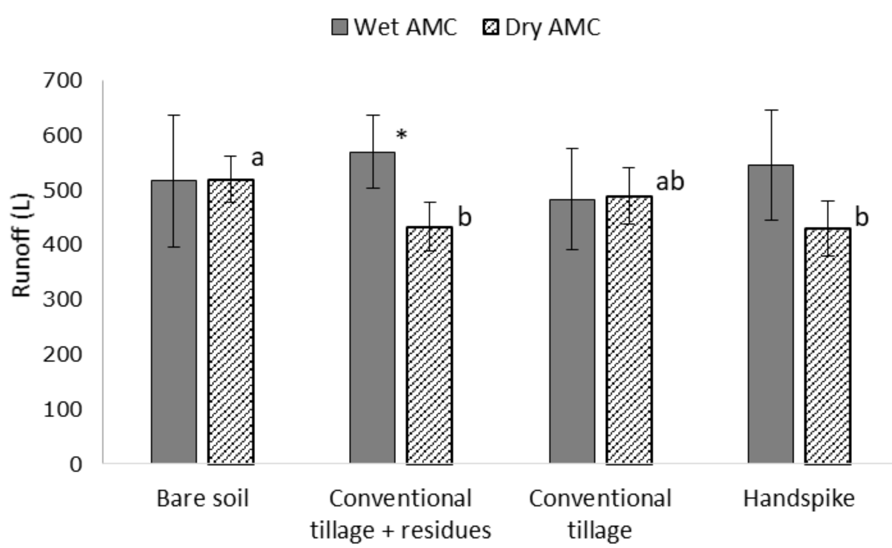

Figure 5. Mean total runoff for each treatment under wet and dry antecedent soil moisture conditions (AMC). Different letters in dry AMC indicate different effects promoted by tillage treatments. The asterisk denotes statistically higher runoff under wet AMC for the Conventional tillage + residues treatment. Error bars indicate data range.

The analysis of variance indicated that tillage treatments had a statistically significant effect on runoff rate ($p \leq 0.05$) under dry AMC, but not under wet AMC. These differences were observed only at the time step 45. Under dry AMC, the CTR treatment had the lowest runoff rate at 11.43 mm/h at the time step 5, suggesting that the presence of residues helped to enhance infiltration early in the simulation. In contrast, the CT treatment exhibited the highest runoff rate with 306.80 mm/h at the time step 25, indicating a rapid increase in runoff due to reduced infiltration capacity. Under wet AMC, the lowest runoff rate was 91.19 mm/h at minute 5 in the CT treatment, while the highest was 324.81 mm/h at the minute 45 in the CTR treatment. The most dramatic changes in runoff rate occurred within the first five to ten minutes of the simulation, highlighting the initial response of the soil to rainfall. After this period, the runoff rates stabilized, reflecting a balance between rainfall input and the soil's infiltration capacity (Figure 6).

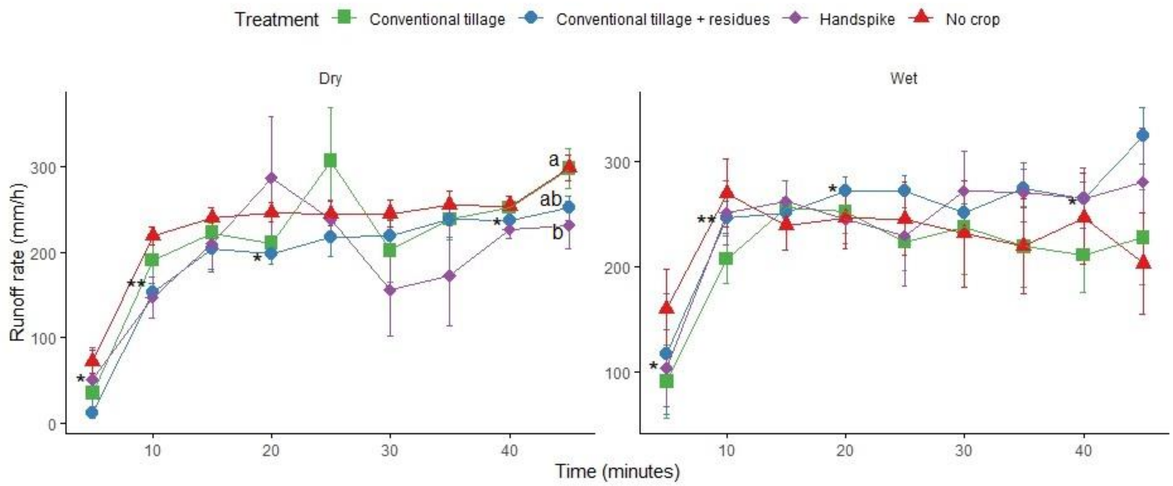

Figure 6. Mean runoff rates for each treatment. Asterisks indicate statistically significant differences (p ≤ 0.05 and p ≤ 0.01) of antecedent soil moisture conditions, while letters denote statistically significant differences (p ≤ 0.05) due to tillage treatments. Error bars indicate data range.

The impacts of AMC on runoff rate showed statistically significant differences at various time points during the simulation. Specifically, significant differences were observed at minute 5 in HS treatment and at the minutes 10, 20 and 40 in CTR treatment (p ≤ 0.05 and p ≤ 0.01) (Figure 6).

Generally, runoff increased with the time of simulation, a trend that is consistent with other studies using simulated rainfall on bare ground, wheat, ryegrass, and purple medic (Huang, Zhao and Wu, 2013). This pattern suggests that as the soil surface becomes increasingly saturated, its ability to absorb additional water decreases, leading to higher runoff rates. Similarly, other researchers have reported comparable maximum runoff rates between conventional tillage and no-tillage treatments, with significant differences observed under very wet soil moisture conditions, where no-tillage plots showed the highest runoff rate (Wilson *et al.*, 2004). These findings underscore the importance of considering both tillage practices and antecedent soil moisture conditions in soil and water conservation strategies. Implementing residue cover and conservation tillage can effectively reduce runoff, particularly in dry conditions, while understanding the dynamics of runoff under varying moisture levels can help in designing more resilient agricultural systems.

Erosion

The analysis of variance detected statistical differences in cumulative soil erosion promoted by tillage treatments during minutes 30 – 40 under wet AMC. However, the Tukey test did not find significant differences between the means of these treatments. Numerically, the HS treatment under wet AMC resulted in the highest total erosion with 802.11 g. In contrast, under dry AMC, the NC treatment experienced the highest erosion at 581.34 g. The least total erosion was observed in the CTR treatment under dry AMC with 249.30 g, and in CT treatment under wet AMC with 311.90 g (Figure 7). The high erosion observed in HS under wet conditions could be due to reduced soil cohesion when saturated, whereas the minimal erosion in CTR under dry AMC, and CT under wet AMC might be attributed to improved soil structure and reduced surface sealing.

Literature generally reports that no-tillage and crop residue coverage prevent soil erosion better than conventional tillage (Nolan *et al.*, 1997; Diallo, Soli and Roose, 2008; Lanzanova *et al.*, 2013; Biddoccu *et al.*, 2020), which is only consistent in our experiment in the case of CTR under dry AMC, but not in the case of no tillage in HS, which produced the highest erosion. Gura *et al.* (2022) conducted a three-year-study on maize and soybean rotation, finding that no-till practices significantly increased soil organic carbon and microbial biomass carbon, reducing erosion susceptibility (Xiaojun, Jianhui and Zhengan, 2013). However, they found no significant effects from crop rotation and residue management. In a simulated rainfall experiment, Stašek *et al.* (2023) showed that reduced tillage and direct seeding reduced soil loss. Mhazo, Chivenge and Chaplot (2016) reviewed literature and found inconsistent effects of no-tillage on erosion prevention, influenced by environmental differences. No-tillage was more effective in temperate zones than in tropical regions with more consolidated soils. This highlights the importance of environmental context in understanding tillage impacts, as observed in our arid zone study.

Most cited studies focus on long-term impacts because information on short-term conservation practices is limited. Short-term studies, typically spanning one to three years under natural rainfall, contrast with our 45-minute rainfall simulation. Short-term studies are crucial for understanding immediate effects of tillage practices and soil moisture on erosion, informing immediate management decisions. The lack of distinct effects from tillage treatments on soil erosion in our study might be due to the experiment's brief duration, unlike the observed effects of soil moisture conditions.

Regarding the effects of AMC, the ANOVA detected a distinct effect ($p \leq 0.05$) in the CTR treatment during minutes 20 – 35, with wet AMC promoting the highest cumulative erosion. Also, the HS treatment showed statistically significant differences ($p \leq 0.01$) during minutes 35 – 45, with higher erosion under wet AMC (Figure 7). These results suggest that dry AMC under no-till cropping conditions and crop residue coverage led to less erosion compared to the same tillage treatments under wet AMC. Wet AMC likely decreases soil cohesion, making it more susceptible to detachment and transport by water. In contrast, dry AMC may enhance the soil's ability to resist erosion due to higher shear strength and reduced pore water pressure. The presence of crop residues further mitigates erosion by protecting the soil surface from the direct impact of raindrops and reducing the velocity of surface runoff. This interplay between soil moisture and surface cover underscores the complexity of erosion processes.

Soil moisture significantly influences soil's resistance to erosion. Typically, dry soil exhibits lower resistance to erosion, which gradually increases with the antecedent soil moisture content. However, once soil resistance reaches its maximum level, it starts to decrease because the soil becomes saturated (Moragoda, Kumar and Cohen, 2022), reducing its shear strength and making it more prone to detachment and transport (Wei *et al.*, 2019). In our current investigation, we consistently observed higher erosion rates under wet AMC across all tillage treatments and time steps of the simulation (Figure 8). This indicates that excessive soil moisture reduces the soil's ability to resist erosive forces, leading to greater soil loss. The observed trends align with the theoretical understanding of soil moisture dynamics (Pierzynsky, Vance and Sims, 2005; Moragoda, Kumar and Cohen, 2022) and highlight the critical role of managing soil moisture to minimize erosion risks, particularly in arid and semi-arid regions where rainfall events can lead to rapid saturation and subsequent erosion.

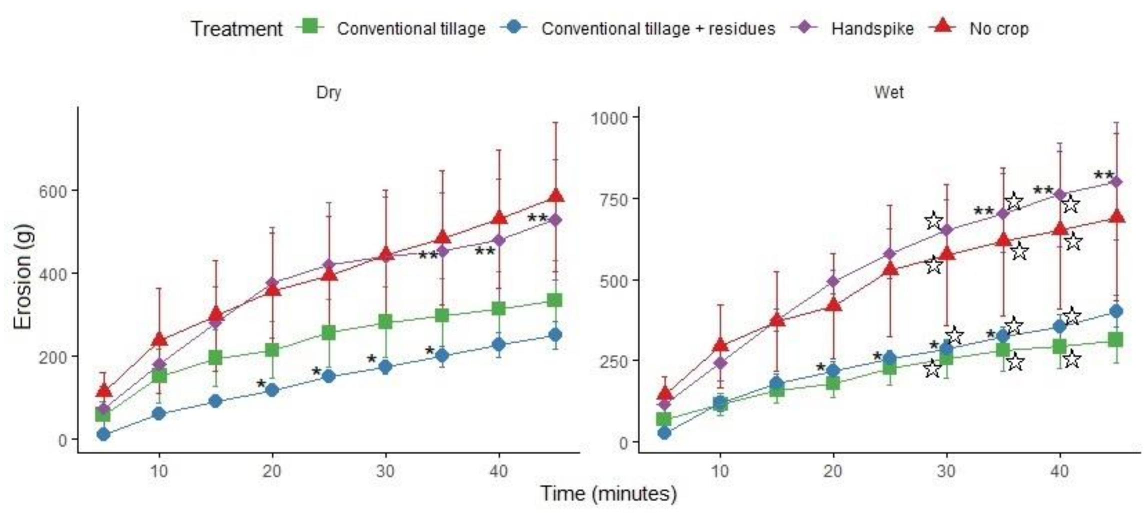

Figure 7. Cumulative soil erosion of the studied tillage and AMC's treatments. The asterisks denote statistical differences caused by the AMC's, one asterisk specifies $p \leq 0.05$, and two asterisks indicate $p \leq 0.01$. Stars indicate statistical differences ($p \leq 0.05$) caused by tillage treatments. Error bars indicate data range.

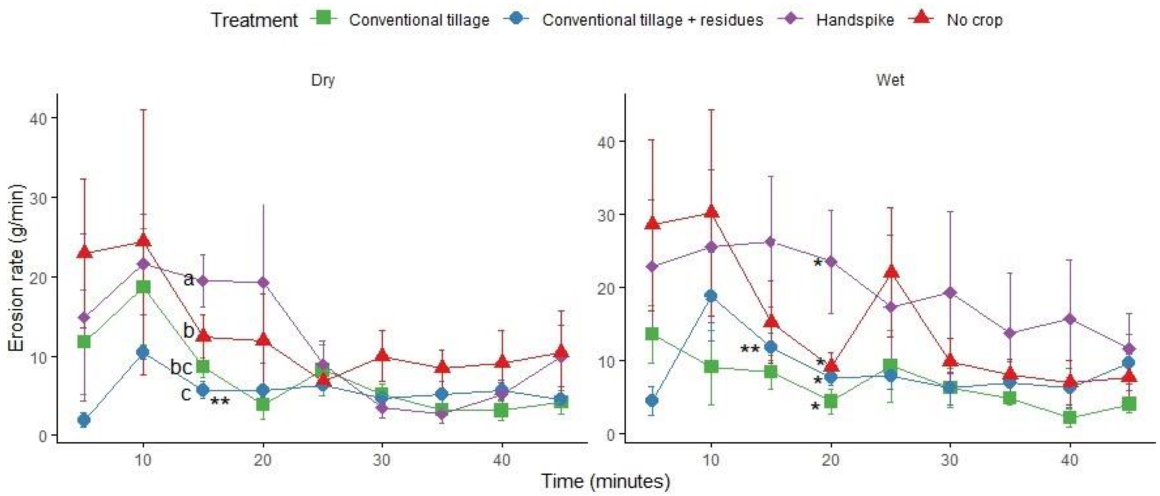

Figure 5. Erosion rate of tillage and AMC's treatments during rainfall simulation. The asterisks denote statistical differences caused by AMC's, and different letters in wet AMC indicate different effects by tillage treatments. Bars indicate data range.

In another investigation, Wei, Zhang and Wang (2007) also found that the largest amounts of soil erosion occurred under wet AMC in peanut and tree crops. This pattern was consistent with the findings of Ziadat and Taimeh (2013), who reported significantly higher soil loss in wet AMC and very wet AMC in rangeland and barley crops. These studies, like ours, highlight the pronounced impact of soil moisture on erosion rates. The consistent observation of higher erosion under wet AMC across different crop types and environments underscores the importance of soil moisture management in preventing soil erosion. Our results align with these findings, as we also observed increased erosion under wet conditions across all tillage treatments. The similarities between these studies and our findings suggest that the relationship between soil moisture and erosion is robust across various agricultural contexts, reinforcing the need for practices that mitigate the impact of excessive soil moisture on erosion.

The present results revealed that dry soils managed with conventional tillage plus soil covered by crop residues promoted the least erosion. Numerous studies have demonstrated the potential of surface cover to reduce soil erodibility. For example, surface residues slow down surface runoff, promoting infiltration and reducing the volume and velocity of water capable of causing erosion (Jin *et al.*, 2008; Mailapalli *et al.*, 2013; Li, Niu and Xie, 2014). These mechanisms are essential for maintaining soil integrity, particularly in regions prone to high-intensity rainfall events.

Given the consistent rainfall and soil texture throughout our experiments, general effects can be assumed. High rainfall intensities, as in current research (Figure 4), have a great impact on soil erosion, which was demonstrated in an investigation by Zhao *et al.* (2021), who evaluated rainfall intensity and duration ranges. They concluded that an intensity of 120 mm/h promoted greater erosion than a rainfall intensity of 60 mm/h under the same soil management. On the other hand, soil texture is one of the major factors impacting erosion (Kilinc and Richardson, 1973), due to its close relation to moisture retention (Magdić *et al.*, 2022), being the clayey and sandy soils the least erosive (Middleton, 1930) and silty soils or fine sands are the most erosive (O'geen, Elkins and Lewis, 2006). Furthermore, the interplay of high rainfall intensity with soil of high sand levels has been associated with more erosion compared to scenarios with lower rainfall intensities and higher proportions of fine particles (Mrubata *et al.*, 2024).

With regard to the observed erosion rate, the tillage treatments showed statistical differences ($p \leq 0.05$) at minute 15 under dry AMC, where the HS treatment presented the highest erosion rate, while the CTR treatment showed the lowest. Under wet AMC, the ANOVA detected differences in erosion rates in minute 20, but Tukey test did not detect differences between the tillage treatments. Regarding the effects of AMC on runoff rate, the ANOVA detected differences ($p \leq 0.01$) in treatment CTR at minute 15, the dry AMC that promoted lower erosion rate. Soil moisture and tillage practices create a complex dynamic, where the protective effects of crop residues in the CTR treatment are more beneficial under dry conditions.

The erosion rate was characterized by initially higher rates followed by a subsequent decrease, then it appeared to stabilize after an augmentation in soil water content (Figure 8). This stabilization phase alluded to by studies such as Lo and Lee (2015) and Mrubata *et al.* (2024) is linked with phenomena like soil crusting, which although not directly measured in our study, it is considered to reduce infiltration and consequently to increase overland flow that occurred at the minute 10 of our experiment (see Figure 6).

CONCLUSIONS

Our study aimed to investigate the impact of agricultural management practices and antecedent soil moisture on short-term soil erosion in an arid zone with sandy clay loam soil of North Central Mexico using simulated rainfall. The comparative analysis between the studied treatments revealed several key findings.

Soil erosion was prevented more effectively by CT and CTR treatments than by HS, particularly under dry AMC. Dry AMC significantly reduced cumulative erosion in HS and in CTR, compared to their corresponding treatments under wet AMC.

These findings contradict the common notion that no-till cropping and crop residue cover are effective in preventing erosion in agricultural lands. This discrepancy might be because these practices have a more significant impact on less consolidated soils than the soil studied here. Additionally, the short-term nature of the current investigation may have influenced the performance of soil management practices compared to other long-term studies.

The erosion results were consistent with runoff data. The CTR and HS treatments under dry AMC produced the lowest runoff, supporting the conclusion that these treatments were effective reducing both erosion and runoff under dry conditions.

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Compliance with ethical standards. Do not apply.

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Author contributions statement (CRediT). P. Bueno-Hurtado – Conceptualization, Funding acquisition, Methodology, Investigation, Data curation, Formal analysis, Writing - original draft. **O. Seidou** - Formal analysis, Writing – review and editing. **A. López-Santos** – Methodology, Writing – review and editing.

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