



SOPHIA BAHDDOU

TECHNICAL AND PRACTICAL INNOVATIONS TO REDUCE SOIL
AND WATER LOSSES BY IMPROVING SOIL PHYSICAL
PROPERTIES

SCHOOL OF WATER, ENERGY & ENVIRONMENT
PhD in Environment and Agrifood

PhD
Academic Year: 2019 - 2024

Supervisor: Professor Wilfred Otten
Associate Supervisor: Professor R. Jane Rickson
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the degree of PhD

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ABSTRACT

Soil erosion is a significant environmental challenge that impacts agricultural productivity, environmental sustainability, and food security. The aim of this research is to better understand the processes of soil erosion by water and wind under different tillage and agronomic measures, with a view to reduce soil and water losses. The research is divided into three main studies. The first study examines the effects of soil surface roughness (SSR) orientation and magnitude on runoff, infiltration, and soil erosion under simulated rainfall conditions. Treatments included up- and downslope, across-slope, random SSR, and a smooth surface. The second study explores the combined effects of wind and rainfall on soil erosion using a novel system comprising rainfall and wind simulators. The study evaluates the role of wind-driven rain (WDR) with varying wind velocities on surface runoff, infiltration, and soil loss, comparing smooth and rough soil surfaces. The third study assesses the influence of different wheat lines (wild type vs dwarf), water regimes (dry vs well-watered), and sowing densities on plant traits, soil properties and predicted erosion rates. The outcome of this research indicates that i) random SSR significantly increases runoff and soil loss, while across-slope SSR does not consistently reduce erosion compared to up- and downslope oriented SSR, ii) WDR significantly accelerates runoff generation and increases soil loss compared to windless rain, with higher wind velocities magnifying these effects, iii) initial SSR patterns change during rainfall events, and WDR exacerbates these changes in SSR, iv) dwarf wheat, higher sowing density and well-watered conditions significantly reduce erosion rates through improved aboveground and belowground plant traits and soil properties, particularly at the later stage of plant growth. In conclusion, this research highlights the importance of considering SSR, wind effects, and plant traits in soil erosion studies to develop effective soil conservation strategies and enhance agricultural sustainability.

Keywords: Drought, Infiltration, Raindrop impact, Rainfall erosivity, Rainfall simulator, Roots, Runoff, Shoots, Soil erosion, Soil surface roughness, Splash erosion, Wind-driven rain, Wheat, Wind tunnel.

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Last but not least, sometimes a little self-appreciation is just what we need (Snoop Dogg's speech, 2018):



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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
CV	Coefficient of variation
DSD	Drop size distribution
EUROSEM	European Soil Erosion Model
GDP	Gross Domestic Product
I.C.E.	International Centre for Eremology
KE	Kinetic energy
LOD	Laser Optical Disdrometer
LOG	Logarithmic
LSD	Least Significant Difference
MMF	Morgan-Morgan-Finney
mMMF	Modified Morgan-Morgan-Finney
OCP	Office Chérifien des Phosphates
REML	Restricted Maximum Likelihood
RS	Rough surface
RUSLE	Revised Universal Soil Loss Equation
SAFA	Sustainable Agriculture For Africa
SE	Standard error
SQRT	Square root
SS	Smooth surface
SSR	Soil surface roughness
UM6P	Mohammed VI Polytechnic University
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation
WDR	Wind-driven rain
WDR1	Wind-driven rain (lower wind velocity)
WDR2	Wind-driven rain (higher wind velocity)
WEPP	Water Erosion Prediction Project
WLR	Windless rain

1 INTRODUCTION

1.1 Soil erosion: a global problem

Soil erosion is a naturally occurring process, but it has been significantly accelerated by human activities and climate change, leading to severe environmental and economic consequences worldwide. The global average soil erosion rate is estimated at $2.4 \text{ t ha}^{-1} \text{ yr}^{-1}$ (Wuepper et al., 2020), and can vary substantially depending on various factors, including climate, topography, soil characteristics and land use practices. Climate change is anticipated to exacerbate soil erosion by increasing the frequency and intensity of extreme weather events, such as heavy rainfall, droughts and strong winds (Bolan et al., 2024). These climatic changes can affect soil properties and vegetation cover and impact the erosive potential of water and wind. According to estimates by the Food and Agriculture Organization and Intergovernmental Technical Panel on Soils (FAO and ITPS, 2015), the equivalent of one football pitch of soil erodes every five seconds.

Soil erosion is a global phenomenon and is becoming increasingly problematic in North Africa and the Mediterranean region (Salhi et al., 2023). Within this region, Morocco stands out as a particularly vulnerable country, with soil erosion by water affecting over 40% of its territory (Dahan et al., 2012). The distribution of soil erosion risk within Morocco is not uniform and erosion rates vary significantly across regions, with the Middle Atlas and Rif mountains experiencing annual soil losses ranging from 5 to $20 \text{ t ha}^{-1} \text{ yr}^{-1}$, respectively (Lamane et al., 2022). The Rif region alone, in the northern part of Morocco, covering only 6% of Morocco's surface area, contributes more than 60% of the total sediments mobilised annually throughout the country (Dahan et al., 2012). In the northern regions, the mean annual rainfall is around 700 mm, but this is concentrated into just 70 days per year (Salhi et al., 2019).

Soil erosion poses significant threats to agricultural productivity and food security, particularly in regions where agriculture is a major economic activity. The removal of fertile topsoil and the reduction of effective rooting depth for crops can lead to

a substantial decline in crop yields and ultimately threaten food production (Pimentel & Burgess, 2013). Furthermore, soil erosion can lead to the degradation of soil physical, biological and chemical properties, reducing soil fertility and water holding capacity, and ultimately diminishing the productivity of agricultural lands (Lal, 2001). This can have cascading effects on rural livelihoods, food security and economic development, particularly in regions where alternative economic opportunities are limited (Borrelli et al., 2017).

Pimentel & Burgess (2013) stated that about 10% of the world's agricultural land faces mild erosion, but 80% is subjected to moderate to severe soil erosion. In Morocco, where agriculture accounts for approximately 12.3% of the GDP (World Bank, 2021) and employs around 34% of the workforce (World Bank, 2020), soil erosion by water poses significant challenges, affecting approximately 2.1 million hectares of valuable agricultural land (Dahan et al., 2012). Dam reservoirs experience substantial siltation, with an annual deposition of 75 million cubic metres of sediment, leading to a 0.5% reduction in storage capacity (FAO and ITPS, 2015; Dahan et al., 2012). This sedimentation not only reduces water availability for irrigation but also impacts downstream water quality and turbidity levels, exacerbating the challenges faced by the agricultural sector.

1.2 Soil erosion processes

Soil erosion can be broadly categorised into different types based on the erosive agents involved. The two primary types are erosion by water and erosion by wind, each involving mechanisms that contribute to the detachment, entrainment and transport, followed by deposition of eroded soil particles (Morgan, 2005).

1.2.1 Erosion by water

Soil erosion by water is a result of soil detachment from the ground surface followed by the entrainment, transport and deposition of the detached material. These processes are due to the erosivity of both rainfall and overland flow (Figure 1-1). Kinnell (2005) identified four detachment and transport systems: (i) raindrop detachment with transport by raindrop splash; (ii) raindrop detachment with transport by raindrop-induced flow transport; (iii) raindrop detachment with

transport by overland flow, and (iv) detachment and transport by overland flow. However, rainsplash is considered the most important detaching agent (Morgan, 2005) as a result of the raindrop energy impacting the soil surface.

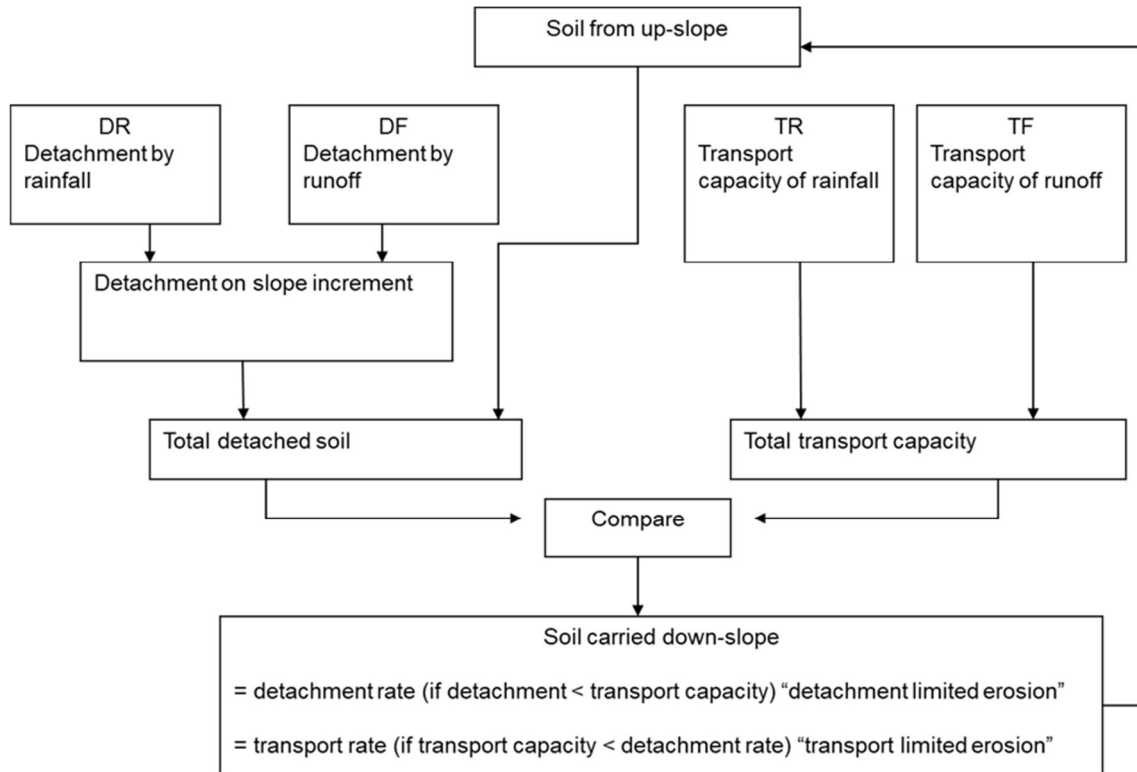


Figure 1-1 Flow chart of the processes of soil erosion by water (Meyer and Wischmeier, 1969 – reproduced in Morgan 2005, page 119)

Soil erosion by water can be measured using various techniques, both in the laboratory and in the field. In the laboratory, widely used methods include rainfall simulators, which mimic natural rainfall events under controlled conditions, and erosion trays or flumes, where soil samples are subjected to flowing water to quantify runoff and sediment loss (Iserloh et al., 2012; Iserloh, Ries, et al., 2013; Le Bissonais, 2016; Polyakov & Nearing, 2003). Some key features that can be precisely manipulated include the spatial and temporal distribution of the rainfall, its intensity, duration, the terminal velocity of the falling droplets, the drop size distribution (DSD), the kinetic energy imparted by the rainfall, and the ability to replicate identical rainfall patterns across multiple simulations (Petru & Kalibová, 2018). In the context of Morocco, several soil erosion studies have used rainfall simulators to represent realistic rainfall intensities and durations of different

regions. For the Haut-Atlas occidental and the region of Meknes, respectively, Cheggour et al. (2009) and Dimanche & Hoogmoed (2002) used an intensity of 80 mm hr⁻¹ of rainfall over 30 minutes. Merzouk & Blake (1991) considered an intensity of 100 mm hr⁻¹ for 30 minutes in the Rif and Atlas Mountains. Al Karkouri et al. (2000) simulated two rainfall intensities of 87.3 mm hr⁻¹ and 75.5 mm h⁻¹ for two different soils in the Rif region. Other studies (Briak et al., 2016; Coelho et al., 2004) used lower rainfall intensities of <60 mm hr⁻¹ to represent regions where rainfall is not very intense.

1.2.2 Erosion by wind

Soil erosion by wind is a dominant process in arid and semi-arid regions characterised by sparse vegetation cover and dry, loose soils (Dahan et al., 2012). Wind is classified as either inactive or active. The level of separation of these two winds defines the critical or effective speed which corresponds to the velocity threshold at which erosion takes place. A wind is qualified as active if it is capable of causing the detachment and entrainment of soil particles (Alali & Benmohammadi, 2013) and its velocity is usually >5 m s⁻¹ (ICARDA, 1998; Benmohammadi, 2000; Cowie et al., 2014; Kabiri, 2005; Karim et al., 2015). The mean wind speed in Morocco ranges from 4 to 10 m s⁻¹ (GWA, 2023).

Erosion by wind occurs through three main processes: surface creep, saltation and suspension. Surface creep refers to the rolling and sliding motion of larger soil particles (known as bedload) along the ground surface, typically over short distances (Morgan, 2005). Saltation involves the bouncing and hopping motion of soil particles, sometimes triggered by stationary particles being bombarded by those already entrained in the airflow. Saltation mainly involves particle size classes of medium and fine sand, but the size fractions moved along the surface depend on the wind velocity (Maurer et al., 2006). Suspension occurs when soil particles are entrained by the wind, sometimes over long distances, contributing to the long-range transport of soil particles (Zobeck & Van Pelt, 2006).

A great number of apparatus and instruments have been developed in attempting to measure each process of soil erosion. The data can be collected either in the field or in the laboratory under simulated conditions. Real conditions in field

experiments vary in time and space which generates a lot of variability in the data generated and thus hinders understanding the processes operating. Experiments under controlled conditions are undertaken in wind tunnels where the processes of erosion by wind need to run as close as possible to natural conditions. Some mobile wind tunnels are also used in field experiments, placed on natural surfaces (Maurer et al., 2006). Soil particles in the test section erode due to the action of the wind and eroded sediments are trapped in collectors placed at the end of the tunnel. Details of the different collectors are described in Appendix B.1 (Table B-1).

1.2.3 Combined effect of rainfall and wind on erosion

While individual processes of soil erosion have been extensively studied, the simultaneous action of wind and water during natural rainstorms can lead to accelerated soil erosion rates, especially in arid and semi-arid regions where sparse vegetation cover and dry soil conditions can exacerbate the erosive effects of water and wind (Visser et al., 2004). The combination of raindrop impact, surface runoff and wind forces can result in a synergistic effect, with each process amplifying the others and leading to more severe soil loss than would be expected from their individual contributions (Erpul et al., 2013). However, most erosion studies have evaluated the individual effects of rainfall, runoff and wind as erosive agents, often treating them as separate processes. Just a few studies have considered the simultaneous effect of wind and water on hydrological and erosion processes (An et al., 2022; Arshad et al., 2019; Erpul et al., 2005, 2013; Iserloh et al., 2013; Mahmoodabadi et al., 2021; Marzen et al., 2016). However, knowledge of how these processes interact and amplify or lessen each other's impacts remains limited.

Recognising the concurrent actions of water and wind in soil erosion studies is crucial for an improved understanding of erosion processes in wind-driven rain scenarios, which are common in many regions worldwide. By investigating the combined effects of water and wind erosion, researchers can gain insights into the complex interactions between these forces, the mechanisms by which they amplify or mitigate each other's impacts, and the influence of variables such as

wind velocities and soil surface conditions on these processes. Lately, there has been a growing interest in soil erosion arising from the combined effects of wind and water (An et al., 2023). A positive relationship was found between wind velocity and soil erosion rates during a rainfall event (Erpul et al., 2003; Mahmoodabadi et al., 2021). Wind may enhance detachment and transport of soil particles by increasing both the kinetic energy (KE) and incidence impact angle of raindrops (Arshad et al., 2019; Erpul et al., 2005, 2013; Iserloh, Fister, et al., 2013; Marzen et al., 2016). These effects are related to wind velocity. Only a few studies have measured the vertical profile of entrained soil particles, including separation of the bedload and suspended particles eroded due to wind-driven rain. In addition to that, measuring hydrological (i.e. runoff and infiltrate volumes) and soil erosion processes (i.e. splash erosion and soil loss by runoff) simultaneously has been poorly studied under wind-driven rain conditions. Therefore, it is important that the effect of wind is critically evaluated in erosion studies to better understand soil and water losses.

To test the combined effects of water and wind on soil erosion processes, researchers have used wind tunnels combined with rainfall simulators. These can be a closed system, like the I.C.E wind tunnel at Ghent University (Gabriels et al., 1997), or an open system like the devices developed by An et al. (2022). In Chapter 3, a combined system of wind and rainfall simulators was used to evaluate the synergetic effects of wind and rainfall on runoff and soil erosion.

1.3 Factors affecting soil erosion

The factors contributing to soil erosion are multifaceted, stemming from an interplay of natural and anthropogenic influences. Climatic factors, such as rainfall intensity and duration (L. Zhao et al., 2021), wind speed and direction (Zobeck & Van Pelt, 2006), as well as air temperature (Cao et al., 2024) play a crucial role in determining the erosive potential of water and wind. Soil characteristics, such as texture, structure (Lal, 2001), organic matter content, aggregate stability (Pimentel & Burgess, 2013), temperature, moisture content (Larionov et al., 2014) all directly impact the susceptibility of soil particles to erosion. Topographic features, including slope steepness and length (Morgan,

2005) and soil surface roughness (Idowu et al., 2001), also significantly influence soil erosion dynamics. Land cover (such as vegetation and mulching) also has an effect on soil erosion (Idowu et al., 2002). Plants play a vital role in moderating soil erosion rates (Morgan, 2005) and there are several soil conservation strategies adapted for cultivated land. This research focuses on the effect of soil surface roughness and tillage orientations on soil and water losses, and the role of vegetation, including the shoots and roots, to improve soil physical properties and plant characteristics, hence reduce surface runoff and soil loss (Figure 1-2).

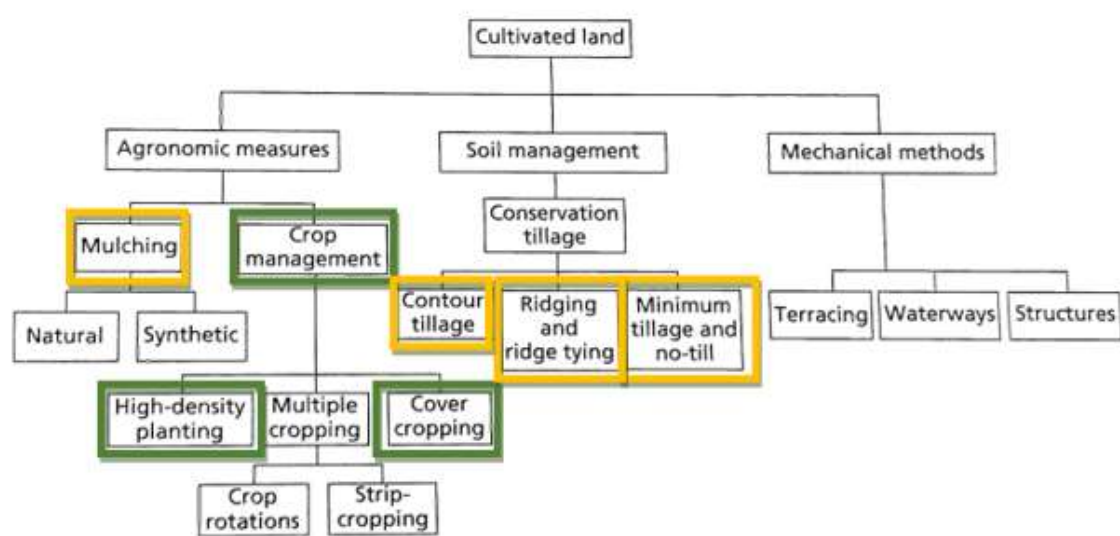


Figure 1-2 Soil conservation strategies for cultivated land (El-Swaify et al. 1982 – reproduced in Morgan 2005, page 161). Yellow boxes correspond to measures related to aspects covered in Chapter 2 and 3. Green boxes correspond to measures related to aspects covered in Chapter 4.

1.3.1 Soil surface roughness

Soil surface roughness (SSR) definitions vary based on the roughness category and magnitude scale (Bullard et al., 2018a; Vermang et al., 2013; Römken and Wang, 1986; Thomsen et al., 2015). Random and oriented roughness patterns, influenced by agricultural practices like tillage and its intensity, have been extensively studied due to their impact on hydrological processes and soil erosion on arable land (Govers et al., 2000). In agricultural systems, soil management practices alter the micro-topography, with different tillage methods affecting the

degree of SSR (da Rocha Junior et al., 2016; Bramorski et al., 2012; Dalla Rosa et al., 2012; Vázquez et al., 2005). SSR influences the time of runoff initiation during rainfall events, the amount of soil and water losses, and the eroded soil by rainsplash. Additionally, initial SSR determines how rainfall modifies the surface roughness during a storm (Vermang et al., 2013). However, the multitude of these interrelated processes is rarely considered or quantified together.

Previous research presented contrasting findings on the relationship between soil surface roughness (SSR) and total runoff and soil loss. While many studies reported that increasing the magnitude of SSR reduced runoff and soil loss (Idowu et al., 2001; L. S. Zhao et al., 2014; Zheng et al., 2014), others showed conflicting results (Helming et al., 1998; Römken et al., 2001). Several mechanisms are proposed for how greater SSR can decrease soil erosion. According to Cogo et al. (1984), this includes: promoting infiltration by storing water in depressions, reducing runoff velocity to limit soil detachment and transport (Cogo et al., 1983), trapping detached sediment, and providing a protective ponding effect against raindrop impact (Gao et al., 2003). However, Darboux & Huang (2005) found rough surfaces initially delayed runoff but ultimately produced higher water flux once steady-state was reached, due to reduced depression storage capacity. The effect of SSR on soil loss was also inconsistent across studies. Helming et al. (1998) observed that on rough surfaces, initial storm runoff concentrated between soil clods, forming concentrated flow paths that increased sediment detachment and transport, leading to greater soil loss - an effect amplified on steeper slopes. Potential reasons for the mixed findings likely stem from differing experimental factors like the scale of the experiments, roughness characteristics, soil properties, slope, rainfall intensities and durations. Overall, there is no consensus on whether increased SSR definitively increases, decreases or has no impact on runoff and soil loss.

Oriented soil roughness created by tillage direction can either enhance or mitigate runoff erosion, depending on whether operations like ploughing or ridging are performed parallel (up/downslope) or perpendicular (across-slope) to the slope

gradient. Up/downslope tillage may increase erosion by channelling surface flow, increasing runoff volume, velocity and its associated KE and hence erosivity (da Rocha Junior et al., 2016; Hou et al., 2021). Conversely, across-slope or contour tillage can delay runoff initiation (Luciano et al., 2009) and trap sediments behind perpendicular ridges (da Rocha Junior et al., 2016; Gebreegziabher et al., 2009; Stevens et al., 2009; L. Zhao et al., 2021). However, Quinton et al. (2004) found no significant difference in soil loss between the two orientations. While contour cultivation is considered a soil conservation practice (da Rocha Junior et al., 2018), it becomes less effective on steeper slopes (Alvarez-Mozos et al., 2011; Chambers et al., 2000; USDA, 2017), leading to substantial runoff accumulation in low-lying areas along the ridges, which may cause the ridges to be overtopped and/or breached at localised points, thereby heightening the potential for erosion to occur (Morgan, 1992).

The impact of wind-driven rainfall on soil and water losses seems to be affected not just by the wind's influence on raindrops and shallow surface flows (as explained above), but also by soil surface roughness characteristics (Ries et al., 2014). In wind-driven rain conditions, the role of SSR may be more pronounced compared to windless scenarios, due to the additional effect roughness has on wind drag profiles that can modify the rainfall erosivity (Marzen et al., 2015). This interplay of rainfall and wind erosivity, and SSR is overlooked in previous studies and the magnitude of the wind-driven rain effect on a rough surface (compared to a smooth one) is not known.

The impact of SSR on splash erosion is complex and not well understood (Zumr et al., 2020). Wu et al. (2016) noted that most prior splash erosion research had focused on smooth soil surfaces, with limited studies examining rough surface conditions. In their investigation considering rough surfaces, they found that soil detachment rates were higher on the rougher surfaces compared to smooth ones. However, the reasons behind these differences in detachment rates between the roughness treatments were not clearly elucidated.

Rainfall causes soil surface roughness (SSR) to evolve over time. These changes in the SSR are influenced by rainfall volume, intensity, KE and drop size.

Generally, SSR decreases during rainfall events as the KE of raindrops breaks down and rearranges exposed soil aggregates on the surface (da Rocha Junior et al., 2016; Eltz & Norton, 1997; Lampurlanés & Cantero-Martínez, 2006; Panachuki et al., 2010). Nevertheless, Dalla Rosa et al. (2012) observed that SSR increased at the start of a rainfall event, as larger soil aggregates broke apart into smaller fragments, resulting in a higher specific surface area from the newly formed aggregates. These aggregates were further destroyed with rainfall duration, ultimately decreasing roughness. On the other hand, initially smooth surfaces may become rougher during rainfall events due to the formation of micro-rills on the soil surface (Huang & Bradford, 1992; Römken et al., 2001). These SSR changes have not been studied for wind-driven rain events, making this aspect one of the knowledge gaps in the literature.

1.3.2 Soil properties and plant traits

Soil erosion is influenced by soil physical properties as well as aboveground and belowground plant traits, with the plant-soil interaction manifested through the effects of roots on soil characteristics.

Soil physical properties significantly influence soil and water loss dynamics. Greater soil cohesion between particles can reduce soil detachment by erosive water forces (Knapen et al., 2007). Factors limiting infiltration rates like soil compaction or surface sealing promote higher surface runoff and erosion potential (Le Bissonnais et al., 1995). Soils with high bulk density and low porosity tend to have reduced infiltration and water storage capacity, increasing runoff and sediment loss. However, high bulk density can also increase soil cohesion, so limiting soil detachment. Soils with lower water retention are more susceptible to surface runoff and erosion due to their limited water storage capacity.

Plant characteristics play a crucial role in mitigating soil erosion (Lees et al., 2021). Aboveground plant traits like canopy cover and ground cover protect the soil surface from the direct raindrops impact, limiting the detachment, entrainment and transport of soil particles (Armstrong & Mitchell, 1987; Durán Zuazo & Rodríguez Pleguezuelo, 2008). Belowground root traits modify soil structure and water retention characteristics, influencing plant water availability (Whalley et al.,

2005). Roots help reinforce and stabilise soil structure by increasing shear strength and cohesion between particles and by creating biopores that enhance water infiltration, leading to less runoff and associated soil detachment and transport (Angers & Caron, 1998; Bodner et al., 2013; Colombi et al., 2018; Gyssels et al., 2005). Specific root traits like total diameter, length, and surface area influence soil cohesion, aggregate stability and erodibility (De Baets et al., 2007; Hudek et al., 2022; Mekonnen et al., 2016; Mwango et al., 2014; Vannoppen et al., 2015). Targeting root traits that build soil structure can improve erosion control and water management (Hallett et al., 2022), with denser rooting reducing compaction and allowing deeper resource access (Jin et al., 2017). Root length density may be a key parameter for estimating root effects on soil detachment and erodibility (Liu et al., 2019).

Vegetation is known to increase soil cohesion and infiltration rates compared to bare soil conditions (Le Bissonnais et al., 1995; Zhou et al., 2006). Wheat cultivation, for instance, generally has a positive impact on soil physical properties. However, the extent of these effects can vary depending on the genotype and associated roots traits. Sowing density also has a significant influence on both soil properties and plant characteristics. Optimum sowing densities generally tend to increase root length density, soil cohesion and shear strength, leading to soil reinforcement and erosion resistance (Tan et al., 2020). However, excessive sowing densities can limit plant growth due to resource competition, negatively impacting plant growth parameters like tillering and individual plant biomass. Drought conditions also affect soil properties, plant growth, and plant-soil interactions, impacting erosion dynamics. Little is known about the interactions between plant traits (as determined by their genotype, sowing density and water regime) and soil properties and their effect on runoff and soil erodibility.

Unravelling the interplay between the above- and belowground plant traits and soil properties that affect soil erosion processes is challenging because it is difficult to disentangle the mechanisms and interdependencies between soil and plant variables. Previous studies by De Baets et al. (2009) and Ghestem et al.

(2014) concentrated on specific aspects of erosion mitigation, such as plant species selection or solely root traits for controlling soil detachment by surface runoff. However, these approaches overlook the holistic and interconnected nature of soil erosion processes. Although Lees et al. (2020) expanded the scope by considering both aboveground and belowground plant traits, their methodology still lacks the inclusion of crucial factors such as soil properties. This highlights the necessity of employing erosion models that encompass all relevant processes and factors for a thorough assessment of erosion dynamics.

Over the years, researchers have developed various models to estimate and predict soil erosion rates, each with its unique strengths and limitations (Appendix B.2). The modified Morgan-Morgan-Finney (mMMF) model (Morgan & Duzant, 2008) is a soil erosion model that predicts mean annual soil loss based on the processes of detachment and transport of soil particles. It uses the Meyer and Wischmeier (1969) concept in which two key factors contributing to soil erosion are evaluated - the amount of soil particles dislodged by rainsplash and surface runoff (detachment), and the quantity of sediment that can be transported by the runoff flow (transport capacity). The model compares these two values and selects the lower one as the annual rate of soil loss ($\text{kg m}^2 \text{ yr}^{-1}$). This approach identifies whether the detachment process or the transport capacity acts as the limiting factor in determining the overall soil loss (Figure 1-1). This model specifically enables the effects of vegetation on runoff and erosion dynamics to be expressed through measurable plant parameters, capturing different treatments of wheat lines, sowing densities and water regimes. The mMMF model has several advantages over other models, making it a suitable choice for many applications. These advantages include the fact that it has modest data requirements unlike the WEPP and EUROSEM models that are data-hungry and are too complex to be used as simple management tools (Morgan & Duzant, 2008). Furthermore, this model is not fully empirical like the USLE or RUSLE models that are based on empirical relationships applied to specific conditions (east of the Rocky Mountains in the US). Finally, the modified MMF does not require high-capacity computing resources (its operating functions can run on a simple Excel spreadsheet). For these reasons, this erosion model has been

successfully applied at plots, hillslopes and small catchments and has been validated in a variety of climatic regions and land use types (Choi et al., 2017).

1.4 Project partnership

This PhD research is part of the overall project FP03 of the programme 'Sustainable Agriculture For Africa (SAFA)'. It is in partnership with Rothamsted Research and Mohammed VI Polytechnic University (UM6P) in Morocco, and funded by OCP group, Morocco.

1.5 Aim and Objectives

The overall aim of this thesis is to better understand the processes of soil erosion by water and wind under different tillage and agronomic measures, with a view to reduce soil and water losses. To achieve this aim, novel methodological approaches have been developed to simulate soil physical properties and hydrological processes.

While soil erosion is a global concern, this thesis specifically addresses the context of Morocco, where a combination of climatic and agricultural factors exacerbates the problem. Morocco experiences high annual rainfall concentrated in short periods, along with moderate to strong wind speeds, which contribute to both water and wind erosion. Moreover, variability in tillage and soil management practices directly affects soil surface roughness (SSR), further influencing the soil's susceptibility to erosion. Compounding these factors, Morocco frequently faces drought conditions, which not only stress crop growth but also alter soil structure and stability, increasing erosion risk during both wet and dry seasons. The thesis chapters are interconnected by their focus on these key drivers of soil erosion. Where possible, a Moroccan relevance was brought back in through, e.g. rainfall intensity, wind speed and selection of the crop. By examining the effects of SSR on water erosion, the combined impact of wind and rainfall on soil detachment, and the influence of wheat cultivation, as the dominant crop in Morocco, under varying water regimes - including drought - and sowing densities, this research addresses critical knowledge gaps.

Objective 1: Investigate the effect of soil surface roughness (SSR) and orientations on runoff, infiltration and soil loss (by rainsplash and overland flow) and the effect of rainfall and overland flow on SSR. (Chapter 2).

Objective 2: Develop and test an innovative laboratory-based experimental system that comprises rainfall and wind simulators, and use this novel system to investigate the effect of wind on the rainfall erosivity for different SSR. (Chapter 3).

Objective 3: Study the effect of vegetation (different wheat lines and sowing densities) subjected to different water regimes on soil physical properties and plant characteristics (shoots and roots). (Chapter 4).

Objective 4: Evaluate the effect of vegetation subjected to the treatments used in Objective 3 on soil erosion rates, as predicted by the mMMF soil erosion model. (Chapter 4).

Figure 1-3 illustrates an overall overview of this thesis research, covering its different aspects and shows how the processes described in each chapter link together and affect soil erosion. These include the effect of different soil surface roughness, the combination of wind and rainfall, as well as the plant-soil interaction and its effects on soil and hydrological properties.

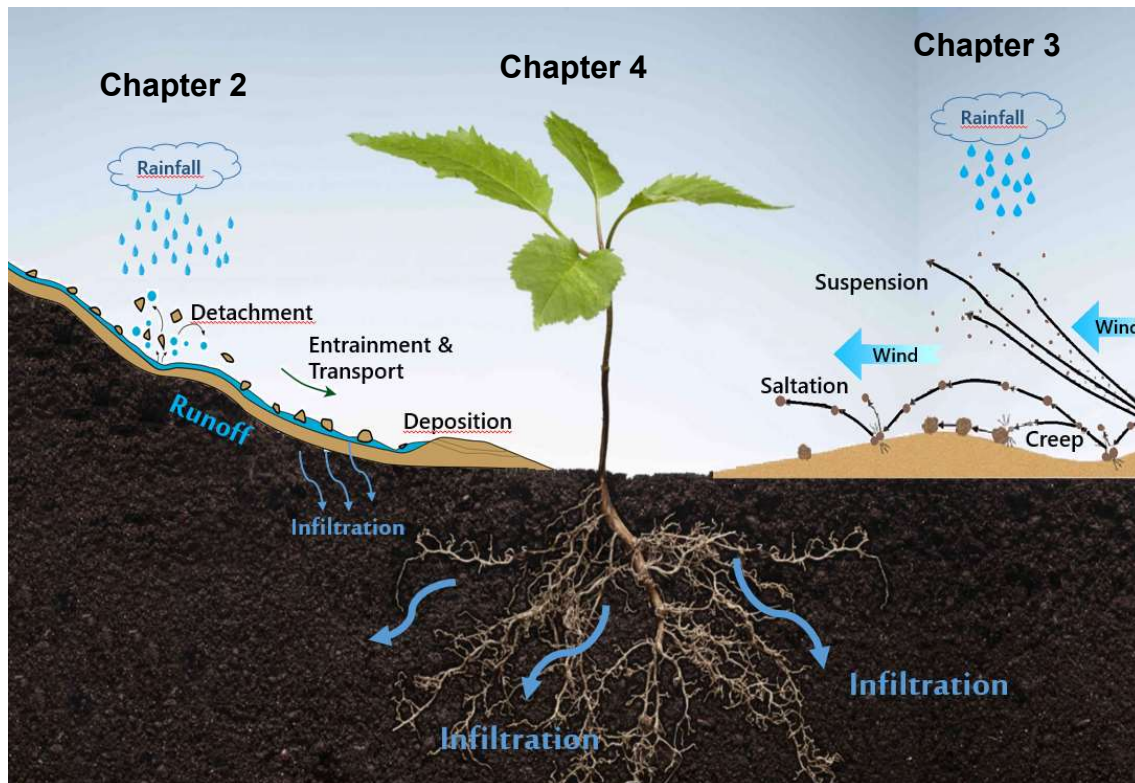


Figure 1-3 Illustration of the different research component of this thesis. The figures were adapted from [UBC Wiki](#), [Fossiliraptor](#), and [CID Bio-Science](#).

1.6 Thesis structure

This thesis is structured as a paper format and comprises three experimental chapters (Chapter 2, 3 and 4), each destined for publication in scientific journals. This format inevitably leads to some repetition of background information, methods and cited literature, as each paper is written as a "standalone" publication. Chapter 1 covers a literature review with identification of knowledge gaps. Chapter 2, covering Objective 1, is a result of a laboratory experiment and the paper was published in *Geoderma* (<https://doi.org/10.1016/j.geoderma.2023.116341>). Chapter 3, covering Objective 2, is also a result of a laboratory experiment and the paper has been formatted for publication. Chapter 4, covering Objectives 3 & 4, is a result of a laboratory experiment conducted at Rothamsted Research and a paper has been formatted for publication. Finally, Chapter 5 synthesises the outcome of this research and its contribution to knowledge and suggests potential future work.

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2 CHANGES IN SOIL SURFACE PROPERTIES UNDER SIMULATED RAINFALL AND THE EFFECT OF SURFACE ROUGHNESS ON RUNOFF, INFILTRATION AND SOIL LOSS

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2.1 Abstract

Soil erosion by water is a result of detachment of particles or small aggregates from the soil surface followed by transport and entrainment of the detached material. One of the elements that affects surface runoff and soil erosion is the soil surface roughness (SSR). Prior research reports that increasing SSR reduces generation of runoff and soil loss. In addition to that, it is widely reported that across-slope oriented roughness is better at controlling soil and water losses. However, to date there have been few studies into the effect of both magnitude and orientation of SSR on runoff, infiltration and soil erosion at the sub process level (i.e. by raindrop splash and overland flow), occurring simultaneously. In this study, the effects of up-down-slope oriented SSR (Treatment A), across-slope oriented SSR (Treatment B) and random SSR (Treatment C) were compared, along with a smooth surface (Treatment D). A moderate slope gradient of 10%, a simulated rainfall intensity of 90 mm hr⁻¹ and storm durations of 15 or 30 minutes were considered. The SSR was measured using the chain method, before and

after the rainfall event. Images of the soil surface were taken using a hand-held laser scanner to monitor the effect of rainfall on the surface morphology. The outcome of this study shows that rainfall erosivity increases the SSR of the initially smooth surface, but decreases that of the initially rough surface, particularly in the random SSR treatment, where the decrease in SSR was 64% of the pre-rainfall condition. This was due to the effects of raindrop impacts and overland flow. The random SSR treatment generated significantly more runoff and soil loss, and less infiltration than all other treatments ($p < 0.001$), but for raindrop splash erosion, there was no significant difference between random SSR and the other treatments. Contrary to expectations, the across-slope oriented SSR did not always reduce runoff and soil erosion compared to the up-down-slope orientation. This can be explained by degradation of surface microtopography by rainfall and runoff, as confirmed by the post-rainfall SSR measurements.

Keywords: Soil surface roughness, raindrop impact, runoff, infiltration, soil loss, splash erosion.

2.2 Introduction

Soil erosion is one of the most serious environmental problems in the world. One of the factors that affects surface runoff generation and soil erosion is soil surface roughness (SSR) which describes irregularities in the soil surface (Morgan et al., 1998). Definitions of SSR depend on the category of surface roughness and its order of magnitude (Bullard et al., 2018a; Vermang et al., 2013; Römken and Wang, 1986; Thomsen et al., 2015). Four main categories of soil surface roughness are recognized: (i) microrelief variations, which are due to individual particles, determined by the soil type, (ii) random roughness, which is due to the non-directional arrangement of soil aggregates, (iii) oriented roughness, which is unidirectional and describes the systematic topographical variations caused by field operations such as tillage and ridging, and (iv) greater orders of roughness, representing topographic variations at the field or landscape scale. Random and oriented roughness (categories ii and iii) have been the focus of many studies because they are determined by land management practices. They also affect various hydrologic and soil erosion processes on arable land (Govers et al.,

2000). In agricultural systems, soil management practices induce changes in the soil microrelief (Bramorski et al., 2012; Dalla Rosa et al., 2012; Vázquez et al., 2005), and different types of tillage affect the degree of soil surface roughness (da Rocha Junior et al., 2016). Soil surface roughness affects the time of runoff initiation during or after rainfall, the amount of soil and water losses, and the amount of soil lost through rainsplash erosion. SSR also affects the way rainfall alters the SSR. The multitude of these processes is however rarely considered or quantified.

Some studies have found that SSR delays runoff initiation during rainfall events, by trapping water in the depressions on the soil surface, so encouraging water infiltration (Darboux et al., 2004; Darboux and Huang, 2005; Vermang et al., 2015). In this way, tillage on the contour also delays runoff initiation time (Zhao et al., 2014b), regardless of rainfall intensity and slope gradient (Zhao et al., 2021). However, any delay in the time to runoff initiation might decrease with successive rain events (Darboux et al., 2004) to a level where there is no difference in runoff generation delay between initially rough and smooth surfaces.

It is widely reported that total runoff and soil loss decrease with increasing magnitude of surface roughness (e.g. Zheng et al., 2014). According to Cogo et al. (1984), increased SSR induced by tillage reduces soil erosion by (i) storing water in the surface depressions which promotes infiltration and reduces runoff generation, (ii) reducing runoff flow velocity which decreases the capacity of flow to detach and then transport soil particles (Cogo et al., 1983), (iii) trapping detached sediment in the surface depressions created by SSR, and (iv) preventing soil detachment by raindrops by the buffering, protective effect of any surface ponded water (Gao et al., 2003). Zhao et al. (2014b) and Idowu et al. (2001) simulated rough and smooth surfaces under a high rainfall intensity and found that increasing SSR reduced soil losses by up to 50%. Zhao et al. (2014a) also found that soil loss for the smooth surface was significantly higher than that for the rough surface, regardless of the rainfall intensities. However, no significant difference in runoff was found between rough and smooth surfaces as the rainfall intensity increases. This is because the surface microtopography decreased and

reduced the effective surface depression storage. On the other hand, the results of Darboux and Huang (2005) did not have the same conclusions. Although the rough surfaces with initial depressions delayed the time to runoff initiation, they produced 10% greater water flux than the initially smooth surfaces, once the runoff reached an apparent steady state. This was due to the sharp decrease in the surface depressions' storage capacity. Regarding the soil loss and sediment concentration, the authors found that the effect of SSR was non-significant, and Darboux et al. (2004) explained that there were no firm conclusions regarding the decreased soil loss from the rough surfaces. Helming et al. (1998) indicated that during an initial storm, runoff concentrated immediately between the soil clods of a rough surface, routing the water within several surface flow paths. The concentrated flow had higher capacity for soil detachment and sediment transport, which explains the greater soil loss for the rough surfaces. This effect was even greater on steeper slopes. Similarly, Römken et al. (2001) found that initially smooth surfaces yielded less soil loss than initially rough surfaces, due to differences in the runoff regime, although the roughness treatment was applied differently (by sieving the soil to different aggregate sizes). There is therefore no consensus on whether random SSR increases, decreases or have no effect on runoff and soil loss. The reason for these mixed results probably lies in different experimental combinations, such as roughness characteristics, slope, soil properties, and rainfall intensities, durations and KE.

Regarding oriented roughness, it is generally thought that tillage direction can either enhance or reduce runoff erosivity, depending on whether the tillage operation is applied parallel to the slope direction (up- and downslope) or perpendicular to the slope (across-slope). Up- and downslope tillage can increase soil erosion because it tends to channel any surface flow down the slope, increasing both the volume and velocity of runoff and its KE to detach, entrain and transport soil particles (Hou et al., 2021; da Rocha Junior et al., 2016). Across-slope tillage (also known as contour tillage) delays the runoff initiation time (Luciano et al., 2009) and can limit soil erosion, due to the effect of perpendicular ridges acting as barriers, behind which surface runoff pools and any entrained sediments are trapped and deposited (Gebreegziabher et al.,

2009; Stevens et al., 2009; da Rocha Junior et al., 2016; Zhao et al., 2021). However, Quinton et al. (2004) found that the mean event soil loss was not significantly different between the two cultivation orientations. Although contour cultivation is assumed to be an appropriate soil conservation measure (da Rocha Junior et al., 2018), it is less effective on steep slopes (Alvarez-Mozos et al., 2011; Chambers et al., 2000; USDA, 2017). This is because it can result in major concentrations of runoff in low spots along the ridges, which may overtop and breach the ridges, thus increasing the risk of erosion (Morgan, 1992).

Raindrop splash erosion is a major component of soil erosion by water because it is considered the main process responsible for initial soil detachment (Morgan, 2005). The effect of SSR on rainsplash erosion is not a straightforward process (Zumr et al., 2020). Wu et al. (2016) concluded that most splash erosion investigations had been conducted on a smooth soil surface and little research had considered rough surfaces. Therefore, they considered that in their study and found that soil detachment rates on the rough surfaces were greater than those on the smooth surfaces. However, these differences between roughness treatments were not clearly explained. Other authors found the opposite trend, of decreasing splash erosion with increasing roughness. There are different types of devices that measure splash erosion but as a separate process. To improve understanding of soil erosion mechanisms, it is important to consider all soil erosion processes both separately and in combination, and yet few studies considered measuring, simultaneously, both splash erosion and soil loss by runoff.

Under the influence of rainfall, the roughness of a soil surface changes over time. This roughness evolution is influenced by the volume and intensity of rainfall. In general, SSR decreases during rainfall events because the KE of the impacting raindrops causes breakdown of soil aggregates on the exposed surface (Eltz & Norton, 1997; da Rocha Junior et al., 2016; Lampurlanés & Cantero-Martínez, 2006; Panachuki et al., 2010). However, Dalla Rosa et al. (2012) noted that there was an increase in the surface roughness at the beginning of the rainfall event due to fragmentation of larger aggregates. As the duration of rainfall increases,

these aggregates were further destroyed, which then decreased the surface roughness. On the other hand, initial smooth surfaces might become rougher during rainfall, due to micro-rill development on the soil surface (Huang and Bradford, 1992; Römken et al., 2001).

The aim of this study is to obtain a better mechanistic understanding of soil erosion processes and the hydrological response of soils occurring simultaneously. To date, there have been few studies into the effect of both magnitude and orientation of SSR on runoff, infiltration and soil erosion (i.e. by raindrop splash and overland flow), occurring simultaneously. Among them, rarely are the studies that quantified the changes in the SSR post-rainfall event to explain the erosion results. The objectives of this research are a) to study the changes in the different SSR morphologies due to rainfall and overland flow, and b) to compare the effects of up-down-slope oriented roughness, across-slope oriented roughness and random roughness, along with a smooth surface on soil and water losses under simulated rainfall. A slope gradient suitable for arable operations was used, and rainfall events (intensity and durations) and a soil texture comparable to those found in soil erosion prone regions.

2.3 Materials and methods

2.3.1 Erosion trays preparation

An air-dried sandy loam soil (16% clay, 27% silt and 56% sand) was sieved through a 4 mm mesh screen and packed into erosion trays of 50 cm length, 25 cm width and 8.5 cm depth. Its moisture content was 2.6%. Each tray was packed with 14.9 kg of sieved soil, in thin layers, giving a bulk density of 1.4 g/cm³, typical for natural sandy loam soil. During packing, each layer of 1.65 kg was compacted using a soil packer, using the same number and intensity of strikes per layer, to achieve a uniform bulk density throughout the profile. The trays were filled up with soil to the level of a V-shaped runoff outlet from which surface runoff samples (along with sediment in the runoff) would be collected during the rainfall event. Each erosion tray was put on a base that contained a perforated steel sheet covered with voile, which prevented the packed soil from falling through, but allowed any infiltrated water to drain and reach the infiltrate outlet. This also

allowed the trays to wet up to the desired initial soil moisture content via capillary action, as described below.

The soil erosion trays were then prepared to simulate different soil surface roughness treatments (Figure 2-1), representing different tillage and cultivation practices, namely: a) oriented roughness – up/downslope direction, b) oriented roughness – across slope direction, c) random roughness – non directional, and d) smooth surface – with no roughness treatment applied, hereafter referred to as Treatment A, B, C and D, respectively.

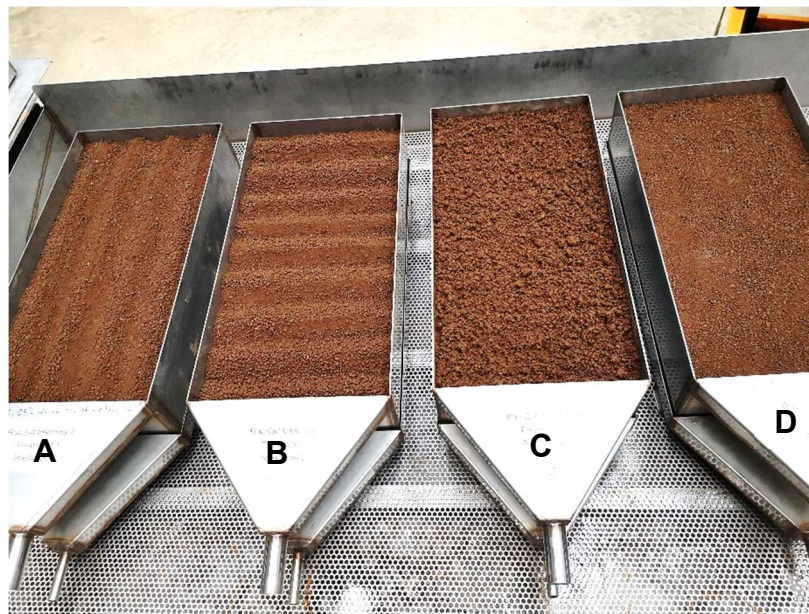


Figure 2-1. Four roughness treatments applied to a sandy loam soil in erosion trays: oriented roughness – up/downslope direction (A), oriented roughness – across slope direction (B), random roughness – non directional (C), and smooth surface – with no roughness treatment applied (D).

Each treatment was replicated eight times, resulting in 32 erosion trays. The soil surface in Treatment D was left intact, i.e. no roughness applied, to simulate the smooth surface. Treatments A and B were applied to the air-dried soil using a profile meter to obtain the oriented roughness in parallel to the slope direction and perpendicular to the slope direction, respectively. The profile meter was adjusted to give a wave-like shape of ridges and furrows of 0.7 cm height and depth, respectively, and with a spacing of 6.25 cm between ridges. As a result, four ridges were obtained in Treatment A and eight ridges in Treatment B (Figure

2-1). The profile meter was slowly dragged up and down the slope (Treatment A) or across the slope (Treatment B) until the roughness treatment required was evenly imparted to the soil surface. Treatment C was applied on a moist soil to obtain soil aggregates, representing random roughness. A metal rake was used at a soil depth of approximately 1 cm, at different directions until clods covered the entire soil surface, representing a random roughness (Figure 2-1). The surface was measured (Section 2.3.3.1) to make sure the roughness treatment applied to the eight replicates was similar.

Soil trays were put in a tank filled with water that reached the trays' base, allowing the soils to wet up by capillary rise for a period of 72 hours. The erosion trays were then removed from the water tank and drained for another 72 hours. Moisture content measurements were taken using a hand-held Delta-T HH2/SM150T soil moisture probe at the centre of each erosion tray.

There were no significant differences in initial soil moisture content between the erosion trays at the start of the rainfall event. The volumetric moisture content measured with the probe gave a mean of 42.67% with a variation of 3.76% between the trays. This is close to an estimated porosity value of 0.47, assuming a particle density of 2.65 g/cm³, which indicates that the soil was near saturation.

2.3.2 Rainfall simulator calibration

A pressurised water, nozzle rainfall simulator was calibrated to deliver representative rainfall events (intensity, duration, associated return periods and drop size distribution) that reflect current and future conditions of a Moroccan region (Table 2-1) [Justification for rainfall characteristics is found in Appendix C.1, Table C-1].

Table 2-1 Duration and occurrence of the selected rainfall event characteristics.

Rainfall intensity (mm hr ⁻¹)	Duration (mins)	Return period (years)
90	15	35
	30	150 (extrapolated)

The rainfall simulator was calibrated by varying the water supply pressure, ranging between 0.5 and 0.7 bar, and by varying the height of the nozzle between 1 m and 1.9 m. A number of locations under the rainfall nozzle were tested for consistent delivery of the desired rainfall characteristics. The slope gradient of the erosion trays was set at 6 degrees (~10%), representative of typical arable field conditions.

The rainfall intensity (RI, mm hr⁻¹) was calculated using Equation (2-1), where V is volume of rain collected (mL), S is surface area of the tray (cm²), t is duration of the test (min).

$$RI = \frac{V}{S} \times \frac{60}{t} \times 10 \quad (2-1)$$

The nozzle that produced the desired intensity was a LECHLER 460.888.30.CG, placed at 1.85 m above the soil surface, and the pressure at the nozzle was maintained at 0.3 bar (supply pressure of 0.5 bar). The positions under the simulator that received the desirable rainfall intensity were identified as locations of the erosion trays during the rainfall simulation experiments. Rainfall catch cups were placed next to the erosion trays during each run to ensure consistent rainfall application.

A laser optical disdrometer (LOD), positioned at 6 different locations under the rainfall simulator, was used twice during the experiment to measure raindrops' size, volume and KE to ensure representative and repeatable rainfall properties. The measurements were repeated five times for each of the six target positions. The mean values (n=60) are summarised in Table 2-2. The KE_t of the simulated rainfall (90 mm hr⁻¹) measured in this study is consistent with the correlation between rainfall intensity and KE presented by Shin et al. (2016).

Table 2-2. Rainfall characteristics obtained using the Laser Optical Disdrometer.

Median drop diameter ^a	D ₅₀ (mm)	2.23
KE as a function of time	KE _t (J m ⁻² h ⁻¹)	2332
KE as a function of volume	KE _{vol} (J m ⁻² mm ⁻¹)	26

^a D₅₀ is calculated from cumulative percentage of drop volume.

2.3.3 Measurements

2.3.3.1 Soil Surface Roughness

Pre-rainfall images of the soil surface were taken to visualize the changes in the morphology due to rainfall. For this, a laser scanner (Creaform EXAscan 3D Handscanner) was used, along with XVelements, a powerful integrated 3D scanning software. The scans were converted and processed using Geomagic Studio® software, then the 3D surface areas were computed.

Soil surface roughness was measured using the fine chain method, before and after the rainfall event to assess the effect of rainfall and overland flow on the SSR. In the fine chain method proposed by Morgan et al. (1993), the SSR, (cm m⁻¹ or %) is defined as the ratio of the straight-line distance between two points on the ground (X) to the actual distance measured over all the microtopographic irregularities (Y) (Figure 2-2). To be a fair test, the denominator of the SSR equation should be the same value in both measurements before and after the rainfall event. Therefore, the equation proposed by Morgan et al. (1993) was slightly modified (Equation (2-2)) [more in Appendix C.2]:

$$SSR = \frac{Y - X}{X} \times 100 \quad (2-2)$$

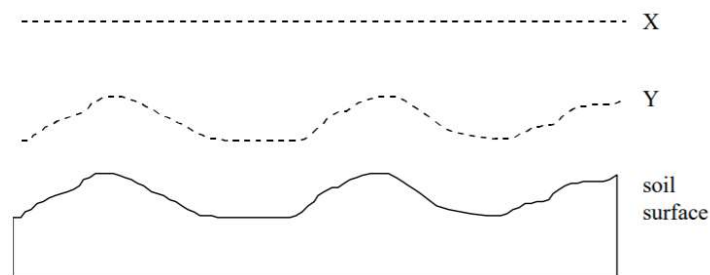


Figure 2-2 Representation of a straight-line surface length (X) and a real surface length measured over the soil surface morphology (Y) which gives an indication of the soil surface roughness.

For Treatment A, three readings of roughness measurements were taken across the width of the erosion tray, because this Treatment presents an up- and

downslope (i.e. unidirectional) oriented roughness. For Treatment B, three readings of roughness measurements were taken down the length of the erosion tray, because this Treatment presents an across-slope (i.e. unidirectional) oriented roughness. For Treatments C and D, six readings of roughness measurements were taken (three across the width and three down the length of the tray), because these treatments present the random roughness (non-directional) and a smooth surface, respectively. For each treatment, SSR is the mean of these measurements. The link size of the chain was of 0.5 mm which enabled the microrelief on the soil surface to be measured.

2.3.3.2 Runoff – Infiltration – Soil loss

For each erosion tray, total volumes of surface runoff and infiltrate were collected after 15 and 30 minutes from the erosion tray's outlet and the base's outlet, respectively, via a system of pipes and buckets, and measured using measuring cylinders. The time taken for runoff and infiltrate initiation (seconds) was recorded. The mass of sediments collected in the runoff was also recorded at 15 and 30 minutes. When the runoff volume was less than 100 mL, the total collected volume was filtered through oven dried, pre-weighed Whatman Number 2 filter paper. When the runoff volume was > 100 mL, the total mixture was thoroughly agitated, and a sub-sample of 100 mL was taken and filtered. The sediment-loaded filter papers were oven dried for 24 hours at 105°C and weighed using a precision balance with a readability of 0.001g. The sediment concentration in the runoff (SC, g L⁻¹) was calculated using Equation (2-3), where M1 is mass of sediment-loaded filter (g), M0 is mass of empty dried filter (g), R: runoff volume (mL).

$$SSC = \frac{(M1 - M0)}{R} \times 1000 \quad (2-3)$$

After the rainfall event, infiltration rate of the immediate soil surface was quantified using a mini disk infiltrometer (Decagon Devices, Inc.) which is a tension infiltrometer that measures the hydraulic conductivity of the soil. This measurement will show if rainfall-induced changes in the soil surface treatments affect infiltration processes. A suction rate of 2 cm, adequate for most soils

(Decagon Devices Inc., 2016), was considered. The water volume (mL) in the infiltrometer tube was recorded over time and the hydraulic conductivity was calculated, based on a method developed by Zhang (1997).

2.3.3.3 Rainsplash erosion

Splash collectors made from fabric (referred in this paper as “voile”) were used to measure detached soil particles by rainsplash. The voiles were suspended over the soil surface, with the lower edge just above the soil surface so not to interfere with surface runoff. The fabric voile was cut into rectangles of 5.5 cm x 9.5 cm and attached to a thread fixed across the width of the tray. For Treatment A, the voile was cut to fit the shape of the ridges and furrows (Figure 2-3a).

Two voiles were used per erosion tray, at two different positions, placed at 15 cm from the top and the bottom of the tray (Figure 2-3b). For Treatment B, two voiles were both put at 15 cm from the top of the tray, one on the ridge and the other one on the furrow (Figure 2-3c).

After the rainfall event, the sediment-loaded voiles were put in pre-weighed tins and oven dried. The detached soil mass is the difference between the weight of tin filled with sediments, with the voile removed, and the empty tin weight (g) and expressed per unit area of the voile.



Figure 2-3 Capturing soil particles detached by rainsplash on the erosion trays. (a) Collector voiles cut to fit the shape of Treatment A. (b) Two collector voiles placed at the top and bottom of the erosion tray. (c) Two collector voiles put on the ridge and in the furrow of Treatment B.

2.3.4 Statistical analysis

The experiment contained two blocks. Each block had sixteen erosion trays, that is four replications per treatment, making the whole experiment a total of thirty-two erosion trays (eight replications for each one of the four treatments). The testing sequence for the erosion trays under the rainfall simulator, in each block, was completely randomized. All the data was combined and statistically analysed accordingly, using the statistical software Genstat[®] (21st Edition), and the differences in the results data between the treatments were assessed by REML (Restricted Maximum Likelihood). This method estimates the treatment effects and variance components in a linear mixed model: that is a linear model with both fixed and random effects. The treatments were assigned to the fixed model, and the random model combined other factors such as the blocks and the order of erosion tests. In addition to that, when significant treatment effects were identified by the REML analysis ($p < 0.05$), the Least Significant Differences (LSD) test was used in order to find out exactly which treatment(s) are different from the others. This test consists of a pairwise comparison of the means with a significance level of $<5\%$.

2.4 Results

2.4.1 Effect of raindrop impact on initial Soil Surface Roughness (SSR)

Table 2-3 and Figure 2-4 present the initial (pre-rainfall) and final (post rainfall) SSR for the different treatments. Before the rainfall event, Treatments A and B had the same degree of SSR, but they differed in the orientation of applied roughness. Comparison of mean initial SSR using the LSD method ($<5\%$ level) showed no significant difference between Treatments A and B. However, the degree of roughness was statistically different between these two treatments and Treatment C ($p < 0.001$), which validates the method used for creating significantly different SSR levels. Before the rainfall event, the highest initial SSR was measured in Treatment C, followed by both Treatments A and B. As expected, these three surface treatments had significantly higher initial SSR than the smooth surface.

Table 2-3 Soil surface roughness (cm m⁻¹ or %), generated using the chain method, for different soil surface treatments, before the rainfall event (initial SSR) and after the rainfall event (final SSR).

Treatments	Surface roughness (cm m ⁻¹ or %)		SSR change (%) ^b
	Before rain	After rain	
A	16.3	13.8	-15
B	14.7	9.5	-36
C	20.5	7.3	-64
D	2.7	5.8	+113

^b Negative values indicate a decrease in surface roughness; a positive value indicates an increase in surface roughness.

The final SSR after the rainfall event remained significantly different between the four treatments ($p < 0.001$). Post rainfall, the SSR decreased for Treatments A, B and C, unlike Treatment D where SSR increased after the rainfall event. The REML analysis showed that the final SSR was significantly different from the initial one ($p < 0.001$). The mean comparison using LSD ($<5\%$) showed that this difference is statistically significant for Treatments B, C and D, where the SSR in Treatments B and C decreased by 36% and 64%, respectively, and increased by 113% for Treatment D. The SSR in Treatment A decreased by 15%, but this decrease between initial and final SSR was not statistically significant (Figure 2-4).

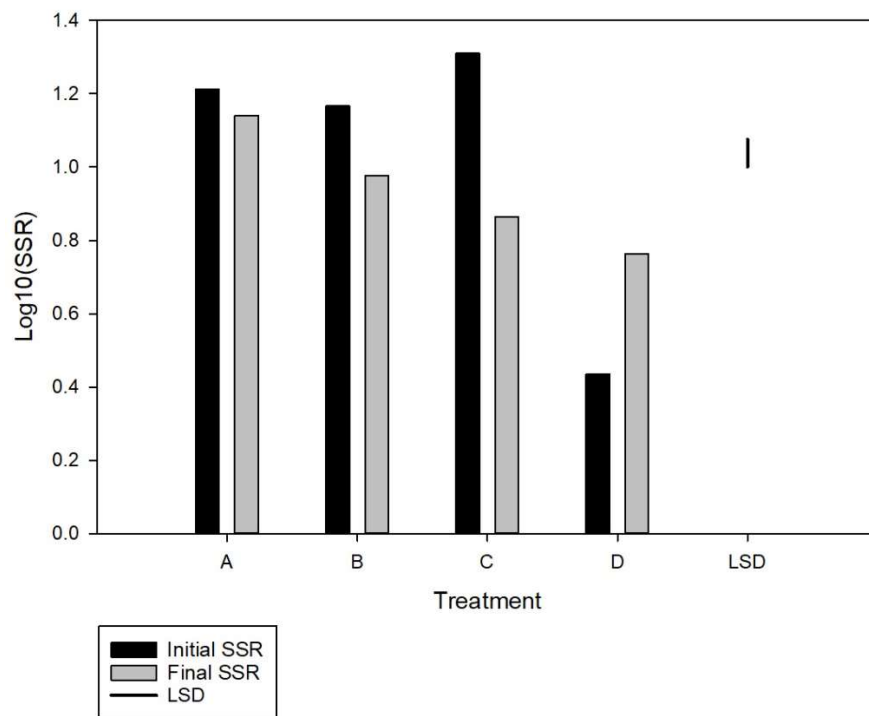
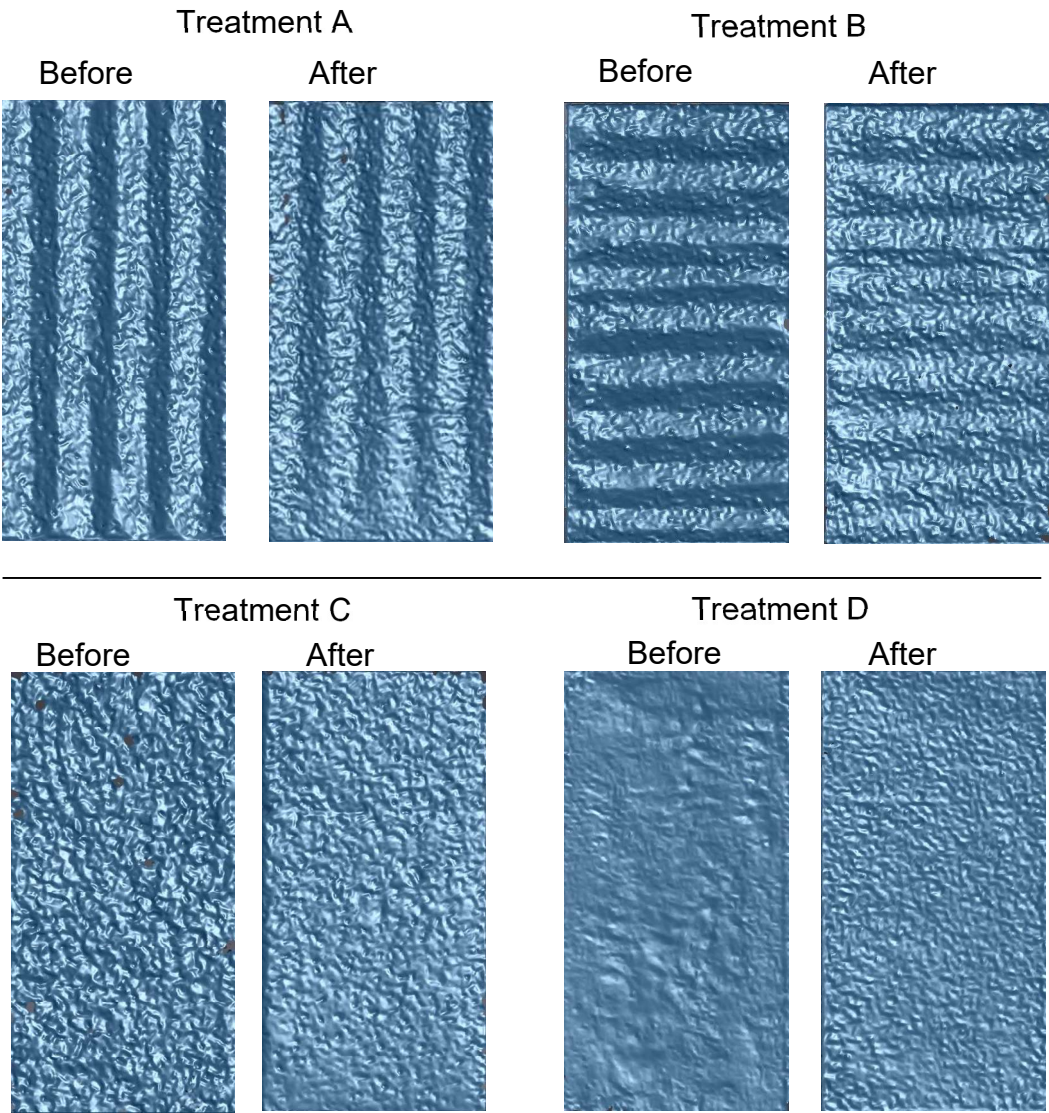


Figure 2-4 Soil Surface Roughness (SSR), expressed in Log10, for each of the four treatments measured before (initial) and after (final) the rainfall event.

Changes in SSR were also confirmed by the laser scanner. The scans were processed and analysed for few replications per treatment. For Treatment A, initial SSR was 16.6% (n=2) and final SSR was 13.8% (n=3) that is a decrease in roughness by 17%. For Treatment B, initial SSR was 14.7% (n=2) and final SSR was 9.1% (n=2) with a decrease of 39%. For Treatment C, the roughness decreased by 65% moving from an initial SSR of 20.4% (n=3) to a final SSR of 7.1% (n=3). On the other hand, the initial SSR (3%, n=1) increased by 95% for Treatment D with a final roughness of 5.9% (n=1). These results align with those of the chain method presented in Table 2-3 and Figure 2-4. Images in Figure 2-5 show the soil surface roughness of the four treatments before and after the rainfall simulation. For Treatments A and B, before applying the rainfall, it can be observed that each ridge was forming a shadow (dark colour in the image). It is clearly noticed that the light colour gets wider, and the dark shadow gets lighter after applying the rainfall, which indicates the reduction of ridge height. For Treatment C, it can be observed that the bumps represent the soil clods and aggregates which became smaller after applying the rainfall due to the soil

disaggregation. For Treatment D, it is distinctly observed that the soil surface before the rainfall application was smooth. After applying the rainfall, small pits were formed due to the raindrop impacts that leads to soil disaggregation. This is represented by the contrast of colours (light vs dark).

Figure 2-5 Changes in the soil surface roughness of the four treatments before and after rainfall simulation. Images from a laser scanner with a resolution of 2 mm. Each image represents the erosion trays' dimensions of 50 x 25 cm.



2.4.2 Runoff, infiltration, soil loss and sediment concentration

2.4.2.1 Time-to-runoff and runoff volume

Time-to-runoff initiation is the period between the start of the rainfall and the generation of the first outflow at the runoff outlet. Time-to-runoff (seconds) was recorded for each erosion tray during the rainfall simulations. Treatment C presented the shortest mean time-to-runoff (124 ± 15 seconds), followed by Treatments D, B and A, where mean time-to-runoff initiation was 166 ± 44 , 243 ± 80 and 249 ± 70 seconds, respectively, from the rainfall start. However, the differences were not significantly different ($p > 0.05$). There was no correlation between the time-to-runoff and the SSR measurements ($r = 0.038$).

Treatment C (random roughness) was associated with the highest mean runoff volume during the 30-minute rainfall event, generating runoff that was 6.8, 3.8 and 5.0 times the runoff volume for Treatments A, B and C, respectively. REML analysis showed that mean runoff volume was significantly different between treatments ($p < 0.001$). However, the LSDs at the 5% level show that the difference is only statistically significant between the treatment with the highest mean runoff volume (Treatment C; random roughness) and the other treatments. There is no significant difference between Treatments A, B and D (Figure 2-6).

For each treatment, approximately 42% of the total runoff was collected in the first 15 minutes of the rainfall event and 58% of the total volume was measured in the latter 15 minutes of the event. The runoff volume increases with rainfall duration ($p < 0.001$) (Figure 2-6).

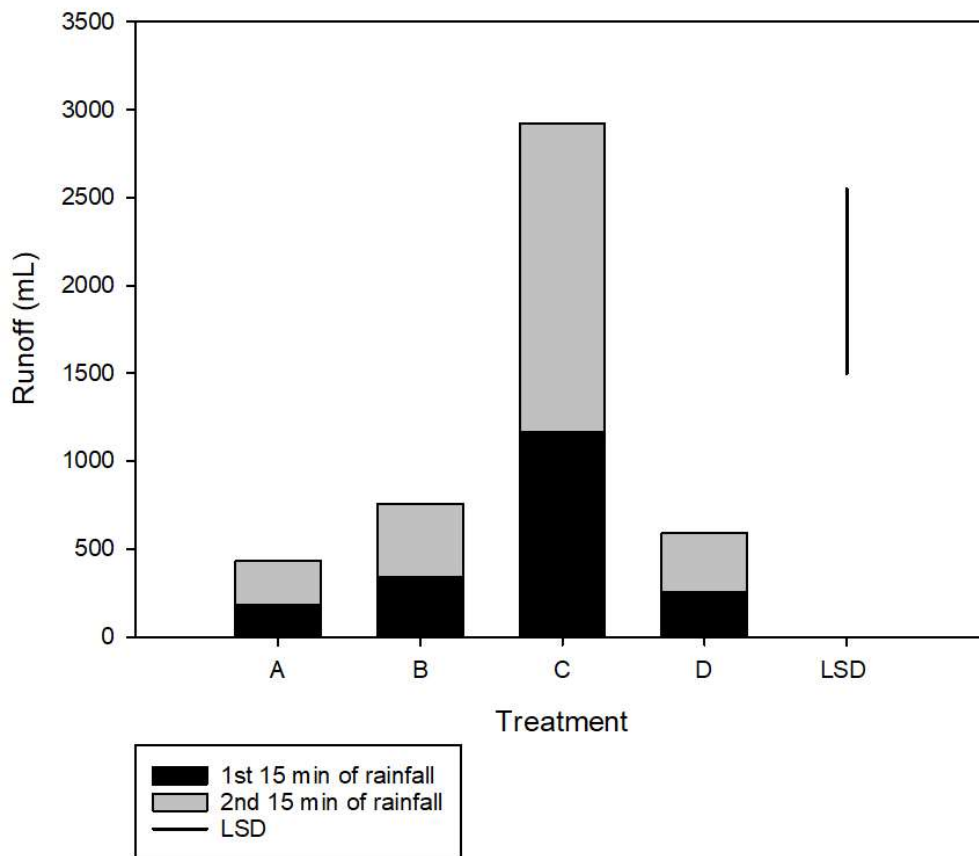


Figure 2-6 Mean runoff volumes (mL) generated by the four surface treatments during a 30-minute rainfall event. LSD was used to compare between means of the 30 min data.

After the rainfall event, two contrasting sets of results were identified for Treatment B (across slope SSR): four replicates had lower runoff volumes than Treatments A and D. In this case, the contour ridges of Treatment B behaved as barriers to overland flow, leading to water ponding behind the ridges and less runoff being generated. However, four other replicates presented higher runoff volumes than Treatments A and D.

2.4.2.2 Time-to-infiltration infiltrate volume and hydraulic conductivity

Time-to-infiltration (seconds) is the period between the start of the rainfall and the generation of the first outflow at the infiltrate outlet. This was recorded for each erosion tray during the rainfall simulations. During the experiments, it was observed that infiltrate was always initiated before runoff. The mean time-to-infiltration initiation ranged from 35 seconds (Treatment B) to 39 seconds

(Treatment C). Statistical analysis showed that there was no significant difference in time-to-infiltration between the treatments ($p > 0.05$).

Mean total infiltrate volume (mL) was significantly lower in Treatment C (random SSR) compared to the other treatments (Table 2-4). For Treatments A, B and C, around 44.5% of the total infiltrate volume was collected in the first 15 minutes of the rainfall simulation and 55.5% was collected in the latter 15 minutes of the event. This shows that infiltrate volumes increase with rainfall duration. However, for Treatment C, the infiltrate volume slightly decreases over time, with 52.5% of the volume collected in the first 15 minutes and 47.5% in the latter 15 minutes of the rainfall event.

Table 2-4 Mean infiltrate volumes (mL) from the four surface treatments during the 15-minute and 30-minute rainfall event.

Treatments	Infiltrate (mL)	
	1 st 15-min event	2 nd 15-min event
A	2950	3381
B	2606	3313
C	2024*	1833*
D	2656	3546

* The difference between Treatment C and the other treatments is statistically significant ($p < 0.05$). LSD values for the 1st and the 2nd 15 min data are 530 and 584 mL, respectively.

Similarly, half of the replicates of Treatment B had lower values of infiltrate volume than Treatments A and D, and the other half generated higher values than those two treatments.

Regarding the hydraulic conductivity measured using the mini disc infiltrometer, the statistical analysis showed that there are significant differences between treatments ($p < 0.001$), specifically between Treatment C and all other treatments (according to LSD). Treatment C had the lowest mean hydraulic conductivity ($7 \times 10^{-4} \text{ cm s}^{-1}$). On the other hand, Treatments A, B and D had hydraulic conductivity with mean values of 33×10^{-4} , 41×10^{-4} , and $36 \times 10^{-4} \text{ cm s}^{-1}$. These

results are consistent in that the lower hydraulic conductivity results in lower infiltrate volume and greater run-off volume.

2.4.2.3 Sediment load and concentration in the runoff

Total soil loss in the runoff (mg) was measured for the four treatments and the difference was statistically highly significant ($p < 0.001$). The mean comparison (LSD) shows that Treatment C had significantly the highest mean total soil loss (Figure 2-7a) as compared with all other treatments. There was a strong positive correlation between runoff volume and soil loss ($r = 0.85$), as soil particles at the soil surface were both detached and then transported by the runoff.

Similar to the runoff data, half of the replicates of Treatment B had lower values of soil loss than Treatments A and D. The other Treatment B replicates generated higher values of soil loss than Treatments A and D (Figure 2-7a).

Sediment concentration in the runoff (g/L) was also significantly different between treatments and the mean values decrease with rainfall duration (between the 1st 15 min and the 2nd 15min) by 37, 65, 39 and 69% for Treatments A, B, C and D respectively (Figure 2-7b).

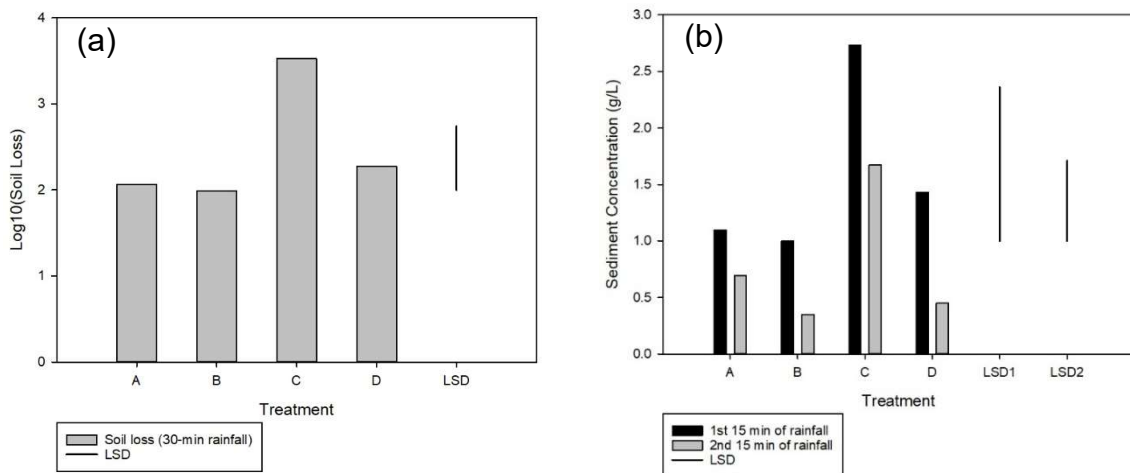


Figure 2-7 (a) Mean total soil loss (mg), expressed in Log10, generated during a 30-minute rainfall event. LSD was used to compare between the means. (b) Mean sediment concentration in the runoff (g/L) collected after the first 15 minutes and the second 15 minutes of the rainfall event. LSD₁ was used to compare between means of the 1st 15 min data, and LSD₂ for means of the 2nd 15 min data.

2.4.3 Rainsplash erosion

The significantly lowest mean splash erosion (1.91 mg cm^{-2}) was recorded for Treatment A after 30 minutes of rainfall. The means of splash erosion for this rainfall duration were 5.2 and 5.9 mg cm^{-2} for Treatments C and D respectively. For Treatment B, splash erosion collected in the furrow was significantly higher than that collected on the ridge ($p < 0.05$), with 8.7 and 3.9 mg cm^{-2} recorded in the furrow and on the ridge respectively.

During the experiment, some additional splash collectors (voiles) were located at the bottom of the erosion tray for Treatments A, C and D. It was postulated that these would catch more splashed material than the voiles positioned at the top of the tray, because of the potentially larger catchment area available above the bottom voile, that could contribute detached and transported splashed material. To test this hypothesis, a paired t-test was run, and the results show that there was a significant difference between the two locations ($p < 0.05$).

2.5 Discussion

Soil erosion by water is a result of particle / aggregate detachment from the soil surface followed by the transport of the detached material (Morgan, 2005). These processes are determined by the erosivity of both the rainfall and the overland flow. Kinnell (2005) identified four soil detachment / transport processes: (i) raindrop detachment with transport by raindrop splash; (ii) raindrop detachment with transport by raindrop-induced flow; (iii) raindrop detachment with transport by overland flow, and (iv) detachment and transport by overland flow. However, rainsplash is considered the most important detaching agent (Morgan, 2005) as a result of the relatively high raindrop KE impacting the soil surface. It is also considered the initial phase of the erosion process (Kinnell, 2005).

2.5.1 Effect of raindrop impact on initial SSR

Zhao and Wu (2015) suggested that the morphology of a soil surface changed significantly after rainfall. Increases or decreases in SSR after exposure to rainfall depend mainly on the original condition of the soil surface (Govers et al., 2000). This was also presented by Huang and Bradford (1992), Magunda et al. (1997)

and Zhao et al. (2014). According to a number of previous studies, rainfall decreases SSR for initially rough soil surfaces, while it increases the roughness of the initially smooth surface. Zhao et al. (2014) noticed that an initially smooth surface developed many discrete crescent-shaped pits following rainfall and related the increase in SSR to the shear force of overland flow. Huang and Bradford (1992) found that increased rainfall amount caused the development of micro-rills leading to a higher surface roughness. Römken et al. (2001) also found that an initially smooth surface became rougher due to rill development and flow incisions. The results of the present study however show that raindrop impacts cause soil particles to be dislodged, transported in the rainsplash jets and redeposited elsewhere on the soil surface (Bullard et al., 2018a). This process generates microrelief in the initially smooth surface, leading to an increase in the surface roughness, post rainfall (Treatment D in Figure 2-5).

Regarding the rough surfaces, the results of this study showed a decrease in SSR of 15% for the up/down-slope roughness (Treatment A) and 36% for the across-slope roughness (Treatment B). Even though their initial surfaces had the same degree of roughness before the rainfall event, the decrease in surface roughness after the rainfall event was greater in Treatment B than in Treatment A. This is because of the contrasting results between replicates observed for Treatment B (discussed later). The average between the two mean values aligns with the results found by da Rocha Junior et al. (2016), who demonstrated a tendency of SSR to decrease after the rainfall event by 22.7% in contour tillage and up/down-slope tillage treatments. The decrease in SSR is due to the KE of raindrops that break down soil aggregates (Kinnell, 2005) and larger surface of structures such as ridges. The detached material is then transported from the microtopographic elevations and deposited in small, local depressions (Kirkby, 2001; Zhao et al., 2019). The local elevations and depressions in Treatment C were not as marked (i.e. high and deep respectively), as the ridges and furrows of Treatments A and B. Therefore, the aggregates in Treatment C were rapidly broken down and deposited in local low spots which makes this treatment the one with the highest relative surface roughness decay after the rainfall event, as mentioned in the results section.

2.5.2 Runoff, infiltration, soil loss and sediment concentration

The random roughness treatment (Treatment C) generated significantly more runoff and soil loss than the other treatments. The soil aggregates were rapidly broken down under the KE of the raindrops hitting the surface, and the water flow rapidly filled the small depressions of the rough surface. Any additional water was then routed between the dispersed aggregates and it entrained the resulting disaggregated, detached material and transported it downslope (Bullard et al., 2018b; Darboux et al., 2004; Helming et al., 1998; Römken et al., 2001). This treatment presented the shortest time-to-runoff initiation. However, the difference between treatments was not significant, mainly because the soil was initially wetted to the same moisture content for all treatments before the rainfall event. Also, the rainfall intensity used (90 mm hr^{-1}) was relatively high which hastened runoff generation, so masking any potential, more nuanced difference between treatments. According to Darboux et al. (2004), when using excessive rainfall events, there was no difference in the runoff delay between initially rough and smooth surfaces.

As a result of more breakdown of aggregates in Treatment C, a surface seal was formed in some places, particularly in the depressions where raindrop impact compacts the soil. The formation of seals can reduce rates of infiltration and increase surface runoff and soil loss (Bullard et al., 2018a). This explains, compared to the other treatments, the markedly high runoff volume, low infiltrate volume and low infiltration rate, generated by the random roughness treatment (Treatment C). The infiltration rate for this treatment ($7 \times 10^{-4} \text{ cm s}^{-1}$) was lower than the rainfall rate ($25 \times 10^{-4} \text{ cm s}^{-1}$), and according to the hydrological basis of erosion, if the infiltration rate is less than the rainfall intensity, then runoff will be generated (Morgan et al., 1998). Also, the present results showed that runoff increased with rainfall duration, and for Treatment C the infiltrate volume decreased with rainfall duration. Zhang et al. (2016) explained that this phenomenon is due to a) the saturation of soil as the rainfall duration increases, and b) the formation of a surface seal over time that would also reduce infiltration.

Sediment concentration in the runoff decreased with rainfall duration from 15 to 30 minutes for all four soil treatments. This can be explained by the availability of loose, easily eroded material during the first minutes of the rainfall event. Once this has been entrained and washed away, the erosion rate declines, as less erodible material remains on the soil surface (Arshad et al., 2019; Cao et al., 2013).

In general, the literature states that across-slope cultivations perpendicular to the slope create a physical impediment to the downslope movement of water. This would result in less runoff and soil loss in comparison with soil tilled up and down the slope (da Rocha Junior et al., 2016; 2018; Luciano et al., 2009). This is the basis of the present study's hypothesis. Indeed, for four replicates of Treatment B, runoff and soil losses were lower than for Treatments A and D. Furthermore, furrows in Treatment A acted like channels that routed the water flow downslope. However, contradictory results were recorded for four other replicates of Treatment B, where higher runoff and soil losses were recorded than for Treatments A and D. This is because the elevation of some ridges was lowered by soil detachment due to raindrop impact, allowing any previously ponded water in the furrows to breach the ridges in the form of concentrated flow paths. So, the ridges were damaged not only by raindrop impact, but also by overland flow coming from ponded water in the furrow, generating more runoff and soil loss. Figure 2-8 shows the case where the ridges maintained their shape versus the flattened ridges further downslope, where resistance to flow decreases (Parsons et al., 1990) due to the cumulative concentrated water upslope that broke down the ridges, along with breakdown due to rainfall impact. The difference between these two contrasting results for the same treatment was significant and measurements of the replicates' final surface roughness confirmed it. On the other hand, the furrows in Treatment A were oriented in the up/downslope direction, which means that there was no ponded water behind the ridges that would lead to an increase in runoff volume. For these reasons, and given that in some cases Treatments B generated more runoff and soil loss than Treatment A, and in other cases it generated less, the mean runoff and soil loss values for both treatments were not significantly different. Soil loss results found by Quinton et

al. (2004) on plots with different roughness orientations suggest a similar conclusion.

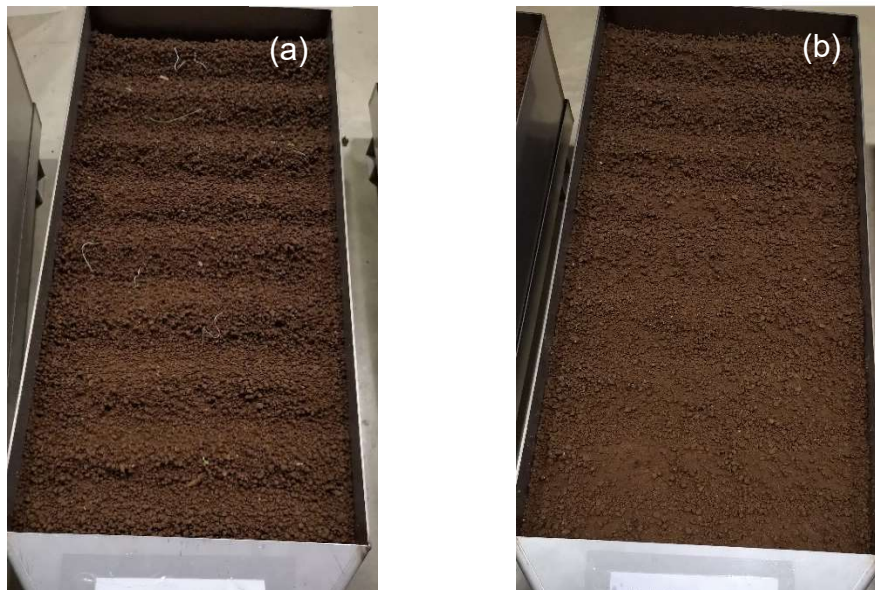


Figure 2-8 Post rainfall images for Treatment B (across slope SSR). (a) Ridges not flattened, intact. (b) Ridges flattened, especially downslope, near the runoff outlet.

Although across-slope contour cultivation is assumed to be an effective soil and water conservation measure (da Rocha Junior et al., 2018), it is less effective on slopes exceeding 10 % (USDA, 2017; Alvarez-Mozos et al., 2011). Quinton et al. (2004) recommended that this management practice should be evaluated at the field scale and on different slope configurations, as it could be a risk on complex, multidirectional slopes where cultivations are difficult to keep exactly on the contour, leading to low spots along the cultivation row. Water would accumulate in these low points and then break through the ridges to form concentrated flow paths with sufficient flow volume, velocity and KE to detach, entrain and transport material. This process also relates to the difference in surface storage capacity between a gentle and a steep slope gradient. The steeper the slope, the smaller the surface storage capacity (Zhao et al., 2021). Once filled, any subsequent rainfall event will cause overtopping of the storage, leading to water breaching the ridges and causing a risk of erosion (Morgan, 1992).

Even though da Rocha Junior et al. (2016) reported lower values of runoff for a contour tillage treatment, this was only under a simulated rainfall intensity of 50.8

mm hr⁻¹. However, when increasing the rainfall intensity to 114.3 mm hr⁻¹, contour tillage presented higher values of runoff, along with the bare soil treatment. This was explained by the possible partial breaking of ridges due to the KE of the higher rainfall intensity applied.

On the other hand, a high rainfall intensity and/or a steep slope gradient might result in the reduced effectiveness of across-slope contour tillage in controlling soil and water losses. In the present study, the rainfall intensity used was of 90 mm hr⁻¹, a value which is between the low and the high intensity values used by da Rocha Junior et al. (2016). Also, the present study used a slope gradient of 10% which is the limit for effective control of soil and water losses by contour tillage (USDA, 2017). This suggests unclear conclusions regarding the effectiveness of across slope soil and water management practices (such as contour cultivations, buffer strips and earth bunds) as demonstrated by the contrasting observations discussed in this paper. More research should be done on this topic, simulating a range of rainfall intensities and slope gradients.

2.5.3 Rainsplash erosion

The hypothesis was that Treatment C (random roughness) would produce more splash erosion than the other treatments because the roughness elements were created by disturbing relatively wet soil, breaking up any initial aggregation and making the soil particles more prone to detachment (Torri et al., 1987). However, the highest splash soil loss was in Treatment B (the across-slope oriented roughness). Even so, the results show no significant difference in splashed soil loss between Treatments B, C and D. This is supported by Morgan (2005), who found that SSR has no control over soil detachment by rainsplash.

Although not statistically significant, the mean splash erosion for the smooth surface (Treatment D) was slightly higher than for the rough surface (Treatment C). This is explained by the rough surface of Treatment C intercepting some of the splashed material in micro-depressions. Also, it was observed that there was a thin water layer on the surface of Treatment C during the rainfall event, especially ponding in the micro-depressions, which might have buffered against splash impacts. Hairsine et al. (1992), Kinnell (2005) and Torri et al. (1987)

claimed that raindrop KE is absorbed by water films, leaving less energy available for soil detachment. However, this contradicts Palmer (1964) and Moss and Green (1983) who found the relationship depends on the size of the impacting drops and hence their KE, relative to the depth of the water film.

For Treatment B (the across-slope oriented roughness), the splashed material collected from the voiles put in the furrows was greater than that captured on the ridges, because the detached particles from relatively higher elevations (i.e. ridges) were moved by gravity and deposited at lower elevations (i.e. in the furrows) (Zhao et al., 2014b). Bullard et al. (2018b) suggested that with increasing range in surface elevation, rates of rainsplash erosion also increase. This explains the higher splash erosion recorded for Treatment B than for Treatment C which has a smaller elevation range than the former treatment. Similarly, Luo et al. (2018) found that soils subject to ridging practices had higher soil detachment rates than other rough surfaces, because more soil surface area was exposed to the raindrops due to the presence of the ridges and furrows. In the same way, Wu et al. (2016) claimed that microrelief (e.g. ridges and furrows), increased local slope gradients and hence increased detachment rates due to increased raindrop impact associated with the slope increase. The opposite was found by Zhao et al. (2014b), explaining that the microrelief increased the area and the local slope of the surface, resulting in decreased rainsplash erosion, as the raindrop impacts were spread over a larger area. This can explain the results found for Treatment A (up- and downslope oriented roughness) which also contains ridges and furrows but presented significantly lower values of splashed sediment than the other three treatments. This could also be explained by the way the splashed sediment was captured, as the voile collectors were put perpendicular to the ridges and furrows (Figure 2-3 a), unlike Treatment B. These results align with the earlier findings related to changes in SSR, where the decrease in soil surface roughness of Treatment B was the smallest.

Understanding the different mechanics of rainsplash erosion on smooth or rough soil surfaces is complex. Splash erosion is dependent on surface microtopography and is sensitive to small changes in soil properties, including

soil surface relief (Zumr et al., 2020). Measurement of rainsplash erosion is strongly dependent on the collection method (Fernández-Raga et al., 2019). Although falling raindrops might have an effect on the particles previously captured in the collection method we used in this study, this effect applied to all experimental runs, trays and treatments, so the measurements are consistent between all trays.

Comparing the rainsplash results from the upslope and downslope position on the erosion trays shows that for all the treatments, the splashed soil captured at the downslope position was higher than that captured further upslope. This is explained by the larger catchment area above the downslope voile, allowing more detached particles to be transported and captured from the whole length of the erosion tray. On sloping land, particles splashed downslope travel further due to gravity than particles splashed upslope, resulting in net downslope splash erosion (Kinnell, 2005; Morgan, 2005; Wan et al., 1996; White, 2006). This aligns with the findings of Wu et al. (2016) who used a splash board to catch detached particles (upslope and downslope) on slopes with different soil microreliefs and found a positive net downslope movement of splashed material on a smooth soil surface. However, for other cultivation treatments (shallow hoeing, contour chisel ploughing), they found lower and even negative net values for splash erosion because of the spatial microrelief structure so that the net movement of the splashed material wasn't necessary downslope.

2.6 Conclusions

The experimental conditions in this study were designed to evaluate the effect of soil roughness and orientation on soil and water losses. The study is unique in comparing random roughness and oriented roughness, with both up/downslope and across-slope orientations, in terms of simultaneous generation of runoff, infiltration, soil loss and soil splash erosion. The study showed that rainfall affected the soil surface of the sandy loam soil by increasing or decreasing its roughness. Smooth surfaces became rougher after detachment of soil particles due to raindrop impacts, whereas on rougher surfaces, surface roughness degraded after the rainfall event, due to the KE of raindrops breaking down ridges

and soil aggregates. This study concluded that random roughness generated significantly more runoff and soil loss and less infiltration than smooth or oriented roughness treatments.

The results of this study show that across-slope oriented roughness does not always give better runoff and erosion control compared with up/down slope cultivations as mentioned in the literature. The contradictory results from the treatment replicates can be explained in part by previous research that showed across-slope cultivation is less effective on slope gradients exceeding 10% (the slope gradient used in the current study was exactly 10%). This suggests more research is needed to observe these effects at different slope gradients as the outcomes may be sensitive to slope gradient.

Even under controlled experimental conditions, the effect of soil surface roughness on splash erosion is complex and the mechanisms operating are not clear. This justifies further experimental work to generate better understanding of the processes at work.

2.7 Credit authorship contribution statement

Sophia Bahddou: Conceptualization, Data Curation, Formal Analysis, Investigation, Methodology, Project Administration, Validation, Visualization, Writing - Original Draft Preparation, Writing – Review & Editing. **Wilfred Otten:** Conceptualization, Funding Acquisition, Methodology, Project Administration, Resources, Supervision, Validation, Writing – Review & Editing. **W. Richard Whalley:** Funding Acquisition, Methodology, Validation, Writing – Review & Editing. **Ho-Chul Shin:** Funding Acquisition, Methodology, Validation, Writing – Review & Editing. **Mohamed El Gharous:** Funding Acquisition, Methodology, Validation, Writing – Review & Editing. **R. Jane Rickson:** Conceptualization, Funding Acquisition, Methodology, Project Administration, Resources, Supervision, Validation, Writing – Review & Editing.

2.8 Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

2.9 Data availability statement

The underlying data can be accessed through [10.17862/cranfield.rd.21829884](https://doi.org/10.17862/cranfield.rd.21829884)

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3 EFFECT OF WIND-DRIVEN RAIN ON SOIL EROSION PROCESSES UNDER DIFFERENT SOIL SURFACE ROUGHNESS

3.1 Abstract

Water and wind often accelerate the detachment, entrainment, transport and deposition of soil particles, leading to soil erosion which is a serious global issue. Previous research has primarily focused on investigating either rainfall or wind separately as erosive agents affecting the soil erosion processes. To date, there has been limited research examining the combined effect of both agents operating simultaneously and their effect on hydrological and soil erosion processes. Additionally, soil surface roughness (SSR) is an overlooked factor in these studies. Understanding the complex erosion dynamics requires a closer examination of the interplay between water, wind and soil properties. Therefore, this research evaluated the role of windless rain (WLR) and wind-driven rain (WDR) with varying wind velocities, on runoff and infiltration, and on soil loss through the processes of both runoff and rainsplash erosion. These processes were assessed on both smooth and rough soil surfaces. Moreover, the effect of the different rainfall events in modifying SSR was quantified in this study. A setup comprising rainfall and wind simulators was designed using a rainfall intensity of 90 mm hr^{-1} , a rainfall duration of 30 minutes, wind velocities of 0, 6 and 10 m s^{-1} , and a slope gradient of 11%. Initial and post-rainfall SSR were measured for all the simulated treatments using a Creaform EXAscan 3D hand scanner. Soil and water losses were measured using purpose-designed erosion trays and sediment collectors. The outcome of this study shows that WDR significantly accelerated runoff generation (time-to-runoff initiation) and produced higher runoff volume and soil loss than WLR. Under the highest wind velocity on a smooth surface, WDR increased runoff volume, sediment load and sediment concentration by 74%, 43% and 143% respectively, compared to the equivalent scenario without wind (WLR). On the other hand, the rough surface mitigated the adverse effect of wind-driven rain on soil and water losses under the lower wind velocity. However, higher wind velocities overcame the mitigating factors, resulting in soil

and water losses comparable to or exceeding those observed under WLR. It is known that rainfall alters initial soil surface roughness by increasing the SSR of initially smooth surfaces and decreasing that of initially rough surfaces. The findings of this study suggest that WDR exacerbates these changes, increasing their magnitude, with roughness of a smooth surface increasing by up to 172% and that of a rough surface decreasing by up to 30% when subjected to WDR. It was concluded that wind increases the erosivity of rainfall which then affects soil erosion processes. However, this effect depends on factors including the wind velocity and the initial soil surface roughness. Therefore, it is important to include these factors in soil erosion studies for an accurate assessment of soil and water losses.

Keywords: Rainfall erosivity, Rainfall simulator, Runoff, Soil loss, Splash erosion, WLR, WDR, Wind tunnel.

3.2 Introduction

Soil erosion involves the detachment, entrainment, transport and deposition of soil particles, often accelerated by erosive agents such as water and wind. In the process of soil erosion by water, raindrop impact and surface runoff play crucial roles as the primary erosive forces (Kinnell, 2005), whereas in erosion caused by wind, the erosion rate is influenced by wind velocity (Zhang et al., 2019). The simultaneous action of wind and water during natural rainstorms can lead to accelerated soil erosion rates, especially in arid and semi-arid regions (Visser et al., 2004). However, most erosion studies have evaluated the individual effects of erosive agents like rain, water and wind. Just a few studies have considered the simultaneous effect of wind and water on hydrological and erosional processes. Recognising the concurrent actions of rain and wind in soil erosion studies is crucial for an improved understanding of erosion processes in wind-driven rain scenarios.

Lately, there has been a growing interest in soil erosion arising from the combined effects of wind and water (An et al., 2023). A positive relationship was found between wind velocity and soil erosion rates during a rainfall event (Erpul et al., 2003a; Mahmoodabadi et al., 2021). Wind may enhance detachment and

transport of soil particles by increasing both the KE and incident impact angle of raindrops (Erpul et al., 2005; 2013; Iserloh et al., 2013; Marzen et al., 2016; Arshad et al., 2019). These effects are related to wind velocity. Helming (2001) found that at the highest wind velocity (10.5 m s^{-1}), rainfall KE could be 3.5 times higher than in windless conditions. Furthermore, after a raindrop impact detaches and propels soil particles and/or micro-aggregates into the airflow, the wind can carry these dislodged particles up to 3 m in rains driven by wind velocities of 6 m s^{-1} , and up to 6 m in rains driven by wind velocities of 10 and 12 m s^{-1} (Erpul et al., 2002), but these trajectories depend on the mass and density of the soil particle. Few studies have measured the vertical profile of entrained soil particles, including the bedload and suspended particles eroded due to wind-driven rain (WDR). In addition to that, measuring hydrological (i.e. runoff and infiltrate volumes) and soil erosion processes (i.e. splash erosion and soil loss by runoff) simultaneously has been poorly studied under wind-driven rain conditions. Therefore, it is important that the effect of wind is critically evaluated in erosion studies to better understand soil and water losses.

Soil and water losses caused by WDR appear to be influenced not only by the wind-imparted modifications to raindrops and shallow surface runoff, but also significantly affected by other variables related to soil surface attributes (Ries et al., 2014), notably SSR. In situations where rain is driven by wind, the influence of soil properties may be more significant compared to conditions without wind, due to the additional effect of profile wind drag (Marzen et al., 2015).

Bahddou et al. (2023) have shown that SSR affects runoff initiation time during a rainfall event, total runoff volume, sediment load and the amount of rainsplash erosion. The authors also showed that erosive forces altered the roughness of the soil surface. Previous research found that SSR decreases due to the rainfall KE breaking down soil aggregates and ridges (da Rocha Junior et al., 2016; Bahddou et al., 2023). On the other hand, smooth soil surfaces become rougher after a rainfall event due to detachment of soil particles caused by the raindrop impacts (Bahddou et al., 2023) and micro-rill development on the soil surface (Huang & Bradford, 1992; Römken et al., 2001). However, these studies only considered the rainfall event, and no study showed the effect of WDR on soil

roughness changes and the effect of the different SSR morphologies on hydrological and erosion processes under WDR events. The practical implications of these processes is that in the field, initial SSR is often determined by soil management techniques that can introduce varying degrees of roughness. Furthermore, in reality, wind and rainfall act together on erosion processes. Therefore, it is reasonable to investigate the combination of erosion by wind and rain considering different soil surface conditions.

The aim of this chapter is to gain a greater mechanistic insight into the hydrological and erosional responses of soils under windless rain (WLR) and WDR. The objectives of this research are to a) compare the effects of WLR and WDR on surface runoff and infiltrate volumes, and on soil loss due to runoff and rainsplash erosion; b) compare the effects of surface topography (i.e. smooth and rough surfaces) on soil and water losses under WLR and WDR events; and c) study the changes in surface conditions (i.e. smooth and rough surfaces) under the different erosive events.

3.3 Materials and methods

3.3.1 Erosion trays preparation

Soil and erosion trays were prepared following the methodology described in Bahddou et al. (2023). An air-dried sandy loam soil (16% clay, 28% silt and 56% sand) was sieved through a 4 mm mesh screen and packed into soil erosion trays of 50 cm length, 25 cm width and 10 cm depth. Each tray was packed with 15 kg of sieved soil, in five layers, using the same number and intensity of strikes per layer, to achieve a uniform bulk density of 1.4 g cm^{-3} throughout the profile. The trays were filled up with soil to the level of a V-shaped runoff outlet from which runoff samples (along with any eroded soil in the runoff) would be collected during the rainfall event. An additional layer of soil was graded up to the upslope lip of the tray (i.e. opposite the tray's funnel), to avoid a windward edge effect during the WDR event. Each erosion tray was put on a base made of a perforated steel sheet covered with voile, which prevented the packed soil from falling through, but allowed any infiltrated water to drain freely and reach the infiltrate outlet. The

perforated base also allowed the trays to wet up to the desired initial soil moisture content via capillary action, as described below.

The soil erosion trays were then prepared to simulate different soil surface conditions (Figure 3-1): 1) smooth surface, and 2) rough surface, with mounds and depressions.



Figure 3-1 Two soil surface conditions applied to a sandy loam soil in erosion trays put in a water bath: 1) smooth surface (a) before wetting up, (b) after wetting up; 2) rough surface with mounds and depressions (a) before wetting up, (b) after wetting up.

The smooth surface was obtained by flattening the upper layer of soil using a packer plate. On the other hand, the rough soil surfaces were created using a specialised tool that formed offset mounds and depressions of 2 cm height and depth, respectively, simulating non-directional surface roughness.

Soil trays were put in a water bath that reached the trays' base, allowing the soils to wet up by capillary rise for a period of 24 hours, after which they were removed from the water bath to allow them to drain. This resulted in a moisture content of $42.66\% \pm 0.21$ (SE) (measured using Delta-T HH2/SM150T soil moisture probe), close to the expected saturated water content of 0.47 for a soil at this bulk density.

3.3.2 Calibration of the rainfall and wind simulators

3.3.2.1 Rainfall simulator

The erosion experiments were run indoors at Cranfield University. The targeted rainfall intensity (90 mm hr⁻¹) and duration (30 min) were selected to simulate natural representative rainfall events.

To achieve that, the rainfall intensity was tested at water pressures ranging between 0.4 and 0.7 bar at a number of locations under the rainfall nozzle. This was done by measuring the intercepted volume of water using catch cups placed on a tilting table. Each test was performed in triplicate. Once the approximate area of interest and water pressure were identified, additional tests were carried out placing an empty erosion tray at different positions under the nozzle to determine locations of rainfall intensity uniformity for the erosion trays during the rainfall and WDR simulations.

The rainfall intensity (RI, mm hr⁻¹) was calculated using Equation (3-1), where V is volume of rain collected (mL), S is surface area of the tray (cm²), t is duration of the test (min).

$$RI = \frac{V}{S} \cdot \frac{60}{t} \cdot 10 \quad (3-1)$$

The nozzle that produced the desired intensity was a LECHLER 490.888.30.CG, placed at 1.5 m above the soil surface, and at a 1-meter distance above the pressure gauge. The pressure was maintained at 0.5 bar and was monitored throughout the experimental run to ensure consistent rainfall intensities. Catch cups were placed next to the erosion trays during each run to ensure consistent rainfall application over space and time.

The Christiansen's coefficient of uniformity (CU, %) (Christiansen, 1942) was used to determine the spatial distribution of rainfall on the test area to ensure a constant rainfall intensity. It is expressed in Equation (3-2), where x is the water collected in the catch can (mL), and m is the average water volume collected (mL).

$$CU = \left(1 - \frac{\sum |x - m|}{\sum x}\right) \cdot 100 \quad (3-2)$$

The Christiansen's coefficient was 98%, indicating an excellent homogeneous distribution of rain on the soil surface.

The trays were set on a slope with a gradient of 6.5 degrees (~11%), to be representative of typical arable field conditions.

3.3.2.2 Wind simulator

[A design of a wind tunnel was previously considered but its construction has not been realised. Details in Appendix D]

A portable 3-phase electric wind simulator was used in combination with the rainfall simulator to generate wind-driven rain and the effect of wind velocity on rainfall erosivity (Figure 3-2). The sloped erosion trays were oriented in the same direction as the generated wind. The wind simulator was calibrated to deliver wind velocities of 6 m s⁻¹, 10 m s⁻¹ to the testing area. In this study, two levels of WDR were simulated, hereafter named WDR1 (for the lower wind velocity, 6 m s⁻¹) and WDR2 (for the higher wind velocity, 10 m s⁻¹). To achieve this, different settings of the equipment were tested, and its position was continuously adjusted while experimenting with different outlet pipes of the wind generator. A smooth, wooden board, 2.5 m long, was placed underneath the wind outlet and extended to the upslope edge of the erosion tray to avoid air turbulence and obtain a uniform wind flow. Wind velocities were measured at different locations of the testing area, where the erosion tray was placed, using a pre-calibrated hot wire anemometer (multicomp^{PRO}). The position that delivered the desired wind characteristics was 2 m (horizontal) between the wind outlet and the erosion tray.

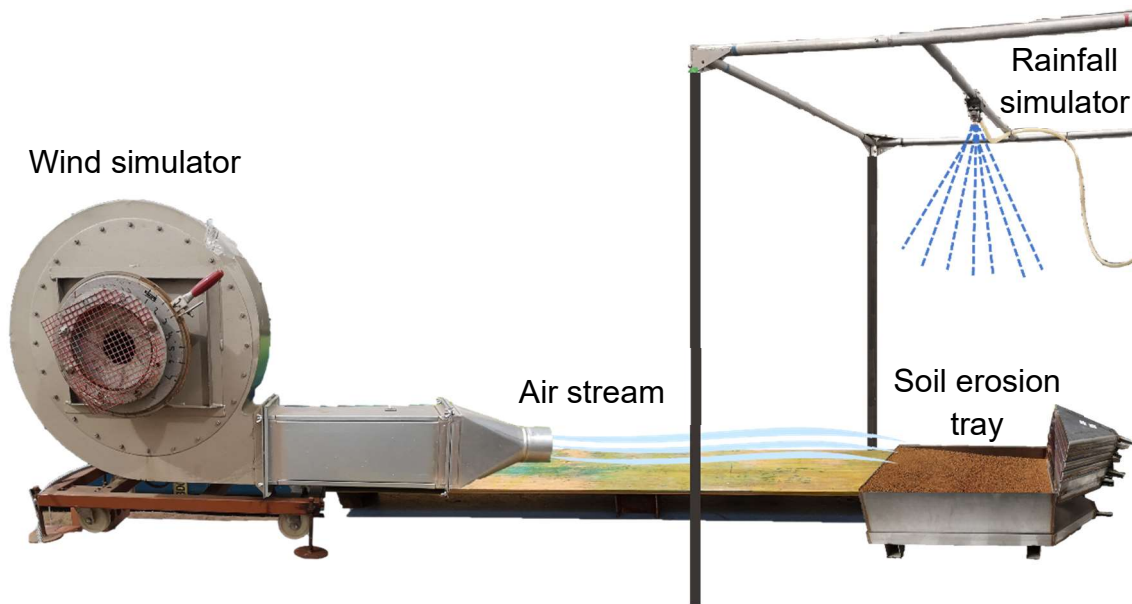


Figure 3-2. Experimental setup combining wind and rainfall simulators, generating wind-driven rain (WDR) on a soil erosion tray.

Figure 3-3 shows the distribution of wind velocities over the length of the testing area (erosion tray). Three dimensional wind profiles (in x, y, z directions) were created at the two experimental wind velocities by measuring the wind velocity at different points across the width and along the length of the tray and at different heights above the erosion tray: 0 cm (at the soil surface), 2.5 cm, 5 cm, 7.5 cm, 10 cm, 12.5 cm. The number of measured points was 180 points per each wind velocity profile (Figure 3-3). Considering the vertical section of the testing area located at 2.05 m of the wind simulator's outlet, the wind velocities at the middle of the section were 6 m s^{-1} and 10 m s^{-1} in the two wind configurations simulating WDR1 and WDR2, respectively.

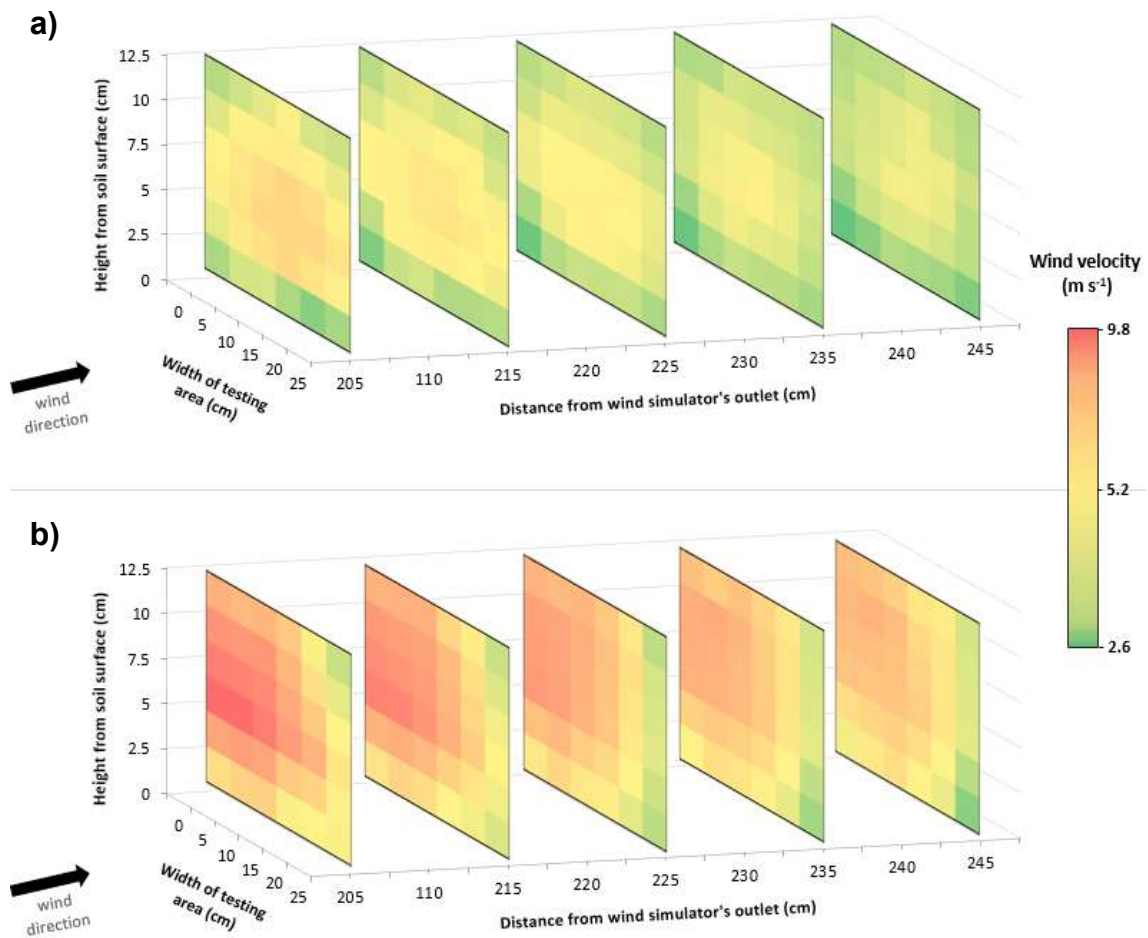


Figure 3-3 Spatial distribution of the wind velocity over the test area (soil erosion tray) with a) the lower wind velocity range, used to simulate WDR1 and b) the higher wind velocity range, used to simulate WDR2.

3.3.2.3 Windless (WLR) and Wind-Driven Rainfall (WDR) Kinetic Energy (KE)

Rainfall erosivity refers to the rainfall's ability to detach, entrain and transport soil particles, crucial for understanding erosion processes (Nearing et al., 2017). It is quantified through the total cumulative KE of an individual rainfall event, which depends on the raindrop distribution and raindrop mass and velocity.

The size, frequency, vertical velocity and direction of raindrops were measured using the high-performance Oxford Laser VisiSizer N60 at Silsoe Spray Unit Applications (Silsoe, UK). The method uses a short dual light pulse to illuminate a screen, capturing images where droplets are visible as dark spots against a

light background. The images are then analysed using the VisiSizer software (Oxford lasers). The laser, rainfall simulator nozzle and wind generator were set up to simulate similar distances and heights between the test area and the rainfall/wind sources as in the experimental setup used for the erosion measurements (Figure 3-4). The water pressure, water flow rate, and wind velocities were also replicated in a same way. The laser was positioned at two different sampling locations under the nozzle: i) central and ii) at 25 cm from the vertical line to the nozzle away from the wind source. The measurements were repeated five times for each of the two locations and for each of the three treatments (WLR, WDR1 and WDR2).

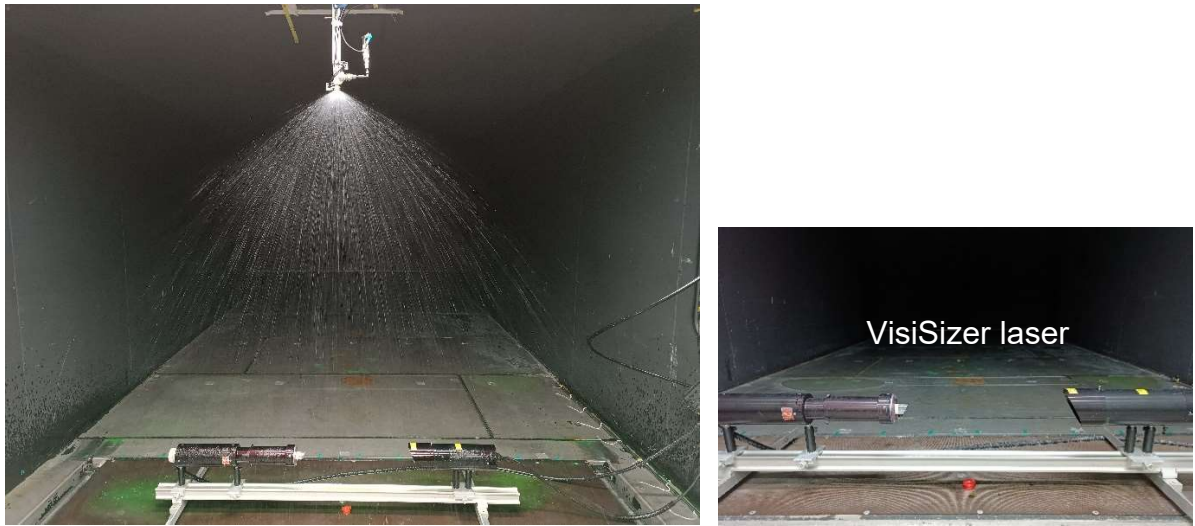


Figure 3-4 VisiSizer laser measuring the raindrops characteristics.

The resultant velocity (v , m s^{-1}) of windless and wind-driven raindrops was calculated from the measured vertical velocity (V_v , m s^{-1}) and the raindrop angle of incidence (α , deg) in Equation (3-3).

$$v = \frac{1}{\cos \alpha} \cdot V_v \quad (3-3)$$

The size, frequency, and resultant velocity of raindrops are used to calculate the resultant kinetic energy (KE_r , mJ) of the windless and wind-driven raindrops, using Equation (3-4), where m is the mass of the raindrop (g).

$$KE_r = \frac{1}{2} m \cdot v^2 \quad (3-4)$$

KE (mJ m⁻² s⁻¹) is defined in Equation (3-5), where ρ is the density of water (g cm⁻³), D is the diameter of the raindrop (cm), and n is the number of detected raindrops falling in each drop diameter and velocity per unit area per unit time.

$$KE = \left(\frac{\pi}{12}\right) \cdot \rho \cdot D^3 \cdot n \cdot v^2 \quad (3-5)$$

The total KE is the sum of all KE calculated for each drop diameter (mm) and velocity (m s⁻¹).

3.3.3 Measurements

3.3.3.1 Runoff – Infiltration – Sediment load and concentration

The measurements followed the methodology described in Bahddou et al. (2023). For each erosion tray, total volumes of surface runoff and infiltrate were collected after 30 minutes of the experimental run from the tray's outlet and the base's outlet, respectively, via a system of pipes and buckets, and measured using measuring cylinders. The time taken for runoff and infiltrate initiation (seconds) was recorded. The mass of sediments collected in the runoff was also recorded after the 30-minute events. When the runoff volume was less than 100 mL, the total collected volume was filtered through oven-dried, pre-weighed Whatman Number 2 filter paper. When the runoff volume was > 100 mL, the total mixture was thoroughly agitated, and a sub-sample of 100 mL was taken and filtered. The sediment-loaded filter papers were oven-dried for 24 hours at 105°C and weighed using a precision balance with a readability of 0.001g. The sediment concentration in the runoff (SC, g L⁻¹) was calculated using Equation (3-6), where M1 is mass of sediment-loaded filter (g), M0 is mass of the empty dried filter (g), R: runoff volume (mL).

$$SC = \frac{(M1 - M0)}{R} \cdot 1000 \quad (3-6)$$

3.3.3.2 Rainsplash erosion

Splash collectors made from metal, and covering the whole breadth of the erosion tray, were constructed to collect the soil particles detached and transported by rainsplash (due to WLR and WDR) at different heights, [0-2.7], [2.7-5.4], [5.4-7.1], [7.1-8.8], [8.8-10.5] and [10.5-12.2] cm, above the erosion tray surface (Figure 3-5). The set of collectors was placed at the end of the erosion tray right on top of the runoff outlet funnel. Plastic bottles were placed at the end of each collector to capture any potential soil particle that was further transported by wind inside each collector.

After the WLR and WDR simulations, the sediment-loaded funnels and bottles were rinsed to collect all the soil particles. The soil particles-water solution was filtered using an oven-dried pre-weighed Whatman Number 2 filter paper. The sediment-loaded filter papers were oven-dried for 24 hours at 105°C and weighed using a precision balance with a readability of 0.001g. The detached soil mass is the difference between the weight of the sediment-loaded filter paper and the weight of the empty paper (g).



Figure 3-5 The erosion tray with a set of collectors downslope collecting the detached soil particles by rainsplash due to windless and wind-driven rains.

3.3.3.3 Soil Surface Roughness

Soil surface roughness was measured before and after the WLR and WDR events to assess the comparative effect of WLR and WDR and runoff on the soil surface morphology during the different three rainfall events (WLR, WDR1 and WDR2). For this, soil surfaces were scanned at 1.5 mm resolution using a laser scanner (Creaform EXAscan 3D Handscanner), along with XVelements, an integrated 3D scanning software. The scans were converted to the appropriate

extension and processed using Geomagic Studio® software, then the 3D surface areas were computed to obtain a calculated 3D surface area. The SSR, % was calculated using Equation (3-7), where A is the plane surface of the soil tray (mm²), and S is the actual area of the soil surface with its microtopographic irregularities (mm²) calculated using the aforementioned software.

$$SSR = \frac{(S - A)}{A} \cdot 100 \quad (3-7)$$

3.3.4 Statistical analysis

The simultaneous effect of rainfall and wind on erosion processes on different soil surface conditions was investigated. Each combination of treatments (Table 3-1) was replicated four times, resulting in 24 erosion trays.

Table 3-1 Treatments and replicates of the experimental design.

Rainfall and wind events	WLR		WDR1		WDR2	
Soil surface condition	Smooth	Rough	Smooth	Rough	Smooth	Rough
Replications	4	4	4	4	4	4

It was a split plot design with a factorial treatment structure; the WLR, WDR1 and WDR2 treatments were randomised to pairs of trays and smooth vs rough surfaces were randomised to individual trays within each pair. The data obtained from the measurements was subjected to analysis of variance (ANOVA) using the statistical software Genstat ® (22nd Edition). A pairwise comparison of the means was performed for the significant cases (with a p-value < 0.05) using the Least Significant Differences (LSDs) at the 5% level of probability.

In some cases, data transformation before analysis ensures that the assumptions needed for ANOVA were met, primarily addressing homogeneity of variance and improving the assumption of normality (i.e. that the residuals generally follow a normal distribution). To ensure the appropriate scale for the analysis, the residual plots were assessed. For the sediment load data and the splash erosion data, the transformation was needed, and the data was expressed in LOG10 scale. For

the sediment concentration data, the square root (SQRT) transformation gave better residual plots (the residuals meet the normality assumption) than the logarithmic (LOG) transformation.

3.4 Results

3.4.1 Time-to-runoff initiation and runoff volume

Time-to-runoff initiation is the period between the start of the rainfall and the generation of the first outflow at the runoff outlet. Time-to-runoff initiation (seconds) was recorded for each erosion tray during the WLR and WDR simulations. Statistical analysis showed that there was a significant difference in time-to-runoff initiation between the three rainfall events ($p = 0.003$), ranked $WDR2 < WDR1 < WLR$ for both the smooth and the rough surfaces, suggesting that the WDR events significantly speeded up runoff generation compared to the WLR event. This was expected as the air flow would add momentum to the surface runoff.

For the smooth surface, time-to-runoff initiation was 51 seconds $\pm$ 4 (SE), 67 seconds $\pm$ 5 (SE), and 103 seconds $\pm$ 8 (SE) for WDR2, WDR1 and WLR respectively. For the rough surface, time-to-runoff initiation was 61 seconds $\pm$ 10 (SE), 81 seconds $\pm$ 7 (SE), and 150 seconds $\pm$ 17 (SE) for WDR2, WDR1 and WLR, respectively. During all events, the rough surface significantly delayed runoff initiation compared with the smooth surface ($p = 0.008$), due to resistance to overland flow.

Mean runoff volume (mL) was significantly different between the three rainfall events ($p < 0.001$). Results showed that the runoff volume was ranked $WLR < WDR1 < WDR2$ for the smooth surface and $WDR1 < WLR < WDR2$ for the rough surface (Figure 3-6). For the smooth surface, the runoff volume on WDR1 and WDR2 increased by 36% and 74% compared to the WLR condition, respectively. On the other hand, for the rough surface, runoff decreased by 49% on the WDR1 event and increased by 15% on the WDR2 event compared to the WLR condition. However, the LSDs at the 5% level showed that there was no significant difference between WLR and WDR2 for the rough surface. The smooth

surface generated runoff volumes that were 1.5, 4.1 and 2.3 times the volumes generated by the rough surface during the WLR, WDR1 and WDR2 events, respectively.

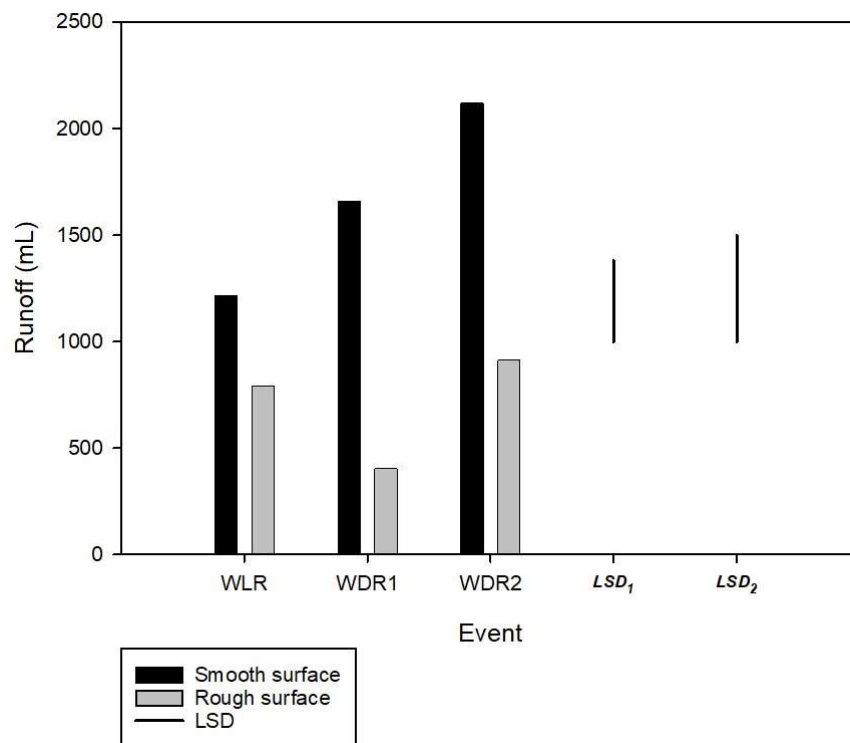


Figure 3-6 Mean runoff volumes (mL) generated during the three 30-minute events (WLR, WDR1 and WDR2) on smooth and rough surfaces. LSD₁ and LSD₂ bars were used to compare between means of the three different events and means of the smooth and rough soil surfaces, respectively.

3.4.2 Time-to-infiltrate initiation and infiltrate volume

Time-to-infiltrate initiation (seconds) is the period between the start of the rainfall and the generation of the first outflow at the infiltrate outlet. This was recorded for each erosion tray during the rainfall simulations (with and without wind). Infiltrate was always initiated before runoff ($p < 0.001$), where the mean value of time-to-infiltrate initiation was 36 seconds $\pm$ 2 (SE), whereas the mean value of time-to-runoff initiation was 86 seconds $\pm$ 8 (SE). There was no significant difference in time-to-infiltrate initiation between the different rainfall events ($p = 0.92$), and between the SSR conditions ($p = 0.61$).

The infiltrate volume (mL) was significantly different between the rainfall events ($p < 0.05$). The infiltrate volume was ranked $WDR2 < WDR1 < WLR$ on the smooth surface. This is expected, as runoff was driven by the wind to the outlet before the water could infiltrate. For the smooth surface, the infiltrate volume for WDR1 and WDR2 decreased by 7% and 16% compared to the WLR condition, respectively. On the other hand, for the rough surface, WDR1 significantly generated the highest infiltrate volume, increasing it by 17% compared to the WLR condition. There was no significant difference between WLR and WDR2 for the rough surface (Figure 3-7).

There was a significant difference in infiltrate volume between the different surface conditions ($p < 0.001$). The rough surface generated infiltrate that was 1.1, 1.3 and 1.3 times the volumes generated by the smooth surface during the WLR, WDR1 and WDR2 events, respectively. As expected, there was a strong negative correlation between mean runoff volumes and mean infiltrate volumes ($r = -0.95$).

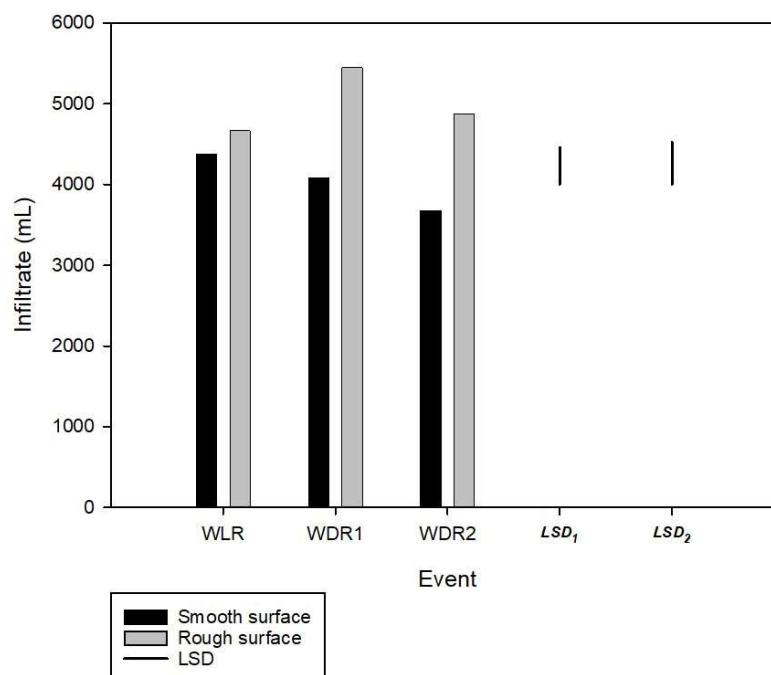


Figure 3-7 Mean infiltrate volumes (mL) generated during the three 30-minute events (WLR, WDR1 and WDR2) on smooth and rough surfaces. LSD_1 and LSD_2 bars were used to compare between means of the three different events and means of the smooth and rough soil surfaces, respectively.

3.4.3 Sediment load and concentration in the runoff

Total sediment load in the runoff (mg) was measured under WLR, WDR1 and WDR2 for both soil surface conditions. The results indicate that WDR2 generated significantly higher sediment loads than the WLR and WDR1 from the smooth surface, where mean values increased by 43% for WDR2 compared to WLR. On the other hand, for the rough surface, there was no significant difference in sediment load between WLR, WDR1 and WDR2. The difference in sediment load between the smooth and rough surfaces was significantly different under WDR2 (Figure 3-8a). There was a strong positive correlation between runoff volume and sediment load ($r = 0.74$), as soil particles were both detached and then entrained and transported by the runoff.

The sediment concentration in the runoff (g/L) was also significantly higher for WDR2 than for the two other events: it increased by 143% for WDR2 compared to WLR. This result is valid only for the smooth surface. For the rough surface, there was no significant difference in sediment concentration between WLR, WDR1 and WDR2. The difference in sediment concentration between the smooth and rough surfaces was significantly different under WDR2 (Figure 3-8b).

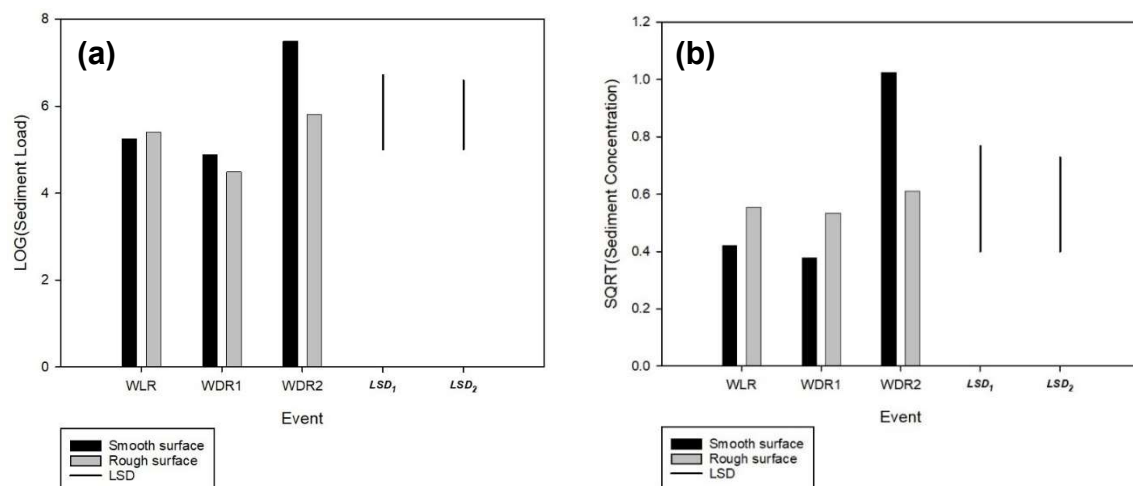


Figure 3-8 (a) Mean total sediment load (mg), expressed in Log, and (b) Mean sediment concentration in the runoff (g/L), expressed in Sqrt, generated during the three 30-minute events (WLR, WDR1 and WDR2) on smooth and rough surfaces. LSD₁ and LSD₂ bars were used to compare between means of the three different events and means of the smooth and rough soil surfaces, respectively.

3.4.4 Splash erosion by rainfall and wind-driven rainfall (WDR)

Soil erosion is a process that starts with the detachment of soil particles mainly due to raindrop impact (Morgan, 2005, Kinnell, 2005). The hypothesis in these experiments was that the interaction of wind on falling raindrops would enhance this sub-process, by increasing raindrops' momentum, fall velocity and KE. All these properties are associated with higher rainfall erosivity (Arshad et al., 2019).

The significantly highest mean splash erosion (mg) for all treatments was recorded in the sediment collector covering a height up to 2.7 cm from the soil surface. Splash erosion at this height was ranked $WLR < WDR1 < WDR2$ on the smooth surface, and $WDR1 < WLR < WDR2$ on the rough surface. There was a significant difference between the three rainfall events and between the six heights of sediment collection ($p < 0.001$), and there is an interaction between both factors, i.e. the rainfall/wind events and the sediment collection heights ($p = 0.002$). According to the LSD, the splash erosion under the WDR2 event was significantly greater, at all heights, than that under the WLR and the WDR1 (Figure 3-9). This was the case for both surface roughness conditions.

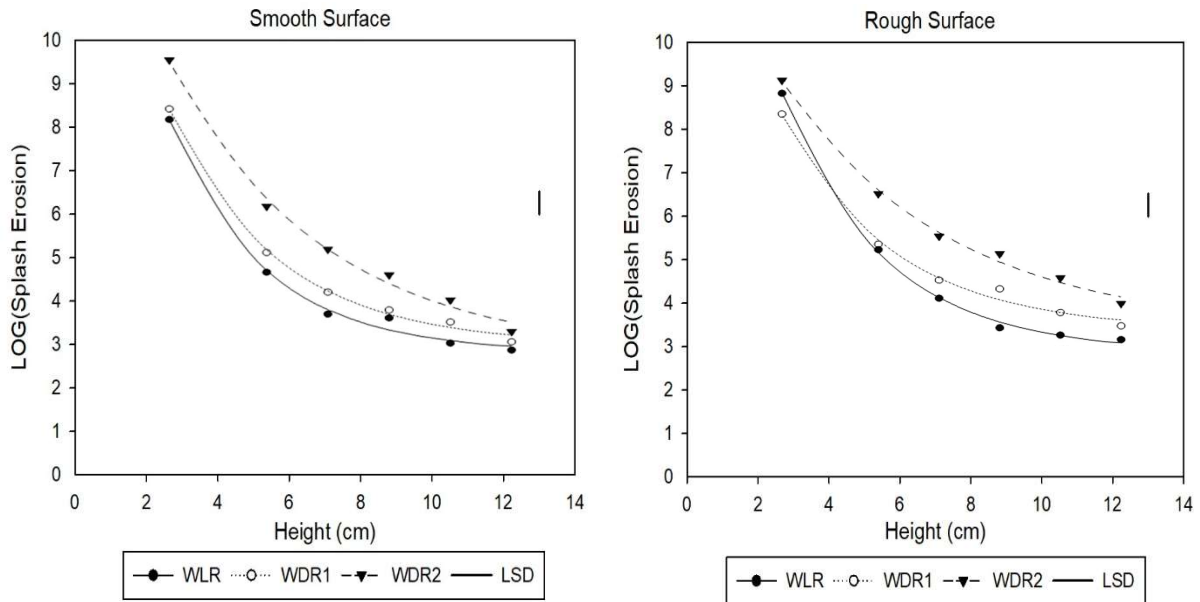


Figure 3-9 Mean total soil loss by rainsplash (mg), expressed in Log, generated during the three 30-minute events (WLR, WDR1, WDR2), collected at different heights above the smooth and rough soil surfaces. LSD bar was used to compare between means of the three different events.

3.4.5 Effect of windless (WLR) and wind-driven rainfall (WDR) on soil surface roughness (SSR)

Table 3-2 presents the initial and final SSR of the smooth surface (hereafter referred to as 'SS') and the rough surface (hereafter referred to as 'RS') after the three different rainfall events (WLR, WDR1 and WDR2). The initial SSR of the rough surface was significantly higher than the initial SSR measured for the smooth surface ($p < 0.001$). This is due to the simulated mounds and depressions of the rough surface which increased the topographic irregularities of the soil surface, which validates the methodology used in this study.

As expected, the SSR of the initially smooth surface increased after both the WLR and WDR events, showing a positive correlation with wind velocity. This increase in SSR was significant between all three events ($p < 0.05$), as presented in Figure 3-10. On the other hand, the SSR of the initially rough surface declined after the WLR and WDR events, with a positive correlation with wind velocity. The final SSR after the three events remained significantly different between the two surface conditions ($p < 0.001$) and was significantly different from the initial SSR for both surface conditions.

Table 3-2 Soil surface roughness (SSR, %) for smooth (SS) and rough (RS) surfaces, before (initial SSR) and after (final SSR) the three 30-minute events (WLR, WDR1, WDR2).

Treatments	Surface roughness (%)		SSR change (%) ^a
	Before rain	After rain	
SS-WLR	4.19	7.29	+74
SS-WDR1	3.1	6.72	+117
SS-WDR2	3.33	9.05	+172
RS-WLR	20.19	16.55	-18
RS-WDR1	24.58	19.25	-22
RS-WDR2	24.89	17.48	-30

^a Positive values indicate an increase in surface roughness; negative values indicate a decrease in surface roughness.

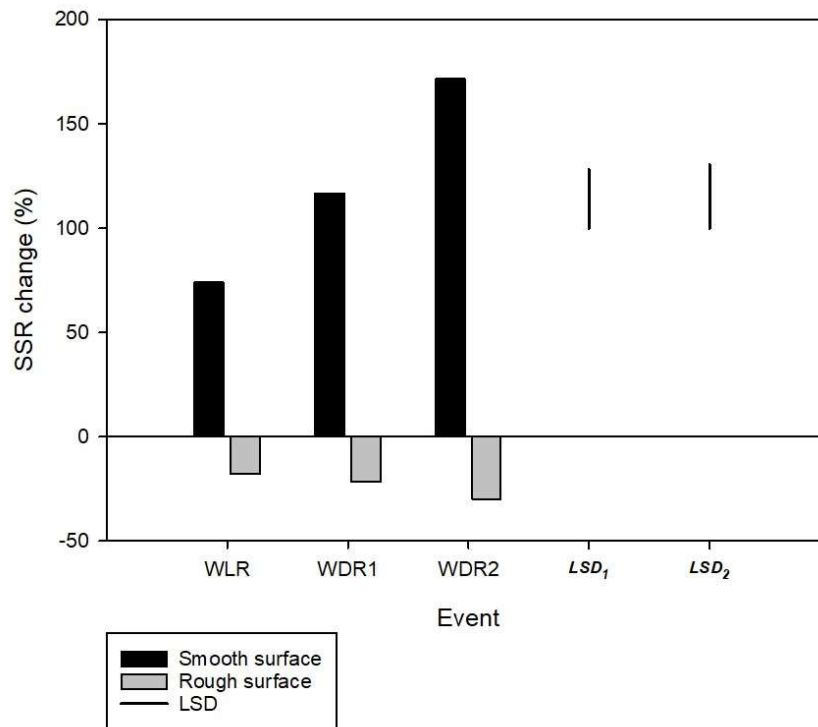


Figure 3-10 Changes in the Soil Surface Roughness (SSR) for each of the two surface conditions during WLR, WDR1 and WDR2. LSD_1 and LSD_2 bars were used to compare between means of the three different events, and means of the smooth and rough soil surfaces, respectively.

Images in Figure 3-11 show the SSR of the smooth and rough surfaces before and after the WLR and WDR events. For the initial rough surface (prior to rainfall), the mounds and depressions formed a contrast of colours (i.e. light and dark), creating areas of both shadow and illumination. It is clearly noticed that the light colour gets wider, and the dark shadow gets lighter after applying WLR and WDR, which indicates the reduction in the magnitude of mounds and depressions. For the smooth surface, it is distinctly observed that the soil surface was smooth before the application of the WLR and WDR events. After the simulated events, small pits were formed due to the raindrop impact that led to soil detachment and concomitant compaction. This is represented by the contrast of colours (light vs dark).

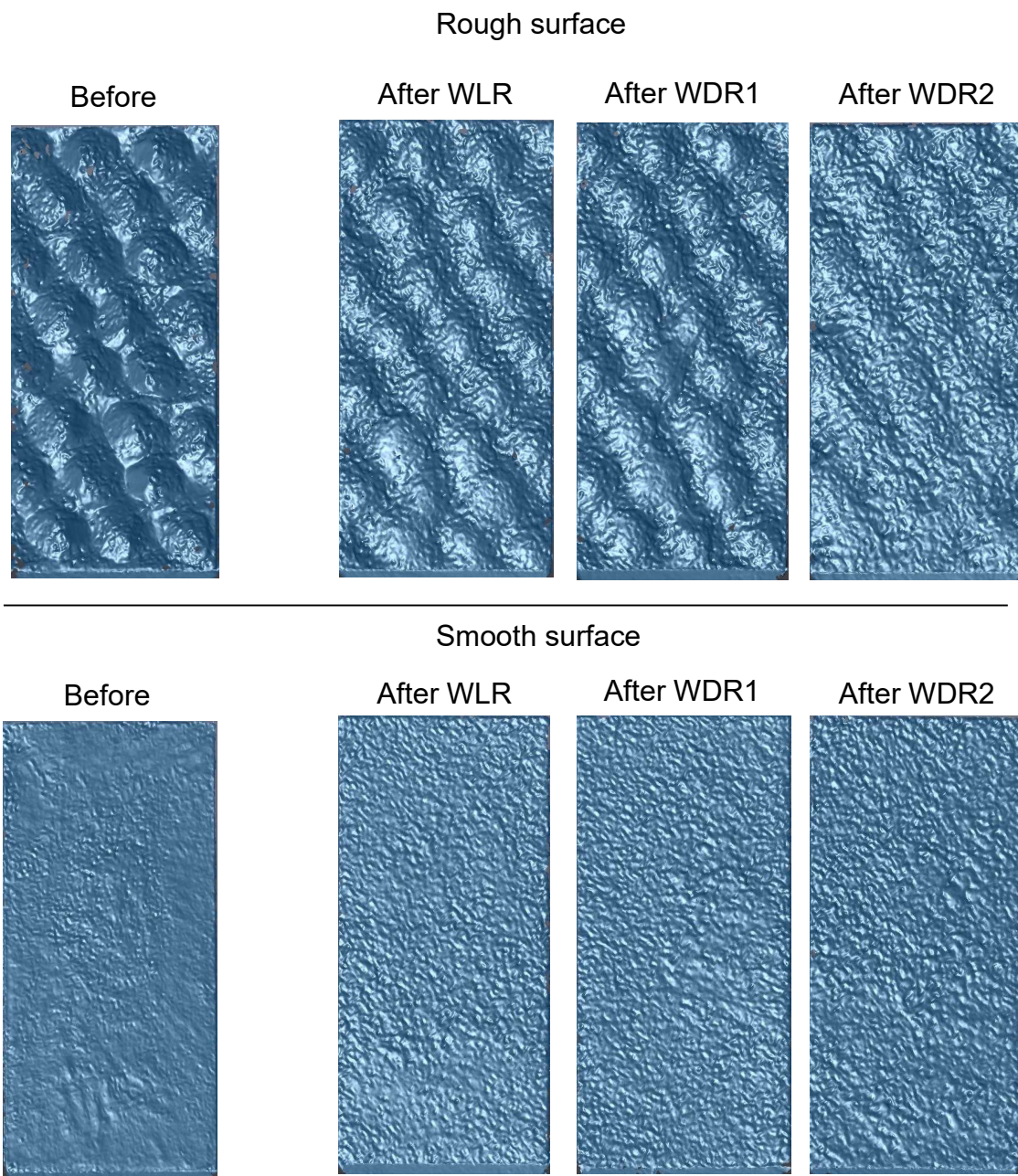


Figure 3-11 Changes in the soil surface of the initially smooth and rough surfaces before and after the windless rain (WLR), wind-driven rain1 (WDR1) and wind-driven rain2 (WDR2) events. Images from a laser scanner with a resolution of 1.5 mm. Each image represents the erosion trays' dimensions of 50 cm x 25 cm.

3.4.6 Windless and Wind-Driven Rainfall Kinetic Energy (KE)

The raindrop size, angle of incidence and vertical velocity of raindrops were obtained from the VisiSizer N60 laser (Figure 3-12). As expected, the raindrops' angle of incidence increased with increasing wind velocity. The angles of

incidence $>50^\circ$ correspond to raindrops < 0.5 mm in diameter under WDR1, because the smaller the raindrop, the more its trajectory is influenced by wind. Under the highest wind velocity, WDR2, raindrops of up to 1 mm in diameter were inclined at 50° to 80° from the vertical. This aligns with the findings of Sharon (1980) who reported that angles of 40° to 70° have been recorded in rainfall driven by a wind velocity of 10 m s^{-1} .

The vertical raindrop velocities were higher during WLR than during WDR conditions. This is because under WLR, the trajectory of the raindrops was vertical (i.e. perpendicular to the test area), whereas under WDR conditions, the angle of raindrop incidence increased, hence the vertical velocity decreased.

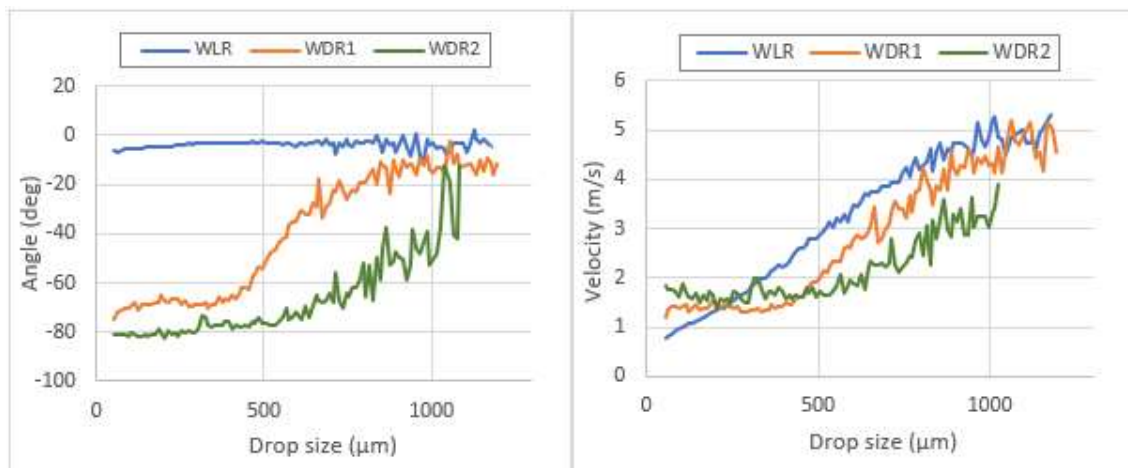


Figure 3-12 Raindrop incidence angle and vertical velocity at different raindrop sizes under WLR, WDR1 and WDR2. The data is the mean of both VisiSizer Laser locations.

Table 3-3 depicts the differences between WLR, WDR1 and WDR2 in terms of the raindrop velocity and KE. After integrating the raindrop incidence angle (Equation (3-3)), the resultant velocity increased in WDR conditions compared to WLR, especially for WDR2 where it increased by 95%. The KE also increased in WDR conditions compared to WLR, especially for WDR2 where it increased by 43.5%. The increase in the KE was attributed to the increase in the resultant velocity. This aligns with the results of Erpul et al. (2003a; 2005; 2008; 2009). The effect of wind on the rainfall KE depends on whether the vertical or the resultant fall velocity is considered (Tilg et al., 2020). Tilg et al. (2020) found that rainfall

KE decreased with increasing wind speed and explained this result by considering the vertical fall velocity of raindrops only. Therefore, the raindrop incidence angle is important when determining the overall KE. Results from other studies may also vary due to the apparatus used; Kim and Song (2018) used a Parsivel disdrometer which is not ideal under windy conditions because of the dispersion and deviation of raindrops which affect drop size distribution and fall velocity. That device does not measure raindrop incidence angle and misclassification of raindrop characteristics could occur due to raindrops not falling perpendicular to the test area (Friedrich et al., 2013).

Table 3-3 Vertical velocities, resultant velocities and resultant kinetic energies of windless and wind-driven rainfall measured by the VisiSizer Laser positioned at two different locations under the nozzle.

		Wind-Less and Wind-Driven Rainfall events		
		WLR	WDR1	WDR2
Vertical velocity (m s⁻¹)	Location1	2.67	2.02	1.52
	Location2	2.22	1.92	1.54
	Mean	2.45	1.97	1.53
Resultant velocity (m s⁻¹)	Location1	2.67	2.84	5.12
	Location2	2.23	2.64	4.43
	Mean	2.45	2.74	4.78
Kinetic energy (mJ m⁻² s⁻¹)	Location1	230	318	428
	Location2	395	401	470
	Mean	313	360	449

3.5 Discussion

Traditionally, soil erosion by wind and by water have been the subject of separate studies. To improve the understanding of how these processes interact, a facility that combines wind and rainfall simulators was constructed for this study. The first objective was to evaluate the effect of wind velocity on the erosivity of rainfall. In

addition to that, the role of wind on rainfall induced erosion is closely related to soil surface characteristics, specifically SSR. This interplay of rainfall erosivity and soil surface roughness was overlooked in previous studies and the magnitude of the wind-driven rain effect on a rough surface is not known. In this study, both smooth and rough surfaces subjected to WLR and WDRs were simulated using two wind velocities.

Purpose-designed erosion trays were used to collect surface runoff and infiltrate volumes, and any sediment load in the runoff; and a set of funnels was built serving as rainsplash sediment collectors. This design facilitates better understanding of the different processes of soil and water losses occurring simultaneously. This is important, as most studies concentrate solely on either erosion agent, thereby potentially limiting the comprehensive assessment of erosion dynamics.

To better understand the effect of wind on rainfall erosivity, raindrops' angle of incidence, velocity and kinetic energy were measured under the experimental treatments (i.e. WLR, WDR1, and WDR2). The device used takes into consideration both the vertical and the horizontal components of the rainfall energy, unlike some studies which consider only the vertical component (Tilg et al., 2020), which will underestimate the effect of the wind on raindrop erosivity.

3.5.1 Runoff, infiltration, sediment load and concentration

For the initially smooth surface, runoff volumes were positively correlated with wind velocity, and sediment load and concentration significantly increased under the WDR2 event as compared with WDR1. This was in accordance with the findings of Erpul et al. (2003b) and An et al. (2023), where wind-driven runoff detached, entrained and transported more soil particles under higher wind velocities, leading to greater soil loss. Compared to windless rainfall, the wind affected the characteristics of the incoming rainfall (Erpul et al., 2013; Arshad et al., 2019) by altering the raindrops' trajectories, increasing their impact incidence (Gao et al., 2021). This alteration resulted in stronger tangential shear stress from the inclined rainfall (Erpul et al., 2005) which added momentum to the surface runoff, increasing its erosivity (i.e. capability to detach and transport soil material

(Iserloh et al., 2013)). Previous research reported that because of increased incidence angle and KE due to increased drop velocities, WDR may be more erosive, enhancing both soil detachment and transport (Erpul et al., 2008; Arshad et al., 2019).

However, contrary to these findings, for the rough surface in the present study, surface runoff volumes significantly decreased under WDR1 compared with WLR. Under low wind velocities, it was observed that WDR on rough surfaces tends to create a more chaotic and irregular flow pattern compared to windless rain. This is due to air turbulence associated with the roughness of the soil surface. In addition to that, wind velocities decrease near the ground surface when roughness is present (Morgan & Rickson, 1995). This decrease in wind velocity is more marked with increasing distance away from the air source (Figure 3-3). The interception of WDR by the mounds investigated in this study might cause rainwater to be diverted or redistributed across the soil surface, leading to a more diffuse distribution of water and potentially reducing the concentration of surface runoff. Moreover, the presence of mounds and depressions disrupts the flow of water, causing it to pool in low-lying areas and infiltrate into the soil rather than flowing over the surface as runoff. The interrupted flow paths and temporary water storage in depressions decrease both the velocity and the volume of surface runoff.

However, under WDR2, runoff and soil loss on the rough surface increased compared to WDR1, to reach values not significantly different from those under WLR. When wind velocity increases to a certain threshold (e.g. 9 m s^{-1} according to Arshad et al. (2019)), the dynamics of soil erosion can change, potentially leading to runoff and soil loss levels similar to, or even higher than, those observed under windless rain conditions. Higher wind velocities during a wind-driven rain event (i.e. WDR2) might change the surface roughness by flattening the mounds (Figure 3-11), leading to increased runoff compared to WDR1, which explains the significant difference between these two events. In addition to that, the mounds and depressions of the rough surface treatment in this study simulate both windward and leeward slopes. Unlike the leeward slope where wind increases runoff and soil loss, under windward conditions, wind decreases runoff

because raindrops fall at an obtuse angle to the slope and are incident in the opposite direction to the soil surface overland flow (An et al., 2022; 2023). This allows more time for the water to infiltrate, reducing runoff generation, so mitigating the erosive impact of water flow. The effects of both windward and leeward slopes (i.e. mounds and depressions) counterbalanced each other, which might explain the non-significant difference between WLR and WDR2 in terms of runoff volume and soil loss.

The rough surface (RS) delayed the time-to-runoff initiation and generated less runoff and soil loss than the smooth surface (SS). The RS generated less runoff volumes than the SS for all rainfall events, and this decrease in runoff volume due to RS was highly significant for WDR1 and WDR2. The depressions on the rough surface retained the water during the rainfall event, which increased the infiltrate volume and delayed the time to runoff initiation compared to the smooth surface. This aligns with the findings of Zhao et al. (2019; 2021). Moreover, rough surfaces after tillage disturbance have a reduced bulk density in the upper layer of the soil and increased soil porosity, so promoting higher infiltration (Sun et al., 2009). At the same time, SSR increases the effective slope length compared with smooth slopes which delays the arrival of overland flow at the bottom of the slope (Zhao and Wu, 2015). This effect is caused by the mounds on the surface creating a physical barrier to the downslope movement of runoff. Salem et al. (2014) found that such surfaces could reduce runoff volumes by 61%. This study demonstrates that surface runoff volume in RS decreased by 58% compared with SS. Sediment load also diminished in correlation with runoff volume reduction. In examining the impact of surface microrelief on soil erosion, Wu et al. (2016) suggested that the spatial structure of the surface microrelief has an important effect on the transportability of sediment. This type of soil surface roughness mimics reservoir tillage, which is used in some countries as a way of soil and water conservation (Zhao et al., 2021).

3.5.2 Rainsplash erosion

In this experiment, besides collecting any eroded soil in the runoff, comprehensive collection of any rain-splashed material was ensured by placing

purpose-designed and built collectors at the downslope end of the erosion tray. The collectors covered the entire breadth of the tray, ensuring a larger and more representative effective catchment area, facilitating the capture of a great number of detached particles from the entire length and width of the erosion tray.

As mentioned earlier, the hypothesis being tested was that the interaction of wind on falling raindrops would enhance the process of soil detachment, entrainment and transport. For eroded material collected at the first height (i.e. up to 2.7 cm above the soil surface), this was true for the SS. However, for the RS, splash erosion decreased under WDR1, although not significantly so. As previously stated, under the WDR1 event, the non-uniform flow patterns and temporary storage of water within depressions may attenuate the velocity of water flow, so reducing the erosivity of surface runoff and minimising soil loss. Nevertheless, for splashed material collected at all heights > 2.7 cm above the soil surface up to 12.2 cm, the hypothesis is accepted. Indeed, the results show an increase of splash erosion during the WDR events compared to the WLR event at these collecting heights, for both the SS and the RS. This increase was positively correlated with wind velocity. According to Zumur et al. (2020), there is a linear relationship between the amount of detached soil material and the rainfall KE. Indeed, the results of this study demonstrate that higher wind velocity (WDR2) generated more splashed material due to the increase of the erosivity of raindrops. This was also reported by Arshad et al. (2019) and Cornelis et al. (2004). It was noted by Mahmoodabadi et al. (2021) that raindrops' size and angle of incidence both increased with higher wind velocities which then contributed to a higher detachment rate. In the absence of wind during rainfall, raindrops falling vertically result in particle movement in all directions. Conversely, in wind-driven rains, particle movement becomes more unidirectional, aligning with the prevailing wind direction, as outlined by Erpul et al. (2003b). Due to the momentum given to the falling drops by the wind, WDR increases the rainfall velocity and thus KE to detach, entrain and transport the soil particles. Moreover, the wind shear velocity has the potential to entrain soil particles into the air flow (de Lima et al., 1992). Once the mass of an entrained particle exceeds the transport capacity of the airflow, it drops to the ground where it bombards other

soil particles which in their turn are detached and entrained into the air flow (Marzen et al., 2017). In the same context, wind increases the transport of soil particles already entrained by the rainsplash-saltation process (Cornelis and Gabriëls, 2004).

At all heights > 2.7 cm above the soil surface, rough surfaces generated more splash erosion than smooth surfaces under both WLR and WDR. The variations in splash erosion among these surface treatments are probably linked to the spatial configurations of the microrelief on the surface. Rainsplash erosion increases with increasing surface relief (Bullard et al., 2018); this is attributed to the increased exposure of soil surface area to raindrops facilitated by the presence of mounds and depressions (Luo et al., 2018). Microrelief on rough surfaces increased the effective slope (and the soil surface area subjected to the rainfall and wind when present), leading to higher detachment rates (Wu et al., 2016).

3.5.3 Effect of windless (WLR) and wind-driven (WDR) raindrop impact on initial Soil Surface Roughness (SSR)

The post-rainfall changes in SSR are primarily influenced by the initial state of the soil surface (Huang and Bradford, 1992; Magunda et al., 1997; Govers et al., 2000). Rainfall significantly changes the soil surface morphology (Zhao and Wu, 2015) by decreasing or increasing the SSR over the rainfall event. The results of this study indicate that the initial SS became rougher after the WLR and WDR events due to raindrop impacts detaching and redepositing soil particles. This aligns with the findings of Bahddou et al., (2023) where detached particles were then transported and redeposited on the soil surface, forming a new microrelief, leading to an increase in the SSR for initially smooth surfaces. In this context, Zhao et al. (2014a) observed that SS exhibited the formation of distinct crescent-shaped pits after rainfall which increased their surface roughness. Likewise, Römken et al. (2001) reported the same changes in surface roughness with rainfall, as a result of the development of rills and flow incisions.

The results of this study suggest that there was a decrease in the SSR of the initially rough surfaces. This agrees with the findings of Zhao et al. (2014b) who

found the initial SSR of a rough soil surface decreased by 23%. Detached soil particles from the mounds on the rough surface were transported to and deposited in lower points and surface depressions, which reduced the magnitude of mounds and depressions, leading to a decrease in the SSR. This was also reported by Kirkby (2001) and Zhao et al. (2019).

The findings show that the initially smooth surface SSR increased by 74% after WLR and by 117% and 172% after WDR1 and WDR2, respectively. The difference between these changes in SSR was significant. Although the changes in SSR for the rough surface were not significantly different for the different rainfall events, they followed the same trend as for the smooth surface, i.e. the decrease in the SSR was more notable for the WDR events. As wind exerts an additional force on rainfall, raindrop erosivity, and soil detachment, transport and deposition are increased. The wind also enhances the momentum and shear force of surface runoff. As a result of these two processes, the change in SSR during wind-driven events was escalated.

3.6 Conclusions

These experiments were designed to better understand the combined effect of wind and rainfall on soil erosion processes. These experiments were unique in directly comparing WLR and WDR scenarios, at varying wind velocities, in terms of simultaneous generation of surface runoff, infiltrate, sediment load and concentration in the runoff, and splash erosion. This was tested for both smooth and rough surfaces.

The outcome of this research showed that on initially smooth surfaces the presence of wind during rainfall events increased surface runoff volumes and soil losses compared to rainfall conditions without wind. These processes were positively correlated with wind velocity, and sediment load and concentration in the runoff significantly increased under the higher velocity, WDR2 event. This is a consequence of the increased rainfall erosivity due to the additional force exerted by wind on rainfall and surface runoff leading to an increase in the rainfall resultant velocity. Adding a horizontal component to the raindrop fall velocity increased its KE and consequently its ability to detach soil particles. However,

initially rough surfaces could mitigate the effect of WDR on runoff and soil loss at low wind velocities, WDR1. This was not the case at higher wind velocities where these mitigating factors were cancelled out, resulting in soil and water losses comparable to or exceeding those observed under WLR conditions. On the other hand, WDR enhanced changes in SSR (i.e. the increase and decrease in the SSR for the smooth and rough surfaces respectively), to a greater extent than seen for WLR events.

The results show that a rough surface delayed the time-to runoff initiation and generated less runoff and more infiltrate than the smooth surface, under the three events: WLR, WDR1 and WDR2. This is due to resistance to surface runoff caused by the mounds associated with the rough surface that created a physical barrier to the downslope water movement, and the depressions on the surface that retained any surface water. However, rough surfaces presented relatively more exposed surfaces for splash erosion than smooth surfaces, due to the increased effective surface area subjected to raindrop impacts.

The findings of this study confirm that wind has an effect on the erosivity of rainfall, erosion processes and consequently to SSR over time. It is important that these effects are considered in erosion studies (for example in modelling of soil erosion processes) to better understand soil and water losses, especially in regions with WDR.

3.7 References

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4 ASSESSING THE INTERACTIVE EFFECTS OF WHEAT LINES, SOWING DENSITIES AND WATER REGIMES ON PLANT TRAITS, SOIL PHYSICAL PROPERTIES, AND PREDICTED SOIL EROSION

4.1 Abstract

Soil erosion poses a significant threat to agricultural productivity, environmental sustainability, and food security. Accurately assessing the factors influencing erosion processes is crucial for developing effective soil conservation strategies and ensuring the long-term viability of agricultural systems. While previous studies investigated the role of vegetation on erosion rates, only a few of them considered the effect of both the aboveground and belowground plant traits on the different processes of soil erosion. However, methods in the literature lack inclusion of other essential factors like soil properties, indicating the need for a method, such as erosion models, that encompasses all relevant processes and factors for a comprehensive assessment of erosion. The aim of this research is to study the effect of different wheat lines subjected to different sowing densities and water regimes on soil properties and plant shoot and root traits, and the subsequent effect on runoff generation and soil loss. To evaluate these effects on soil erosion rates, the modified Morgan-Morgan Finney (mMMF) model was used. All data was statistically analysed using ANOVA and regression models. The outcome of this study shows that the dwarf wheat line exhibited better drought tolerance, maintaining plant height under water stress, and demonstrated higher root density, particularly at higher sowing densities and under dry conditions. It exhibited superior erosion control capabilities (reduced soil loss by 25%), as predicted by the model, compared to the wild-type wheat line, particularly at later growth stages, due to its higher canopy cover, ground cover, and root development, providing better soil protection. Higher sowing densities increased canopy cover, ground cover, and total tiller number, despite reducing individual plant tillering due to competition, but improved soil structure, hydraulic conductivity, cohesion, and reduced soil loss by 31%, compared to lower sowing density, through increased root length density. Drought stress significantly

impaired plant growth, reducing canopy cover, tillering, plant height, aboveground biomass, and root length density, leading to increased predicted erosion risks, while well-watered conditions promoted plant growth and soil protection and reduced soil loss by 23% compared to drought conditions. Plant presence significantly reduced runoff and soil loss by 38% and 41%, respectively, compared to bare soil, with strong positive correlations between number of tillers, root length density, and hydraulic conductivity, and negative correlations between soil loss and plant traits and soil properties, underscoring their importance in erosion control. These findings emphasise the need for integrated management approaches considering plant genetics, sowing practices, and environmental factors for sustainable soil conservation and erosion control.

Keywords: Drought, Dwarf wheat, MMF soil erosion model, Runoff, Shoots, Soil loss, Roots

4.2 Introduction

Soil erosion is a significant environmental concern contributing to land degradation and reduced agricultural productivity. There are several factors causing erosion such as soil properties (soil cohesion, infiltration rate, bulk density, porosity and water retention characteristics), plant traits (aboveground and belowground, notably roots), and agricultural practices (crops and sowing densities).

Soil properties can alter the dynamics of soil and water losses. For example, low soil cohesion can increase the detachment of soil particles by water erosion (Knapen et al., 2007). Reduced infiltration rates, caused by factors like soil compaction or surface sealing, can limit water entry into the soil, leading to higher surface runoff and erosion (Le Bissonnais et al., 1995). High bulk density and low porosity, often resulting from soil compaction, can decrease infiltration and water holding capacity, and increase surface runoff and soil loss. Soils with lower water retention capacity are more prone to surface runoff and erosion, as they have a limited ability to store water, leading to increased overland flow and soil loss.

Plant traits play a crucial role in mitigating soil erosion (Lees et al., 2021). Aboveground plant traits such as canopy and ground cover, protect the soil surface from the direct impact of raindrops, reducing runoff, and the detachment and transport of soil particles (Armstrong & Mitchell, 1987; Durán Zuazo & Rodríguez Pleguezuelo, 2008). Belowground plant root traits modify the soil structure causing changes in water retention characteristics of soil, leading to differences in water availability for the plant (Whalley et al., 2005). Roots reinforce the soil structure by increasing shear strength and cohesion while creating biopores that enhance infiltration, ultimately reducing runoff and associated soil detachment, entrainment and transport (Angers & Caron, 1998; Bodner et al., 2013; Colombi et al., 2018; Gyssels et al., 2005). Previous research has studied the effect of different root traits on erosion, such as total root diameter, total length (Hudek et al., 2022; Mekonnen et al., 2016; Mwango et al., 2014) and total surface area (De Baets et al., 2007; Vannoppen et al., 2015). These traits affect soil cohesion and aggregate stability, hence influencing soil detachment processes. According to Hallett et al. (2022), targeting root traits that build soil structure can improve erosion control, and water management. Such soil structural improvements may also reduce compaction and allow deep-rooting cultivars to access deeper soil resources (Jin et al., 2017). Liu et al. (2019) found that root length density was the best parameter for estimating the effects of roots on soil detachability and erodibility.

Disentangling the above and below ground soil and plant properties that affect erosion is challenging as it is difficult to separate the complex feedback mechanisms and interdependencies between soil and plant variables. The most suitable method to evaluate this is through modelling, even though not all factors are currently explicitly considered in soil erosion models. First, a description is provided on how the aforementioned above-ground and below-ground traits can be controlled and quantified specifically for wheat. Subsequently, a description will follow on how these traits can be incorporated into generic soil erosion models.

Wheat (*Triticum* spp.) stands as one of the most pivotal crops globally, serving as a staple food source for billions. In Morocco, it is considered the dominant crop with a production of over 7.5 million metric tons in the year of 2021 alone (Statista, 2024). Ma et al. (2019) found that compared with bare land, mean runoff rate on maize, soybean, and winter wheat fields was reduced by 24%, 32%, and 94% respectively, and sediment yield was decreased by 44%, 55%, and 99% respectively. Similarly, Yan et al. (2023) found that wheat reduces runoff and soil loss more than soybean and corn before harvest. This suggests that choosing winter wheat as a crop can be an environmentally sustainable option for soil and water conservation.

4.2.1 Effect of wheat lines on plant traits (shoots and roots) and soil properties

It is known that vegetation increases soil cohesion and infiltration rate compared to bare soil conditions (Le Bissonnais et al., 1995; Zhou et al., 2006). As an annual cereal crop, wheat generally has a positive impact on soil physical properties, primarily through canopy cover and root development. However, the extent of these effects can vary depending on the specific wheat line and its associated roots characteristics. The severe dwarf Cadenza line carries the *Rht-B1c* gene, which results in a much shorter plant stature compared to the tall Cadenza. Wheat genotype was found to have a significant effect on shoot biomass and total root length (Wang et al., 2021). However, little is known about the effect of wheat genotype variability on soil physical properties and their interaction with plant traits and effect on soil erosion.

4.2.2 Effect of sowing densities on plant traits (shoots and roots) and soil properties

Sowing density has a significant influence on plant traits. Although not specific to wheat, Hecht et al. (2016) studied barley cultivars at different levels of sowing density ranging between 24 to 340 seeds m⁻² and reported that higher sowing densities of barley resulted in greater tiller density and biomass production per unit area, indicating increased canopy cover. However, although the aboveground biomass per unit area increases with sowing density, the individual

plant biomass generally decreases due to competition for resources (Tan et al., 2020). Little is known about the effects of wheat sowing density on soil properties such as infiltration rate and soil cohesion. However, Hecht et al. (2016) found that root length density in the topsoil increased linearly with increasing sowing density. So, denser root systems from higher sowing densities can potentially improve soil structure and porosity through greater root growth and organic matter inputs. Tan et al. (2020) concluded that sowing density indirectly plays a role in soil reinforcement and erosion resistance through the belowground biomass. Gyssels et al. (2007) showed that double drilling of cereals, a technique that doubles seedling density, in concentrated flow areas reduce soil loss from rill and gully erosion by up to 40% without significantly affecting crop revenues.

4.2.3 Effect of drought on plant traits (shoots and roots) and soil properties

Drought stress affects plant-soil interactions and growth dynamics (Whalley et al., 2006). For plants, dry soil conditions can trigger stress responses aimed at conserving water. One such response is reduced plant growth and plant height associated with impaired cell elongation and leaf senescence (Shao et al., 2008). This can increase exposure of soil to rainfall, causing a greater risk of soil erosion. The production of side shoots, known as tillering, is also frequently reduced in dry soil conditions as plants allocate limited resources towards survival rather than more soil-protecting vegetative growth. In terms of root characteristics, plants growing in dry soils may develop deeper and more extensive root systems to access water from deeper soil layers (Comas et al., 2013). In contrast, well-watered soils have higher root length density in the upper soil layers due to the availability of water near the surface (Huang & Gao, 2000). An extensive root system in soils' upper layers is important for reducing soil erodibility and erosion risk (Gyssels et al., 2005). In soils, dry soil due to low moisture content increases soil strength (Whalley et al., 2008). Huang et al. (2012) found that increasing moisture content decreased shear strength of the soil. Low soil moisture generally increases infiltration rate but can also reduce it due to hydrophobicity and water repellency.

4.2.4 Evaluating the effect of different plant traits on soil erosion risk

Ground cover and aboveground vegetation reduce soil detachment by dissipating the rainfall KE (Morgan and Rickson, 1995). The research by De Baets et al. (2009) and Ghestem et al. (2014) focused on specific aspects of erosion control, such as plant species selection or solely root properties to control soil detachment by surface runoff. These approaches overlook the holistic nature of the soil erosion processes. While Lees et al. (2020) expanded on this by considering aboveground and belowground plant traits and their potential effects on rainsplash and detachment, their method still lacks inclusion of essential factors like soil properties, indicating the need for a method, such as erosion models, that encompasses all relevant processes and factors for a comprehensive assessment of erosion. The Morgan-Morgan-Finney (MMF) model (Morgan et al., 1984) is a soil erosion model that predicts soil loss based on the processes of detachment and transport of soil particles. It uses the Meyer and Wischmeier (1969) concept in which the detachment and transport capacities are compared. The Revised MMF (Morgan, 2001) incorporated flow detachment and plant height effects, while the Modified MMF (Morgan & Duzant, 2008) added soil particle-size selectivity, sediment deposition, and vegetation cover effects. In this study, the model mMMF model was used to evaluate how variations in plant traits and soil properties caused by different wheat lines, sowing densities, and moisture regimes affect runoff and soil losses at different growth stages of the plants. Model outputs can be used to identify treatments that effectively reduce erosion and conserve soil and water resources.

4.2.5 Objective and hypotheses:

The aim of this research is to study the effect of different wheat lines subjected to different water regimes and sowing densities on the generation of runoff and soil erosion. Research hypotheses include that:

- (i) different wheat lines affect plant traits associated with erosion processes, namely canopy and ground cover, number of tillers, and root length density;

- (ii) drought affects plant traits associated with erosion processes, by reducing canopy cover, plant height, number of tillers, and root length density;
- (iii) higher sowing densities affect plant traits associated with erosion processes, by increasing root length density which reinforces soil strength, and increases infiltration; and
- (iv) changes in plant traits (due to genotype, sowing density and water regime) affect soil erosion rates, as predicted with a process-based soil erosion model.

4.3 Materials and methods

4.3.1 Soil preparation

The soil came from Butt Close field, Rothamsted Research's Woburn Experimental Farm (52°00'44.9"N, 0°35'51.6"W). It is a loamy sand (87.3% of sand, 5.5% of silt and 7.2% of clay) and is categorised as a Cambic Arenosol, following the FAO classification. Soil (topsoil at 15 cm depth) was sampled (6 April 2023) from the site and was air-dried in a glasshouse. A <2 mm mesh screen was used to sieve the air-dried soil, which was then packed into cylindrical columns 30.5 cm deep and 25 cm wide (with an internal diameter of 23.5 cm). Each column was covered at the bottom with a fabric mesh and was uniformly packed with 18 kg of sieved soil divided into six layers which were individually compacted with a soil packer, using the same number and intensity of strikes per layer, to achieve a uniform bulk density of 1.38 g cm⁻³ throughout the profile. To reduce discontinuities between layers, each soil layer was lightly scraped before adding the following layer. The soil moisture content of 20 samples taken randomly from the sieved air-dried soil bags was measured using the oven-drying method. Their mean value was 0.6 % with a standard error of 0.00036 (CV = 0.25%).

4.3.2 Treatments

In this experiment, two wheat lines were used, the wild-type cadenza (hereafter named 'Tall' wheat) and a Near Isogenic Line (NIL) containing Rht-B1c allele in a Cadenza background (hereafter named 'Dwarf' wheat). Their thousand kernel

weights (TKWs) are 50.4 g and 41.1 g, respectively. Two sowing densities were considered, 2 seeds per column and 5 seeds per column, i.e. 46 and 115 seeds m^{-2} , respectively, to simulate a low and high sowing density. By comparison, Hecht et al. (2016) simulated different levels of sowing density ranging between 24 to 340 seeds m^{-2} . The wheat seeds were allowed to germinate between wet paper sheets in covered Petri dishes before they were transplanted into the soil column.

Each layer of soil from all columns was irrigated, using a watering can, during soil packing to ensure water uniformity throughout the soil profile. After applying water to one layer of a soil column, this later was covered before moving to the next column, to avoid water evaporation and to ensure consistent moisture content between soil columns. During packing, 160 mL of Letcombe's nutrient solution (Table E-1) was applied per one layer of soil. 100 mL to 200 mL of nutrient solution was added on a weekly or fortnightly basis depending on the different plant growth stages (Nguyen et al., 2019). The nutrient solution was prepared freshly from stock prior to each application to prevent chemical sedimentation. The volumetric water content of the soil was adjusted to approximately 20%, i.e. 2.7 L of water per column, including the nutrient solution. Pre-germinated seeds were sown at 1 cm depth from the soil surface. The plants were subjected to two water regimes, 'well-watered' and 'drought'. Half the number of columns were regularly watered to maintain the 'well-watered' soil moisture content ($\approx 20\%$), while the drought treatment columns were left to dry out, for 3 days, until the water content reached 8%. Soil moisture content probes (WET150 Delta-T) were inserted 5 cm below the soil surface to monitor soil moisture content. Water was added to the columns to achieve the required water contents (i.e. 20% and 8%). In addition to that, soil sub-samples were also taken from a replica trial column at different depths to measure the moisture gradient through the soil profile.

Different soil and plant properties, above- and below-ground traits, were measured (section 4.3.3) at two different growth stages, up to approximately 25% and up to approximately 75% canopy cover, to observe the effects of the treatments on the soil and plant properties and the effects of these characteristics

on predicted soil erosion processes over time. The experimental treatments were 2 wheat lines x 2 sowing densities x 2 water regimes x 2 growing stages x 3 replicates, giving a total of 48 columns, plus 3 replicates of the bare soil columns used as the control. The experiment was conducted at Rothamsted Research in a growth room with a controlled environment with day/night temperatures of 22 and 18 °C, respectively, and a 16 h day length. The relative humidity was 70% during the day and 80% at night. Lighting was by fluorescent tubes, and the average photosynthetic photon flux density was 379 $\mu\text{mol m}^{-2} \text{s}^{-1}$.

4.3.3 Measurements

4.3.3.1 Plant physical traits

To test the research hypotheses, plant traits were measured from all planted columns, representing different treatments, at both growth stages. The first measurements (at the 1st growth stage) were taken 20 days after sowing, and the second measurements (at the 2nd growth stage) were taken 42 days after sowing.

4.3.3.1.1 Canopy cover

The canopy cover is the percentage of the soil area covered by the plants canopy. It was measured by taking top view images of the planted soil columns at different growth stages. The images were captured using a camera Canon DSLR fixed on a tripod to maintain the same height. Positions of the tripod were marked for consistency between images of different growth stages. The camera was connected to the software 'Imaging Edge' for an easy capture of the image via the smartphone. The obtained images were then processed using the image processing programme 'ImageJ'. The images were segmented and cropped to fit the circle of the column, ignoring any leaves overshooting the perimeter of the column. The contrast of colours between the plants and the soil was adjusted using the programme tools, and the proportion of the area covered by the plants (%) was calculated.

4.3.3.1.2 Ground cover

The ground cover is the percentage (%) of ground surface covered with plant components (stem and leaves) that touch the soil surface. It was calculated by

using a measuring tape in four transect lines across the circular columns (diameters) on the soil surface equally divided in 24 points forming a 1 cm interval in each line. The number of points where plants components touch the lines were recorded. The ratio of the covered point to the total number of points was calculated for each line per column and a mean value per column was determined. This method was well described by ROC™ (2020).

4.3.3.1.3 Plant height

The plant height was measured, at both growth stages, as the vertical distance from the soil surface to the highest point of the plant accounting for any bending or curvature of the leaves. This was measured using a graduated scale on each plant per column and a mean value per column was calculated (cm).

4.3.3.1.4 Plant diameter

Diameter of plant elements at the ground surface (cm) was calculated by measuring the circumference zone at the soil surface occupied by the total stems (tillers) of each plant per column. The diameter was then calculated and an average value of plants per column was calculated.

4.3.3.1.5 Aboveground biomass

Before harvest, the number of tillers was counted for one plant per column then multiplied by the number of plants per column. The aboveground plant material was harvested for both growth stages, weighed, oven-dried at 80°C for 24 h and weighed again, with an analytical balance with a readability of 0.001 g, to obtain the fresh and dry weights.

4.3.3.1.6 Root length density and diameter

At the second stage of plant growth, soil cores were collected at the exact area of the plant from the soil columns of the second crop growth stage using a manual core sampler containing a transparent sample liner tube (5 cm diameter and 30 cm depth). The tube was cut in sections and the top 10 cm of the soil sample was washed in a sieve, and roots were retained. The root subsamples were preserved in a 50% ethanol solution and stored in a cold room. The roots were scanned using an EPSON Expression 11000XL Flatbed Scanner, and the scans were

processed with WinRHIZO™ 2016a software to obtain root parameter data such as root length density (cm cm^{-3}), average root diameter (mm) and root length across 10 different diameter classes ranging from 0.05 mm to over 2 mm.

4.3.3.2 Soil physical properties

To test the research hypotheses, soil physical properties were measured from all columns, representing different treatments, at both growth stages. The first measurements (at the 1st growth stage) were taken 23 days after sowing, and the second measurements (at the 2nd growth stage) were taken 45 days after sowing.

4.3.3.2.1 Porosity

Soil cores of 6.5 cm diameter and 8 cm depth were collected in PVC cylinders from the soil columns of the second crop growth stage and the bare soil columns. The samples were well wrapped, carefully packed and transported to the laboratory for scanning. X-Ray Computed Tomography (X-Ray CT) scanning was conducted using advanced X-ray μ CT technology, a state-of-the-art Phoenix v|tome|x m scanner (Waygate Technologies (a Baker Hughes Company), Wunstorf, Germany) at the Hounsfield Facility, The University of Nottingham, Sutton Bonington Campus, UK, to analyse soil structure (porosity). The samples underwent scanning using X-rays generated at 170 kV voltage and 150 μ A current. Each scan acquired 2160 projection images over one rotation of 360°, with an exposure timing of 333 ms per image. The spatial resolution was optimised to 54 μ m with a total scan time of 12 minutes per sample. Phoenix Datos x 2 reconstruction software (Waygate Technologies (a Baker Hughes Company), Wunstorf, Germany) was used to reconstruct the scanned samples as 16-bit images. The images were optimised to rectify potential sample movement during the scanning process in addition to a beam hardening correction factor of 8. The reconstructed 3D volume was visualised using VG Studio Max 2023.1 software (Volume Graphics GmbH, Germany).

Soil porosity was analysed using the open-source image processing software, ImageJ (Schneider et al., 2012). The contrast was enhanced, and a region of interest was selected at the centre of each soil sample (630 x 630 pixels) and the first 100 image slices from the top and the bottom of each soil core were excluded

from analysis to avoid any differences between the cores due to the potential surface irregularities. The segmentation process was based on the 'Li' threshold algorithm. The images underwent visual inspection to confirm the adequacy of the segmentation process. As a result, a binary image was generated, where pores and soil solid materials were depicted by white and black pixels, respectively. The porosity data was then collected using the 'analyse particles' function. To prevent the misclassification of noise from the non-solid fraction of the soil samples, pores smaller than four pixels were excluded from the image analysis.

4.3.3.2.2 Soil cohesion

Soil cohesion (kPa) was measured using the Hand Vane Tester (PILCON, Rig and Supply Limited) which is a portable instrument for the determination of shear strength of cohesive soils. The instrument comprises a torque head direct reading scale which is turned by hand. A non-return with a pointer indicates the reading. This soil property was measured for both crop stages, as well as the bare soil.

4.3.3.2.3 Hydraulic conductivity

Hydraulic conductivity (cm s^{-1}) was quantified using a mini disk infiltrometer (Decagon Devices, Inc.) which is a tension infiltrometer that measures the hydraulic conductivity of the soil. This measurement shows if differences in the applied treatments affect infiltration processes. A suction rate of 2 cm, adequate for most soils (Decagon Devices Inc., 2016), was considered. The water volume (mL) in the infiltrometer tube was recorded over time and the hydraulic conductivity was calculated, based on a method developed by Zhang (1997). This soil property was measured for both crop stages, as well as the bare soil.

4.3.3.2.4 Soil water release characteristic and soil bulk density

Soil samples were collected using stainless-steel cylinders (5 cm diameter and 5 cm depth) from the soil columns and placed on pressure plates at 3 m height. Soil water release curve tracks the controlled release of water in the soil matrix from the saturated state as the soil water potential is decreased (from 0 at saturation to decreasing negative values down to -25 kPa). The samples were then put in a 5-bar pressure plate extractor (#1600 SOILMOISTURE equipment

co) subjected to a pressure of 0.33 bar, hereafter referred to as moisture content at field capacity (g g^{-1}). Soil water release characteristic is commonly known by a number of different terms including the retention curve, the moisture characteristic and the soil water characteristic. Soil water potential is more typically termed matric potential. The curve is shown as a plot of soil water content as a function of matric potential. The shape of the water retention curve was characterised by the Van Genuchten model (van Genuchten, 1980), as shown in Equation (4-1).

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha |\psi|)^n]^{1-1/n}} \quad (4-1)$$

Where: $\theta(\psi)$ is the water content as a function of the suction pressure [g g^{-1}];

$|\psi|$ is suction pressure (cm of water);

θ_s saturated water content [g g^{-1}];

θ_r residual water content [g g^{-1}];

α is related to the inverse of the air entry suction, $\alpha > 0$ (cm^{-1}); and,

n is a measure of shape and is affected by the pore-size distribution (dimensionless).

Bulk density (g cm^{-3}) was calculated by dividing the dry mass of soil by its total volume. The soil was oven-dried at 105°C for 48 hours.

4.3.4 Soil erosion prediction model

To evaluate the impacts of different plant traits and soil properties (as determined by different wheat lines, sowing densities and moisture regimes) on soil erosion and runoff, the modified Morgan-Morgan-Finney (mMMF) model was employed. This is a semi-empirical model, which provides a basic mathematical representation of runoff and erosion processes, as typically found in more process-based models. However, the model is also easy to use, as it requires a relatively limited number of input parameters, as is more common to empirical models, such as the Universal Soil Loss Equation (Zema et al., 2020). In addition to rainfall, soil and slope factors affecting erosion, the Modified Morgan, Morgan and Finney model (Morgan & Duzant, 2008) specifically enables the effects of

vegetation on runoff and erosion dynamics to be represented by measurable plant parameters. Input parameters to the model are shown in Table 4-1. The output parameters are annual total runoff (mm) and annual total soil loss (t ha^{-1}), as predicted by the model.

Table 4-1 Input parameters for the Modified Morgan, Morgan and Finney (mMMF) model (Morgan & Duzant, 2008).

Factor	Parameter	Definition	Source
Climate	R	Mean annual rainfall (mm)	Moroccan data
	R_n	Mean annual number of rain days	Moroccan data
	I	Typical intensity of erosive rain (mm h^{-1}). Use 10 for temperate climates, 25 for tropical climates and 30 for strongly seasonal climates (e.g. Mediterranean type or monsoon)	Model's guide
Soil	%c	Percentage clay	Textural analysis
	%z	Percentage silt	Textural analysis
	%s	Percentage sand	Textural analysis
	ST	Percentage rock fragments on the soil surface	-
	MS	Soil moisture content at field capacity (% w/w)	Measured
	BD	Bulk density of the top soil layer (Mg m^{-3})	Measured
	EHD	Effective hydrological depth of the soil (m)	Model's guide
Slope	RFR	Roughness of the soil surface (cm m^{-1})	-
	S	Slope steepness ($^\circ$)	Moroccan data
Vegetation	L	Slope length (m).	Model's guide
	PI	Permanent interception expressed as the proportion (between 0 and 1) of rainfall.	Model's guide
	E_t/E_0	Ratio of actual to potential evapotranspiration.	Model's guide
	CC	Canopy cover expressed as a proportion (between 0 and 1) of the soil surface protected by the vegetation or crop canopy.	Measured

Factor	Parameter	Definition	Source
	GC	Ground cover expressed as a proportion (between 0 and 1) of the soil surface protected by vegetation or crop cover on the ground.	Measured
	PH	Plant height (m), representing the effective height from which raindrops fall from the crop or vegetation cover to the soil surface.	Measured
	D	Mean diameter (m) of the individual plant elements (stems, leaves) at the ground surface.	Measured
	NV	Number of stems per unit area (number m ⁻²) at the ground surface.	Measured

Table 4-1 is divided into four categories, climate, soil, slope and vegetation. To evaluate the effect of different plant traits alone, the other input parameters were held constant for each model run. Regarding the climate parameters, a Mediterranean climate was simulated with a mean annual rainfall of 700 mm and 70 rain days per year. These values were chosen to reflect the climatic conditions observed in Morocco, particularly in regions prone to soil erosion by water such as the northern regions (Salhi et al., 2019). A typical erosive rain intensity of 30 mm h⁻¹ was considered for the mediterranean climate, as indicated in the model input guide. The soil texture parameter (i.e. % clay, silt and sand) is available from the textural analysis of the soil used in these experiments (i.e. 7.2% clay, 5.5% silt and 87.3% sand). The input parameters of 'rock fragments' (ST) and 'soil roughness on the soil surface' (RFR) are not applicable in the experimental soil. The input parameter of 'Soil moisture content at field capacity' (MS; w/w) and 'Bulk Density' (BD; Mg m⁻³) were measured as described in section 4.3.3.2.4. These parameters were measured at the two stages of plant growth. A guide value of the 'effective hydrological depth' (EHD; m) is given as 0.12 m (Morgan & Duzant, 2008). The model's slope parameters were identified as 6 degrees (slope steepness, S) and using the guide values from the model's parameters (slope length, L). The model's plant parameters were measured at the two stages of plant growth, as described in section 4.3.3.1, and E_i/E₀ ratio for wheat was

identified from guide values in the model. The model is based on mean annual figures.

It is important to appreciate that the model's operating functions are based on mean annual figures. Besides the annual values of the climate input parameters, the other input parameters measured at specific time points (1st and 2nd crop growth stages) are considered representative of mean annual figures. They align with the parameters' guideline values proposed by the model for wheat and loamy sand soil (e.g. canopy cover percentage and moisture content at field capacity).

According to Morgan and Duzant (2008), runoff occurs when the daily rainfall exceeds the soil moisture storage capacity of the soil (R_c ; mm). R_c depends on MS, BD, EHD and the E_t/E_0 ratio of the land cover and presented in Equation (4-2).

$$R_c = 1000MS \times B \times EHD \times \left(\frac{E_t}{E_0}\right)^{0.5} \quad (4-2)$$

The annual runoff is calculated using Equation (4-3).

$$Q = Rf \exp\left(-\frac{R_c}{R_0}\right) \left(\frac{L}{10}\right)^{0.1} \quad (4-3)$$

Where R_0 is the mean rain per rain days and equals to R/R_n , where R_n is the mean annual number of rain days. L is slope length (m) and the Rf , the effective rainfall (mm) is expressed in Equation (4-4) as:

$$Rf = R(1 - PI) \frac{1}{\cos S} \quad (4-4)$$

Where PI , the permanent interception by the vegetation cover, is a proportion between zero and unity. This parameter was identified from the model's input parameters. The effect of slope angle (S ; degrees) on the quantity of rain received per unit area was also considered.

The sediment phase involves three separate predictive equations. One equation calculates the rate at which soil particles are dislodged by the impact of raindrops

(rainsplash detachment rate). Another equation determines the rate of soil particle detachment caused by the surface runoff flow (runoff detachment rate). The third equation estimates the amount of sediment that can be carried by the overland flow (transport capacity of overland flow). The model evaluates two key factors that contribute to soil erosion - the amount of soil particles dislodged by rainsplash and surface runoff (detachment), and the quantity of sediment that can be transported by the runoff flow (transport capacity). It compares these two values and selects the lower one as the annual rate of soil loss. This approach identifies whether the detachment process or the transport capacity acts as the limiting factor in determining the overall soil loss from the area under consideration (Morgan, 2005). The details are described in Morgan & Duzant (2008).

4.3.5 Statistical analysis

The experimental design was a randomised complete block design (RCBD) with sixteen combinations of two wheat lines, two plant densities, two water regimes and two growth phases, in each block, plus the bare soil. Each treatment combination was replicated in triplicate. The statistical analyses were performed using the statistical software Genstat® (22nd Edition). The comparison between the treatments was achieved by analysing the data with a general analysis of variance (ANOVA). A pairwise comparison of the means was performed, where significant differences ($p\text{-value} < 0.05$) were observed, using post-hoc Fisher Least Significant Differences (LSDs) analysis at the 5% level of probability. To analyse the relationship between measured variables, regression analyses were conducted. The residual plots were assessed at each statistical analysis to ensure the homogeneity of variance and the assumption of Normality. In some cases, data transformation ensures that the assumptions needed for Analysis of Variance are met (i.e. that the residuals generally follow a normal distribution). For instance, the canopy and ground covers data needed to be transformed and expressed in square root (SQRT) before the analysis. The SQRT transformation in this case gave better residual plots than other transformations such as the LOG.

4.4 Results

4.4.1 Effect of wheat lines on plant traits and soil properties

4.4.1.1 Effect of wheat lines on plant traits

There was a significant difference between wheat lines in canopy cover ($p < 0.001$), and a significant interaction between wheat lines and growth stages ($p < 0.001$). At the second growth stage, the dwarf wheat generated significantly more canopy cover than the tall wheat regardless of the different sowing densities and the water regimes (Figure 4-1a). Similarly, the dwarf line had a higher ground cover than the tall wheat ($p = 0.003$) (Figure 4-1b), as expected, because the height of dwarf wheat was 21% shorter than the tall wheat and had a more prostrate growth habit than the tall wheat, therefore, more leaves touched the ground as the plant grew. The dwarf wheat had significantly more tillers per plant than the tall wheat ($p < 0.001$), with a difference of 28%. However, the fresh and dry aboveground biomass of the tall wheat were significantly higher than those of the dwarf wheat, especially under the well-watered treatment (Figure 4-1c and Figure 4-1d). This might be because of the significant difference in plant height between the two wheat lines which affected the weight of the biomass.

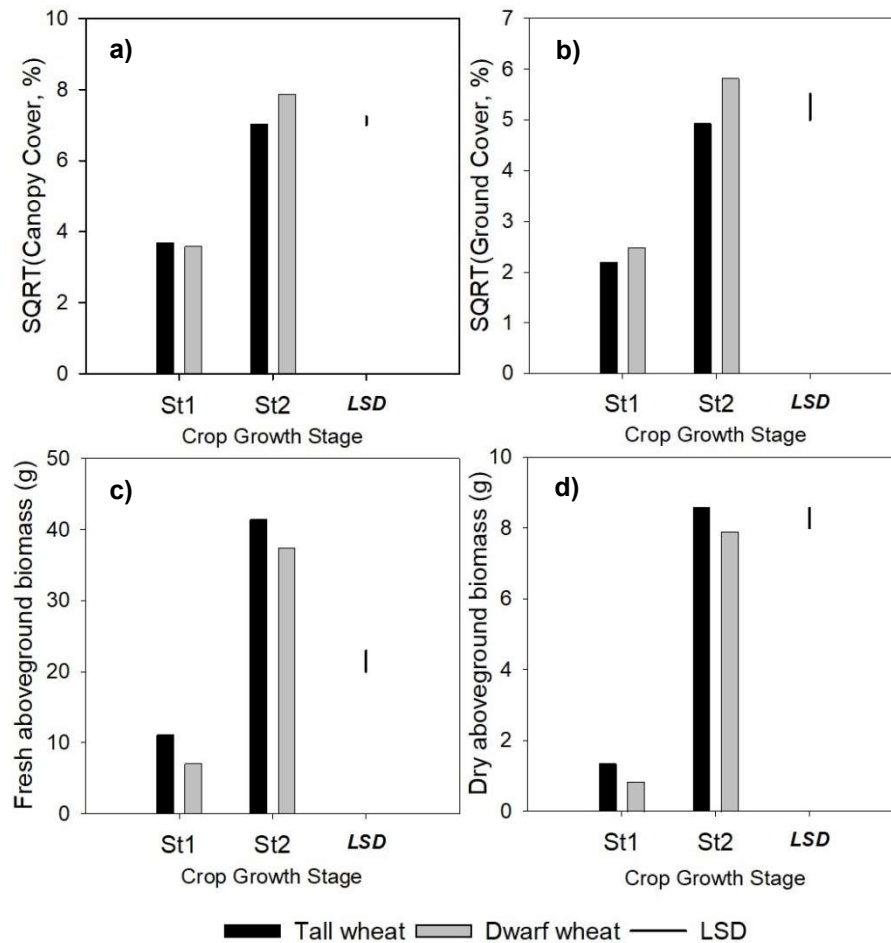


Figure 4-1 a) canopy cover, b) ground cover, c) fresh aboveground biomass, and d) dry aboveground biomass measured for both wheat lines: ‘Tall wheat’ and ‘Dwarf wheat’ at two growth stages ‘St1’ and ‘St2’. LSD bar used for a pairwise mean comparison.

Total root length density was higher for the dwarf wheat than for the tall wheat and this difference was significant when the root diameter was greater than 1.5 mm. ($p = 0.001$). This finding does not support Mawodza et al., (2023) who found that genotype does not affect root length density. These varying results might be attributed to differences in genetic backgrounds and/or the growing environment.

Data of all treatments at the second growth stage were pooled and regression analyses was undertaken to depict the effect of tillering on the canopy cover (Figure 4-2) and on the root length density (Figure 4-3). The regression models were statistically significant ($p < 0.001$). The correlation coefficients show a strong positive relationship between number of tillers and canopy cover ($r = 0.85$), and

between number of tillers and root length density ($r = 0.80$). This was expected, as each tiller would develop its own shoots and roots. So, increased number of tillers would increase canopy cover and root density.

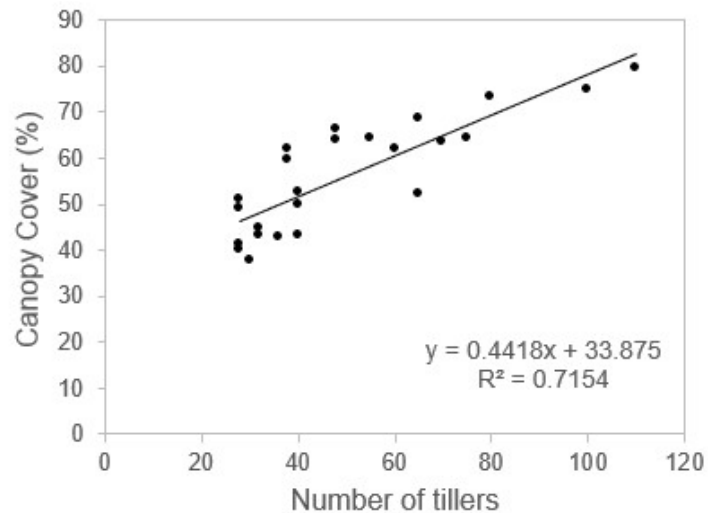


Figure 4-2 Relationship between the number of tillers and canopy cover. The data points represent individual values, while the regression line illustrates the best-fit linear relationship between the two variables.

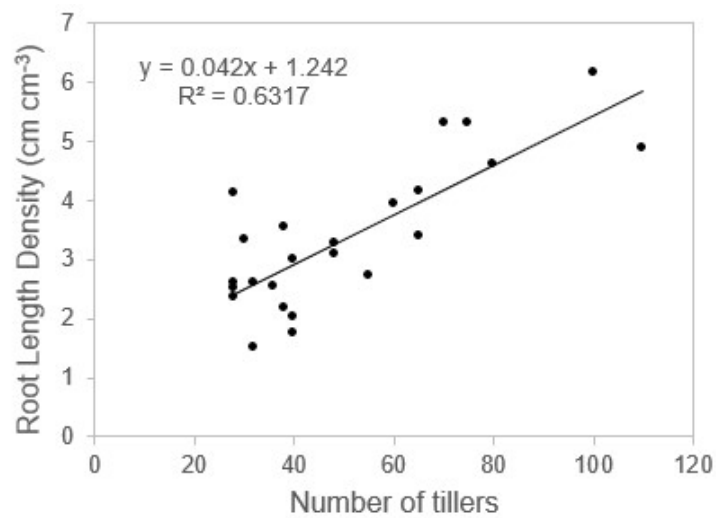


Figure 4-3 Relationship between the number of tillers and root length density. The data points represent individual values, while the regression line illustrates the best-fit linear relationship between the two variables.

4.4.1.2 Effect of wheat lines on soil properties

The results show that the hydraulic conductivity increased in planted soil (when pooling data of all treatments) compared to bare soil ($p = 0.005$) and the LSD shows that this difference was significant at the second stage of plant growth. Data of all treatments at the second growth stage were pooled and a regression analysis was done to depict the effect of root length density on hydraulic conductivity (Figure 4-4). The regression model was statistically significant ($p = 0.002$) indicating a significant relationship between the root length density and hydraulic conductivity. The correlation coefficient showed a strong positive relationship between the two variables ($r = 0.61$). Comparing the two wheat lines, there was no significant difference in hydraulic conductivity between them ($p = 0.76$) (Figure 4-5).

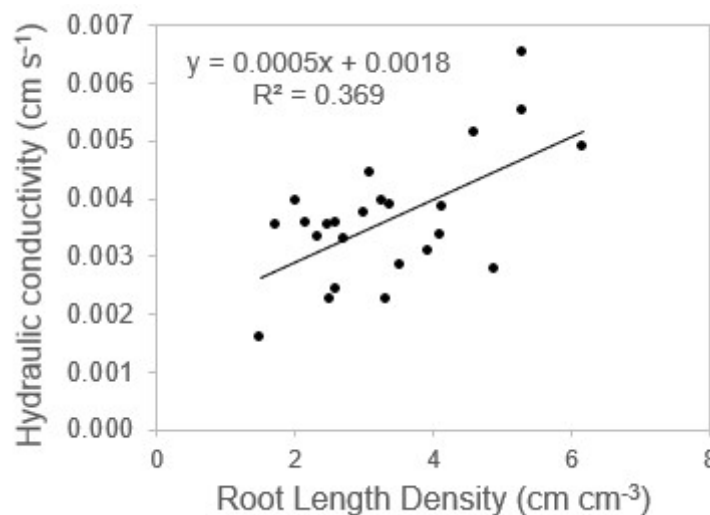


Figure 4-4 Relationship between root length density and hydraulic conductivity. The data points represent individual values, while the regression line illustrates the best-fit linear relationship between the two variables.

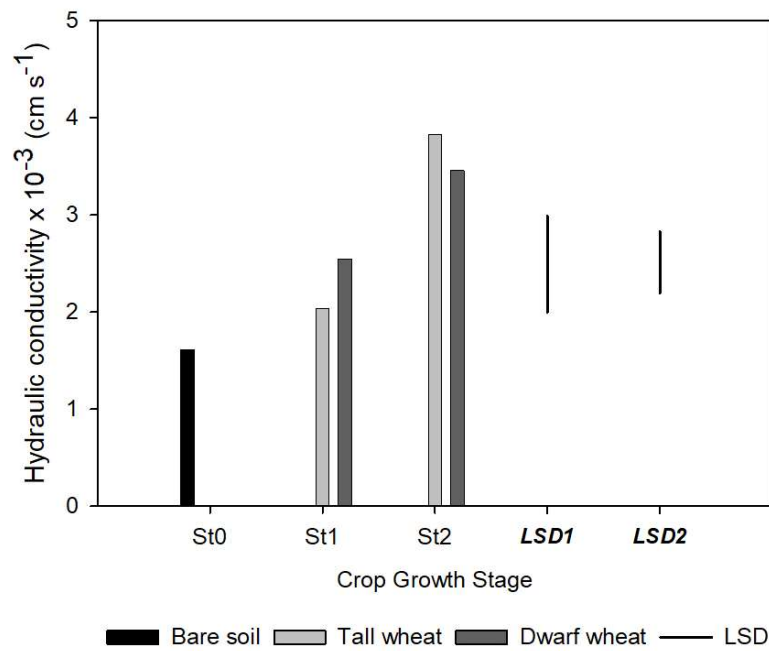


Figure 4-5 Hydraulic conductivity measured for a bare soil ‘St0’ and planted soil with two wheat lines: ‘Tall wheat’ and ‘Dwarf wheat’ and at two growth stages ‘St1’ and ‘St2’. LSD1 bar was used to compare between bare soil and any of the four means. LSD2 bar was used for a pairwise comparison between the four means.

The soil moisture content was significantly higher at the second stage of plant growth compared to the first growth stage, with $p = 0.011$, $p < 0.001$, $p = 0.002$ at the pressures -5, -10 and -33 kPa, respectively. There was no significant difference between treatments of the different factors, i.e. wheat lines, sowing densities, moisture regimes (drought vs well-watered). At field capacity, soil moisture content was significantly higher in planted soil compared to bare soil ($p = 0.013$) with mean values of 0.127, 0.163 and 0.197 g/g in bare soil, 1st growth stage and 2nd growth stage of plants, respectively. Figure 4-6 shows the soil water release curves for the first and the second growth stages of plant growth at pressures from -0.5 to -33 kPa. The Van Genuchten model's parameters were statistically analysed for growth stage 0 (bare soil), growth stage 1 and growth stage 2 (Table 4-2). The results show that the residual water content θ_r was significantly higher at the second growth stage. The n value was significantly higher at the first growth stage which resulted in a steeper slope of the soil

moisture retention curve and indicated a rapid release of water as matric potential decreases.

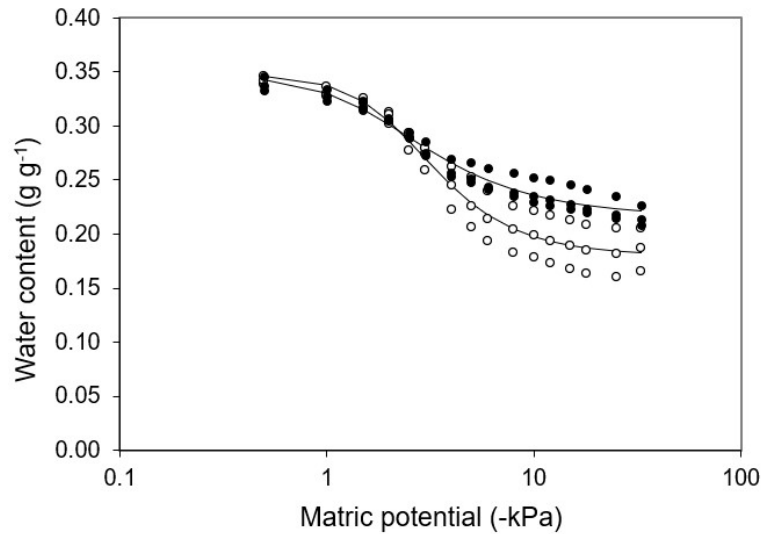


Figure 4-6 Water release curve measured on planted soil (data of different treatments pooled). The open circles represent the first growth stage, and the solid circles represent the second growth stage. The curves were obtained via the Van Genuchten equation.

Table 4-2 The Van Genuchten model's parameters (mean values) for growth stage 0 (bare soil), growth stage 1 and growth stage 2. Different letters (a, b) indicate significant differences between growth stages.

	θ_s	θ_r	α	n
Growth Stage 0	0.370 ^a	0.051 ^a	1.72 ^a	1.447 ^a
Growth Stage 1	0.348 ^a	0.180 ^{ab}	0.42 ^a	2.566 ^b
Growth Stage 2	0.352 ^a	0.213 ^b	0.67 ^a	2.059 ^{ab}

Soil cohesion in the presence of plants (when all data of planted soil are pooled) was significantly higher than that of a bare soil ($p < 0.001$) at both stages of crop growth and there is a significant difference between the first and the second crop stage. However, there was no significant difference in soil cohesion between wheat lines ($p = 0.876$) (Figure 4-7). Data of all treatments at the second growth stage were pooled and a regression analysis was undertaken to study the effect of root length density on soil cohesion. The statistical analysis indicates that there

was no significant relationship between the root length density and soil cohesion ($p = 0.98$), with a correlation coefficient of 0.0053.

Plants significantly decreased the bulk density compared to the bare soil ($p = 0.014$). Bulk density significantly decreased from bare soil to the first stage of plant growth, then increased from the first to the second stage of crop growth (LSD = 0.057). However, there was no significant difference between wheat lines in terms of bulk density ($p = 0.595$) (Figure 4-8).

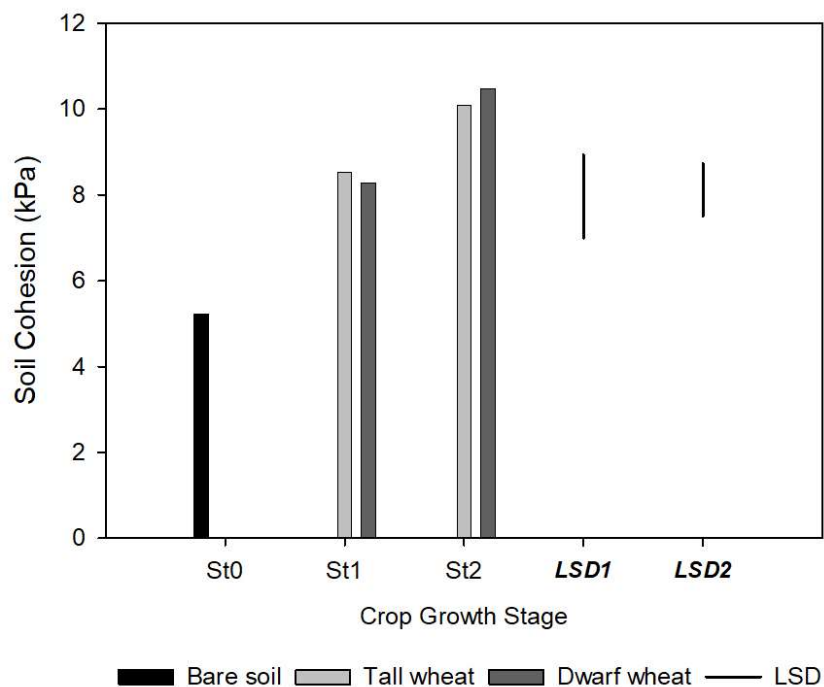


Figure 4-7 Soil cohesion measured for a bare soil 'St0' and planted soil with two wheat lines: 'Tall wheat' and 'Dwarf wheat' and at two growth stages 'St1' and 'St2'. LSD1 bar was used to compare between bare soil and any of the four means. LSD2 bar was used for a pairwise comparison between the four means.

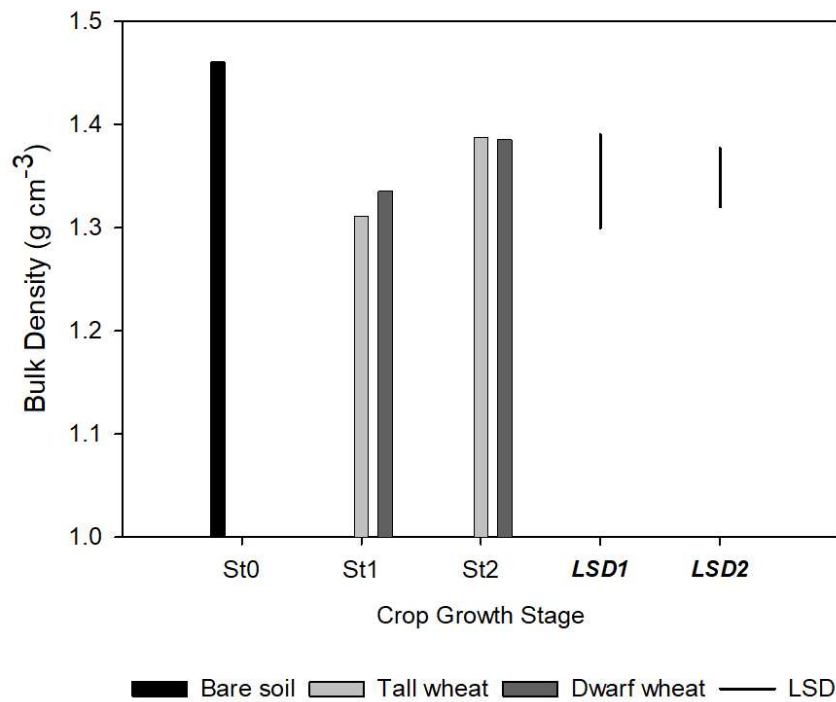


Figure 4-8 Bulk density measured for a bare soil ‘St0’ and planted soil with two wheat lines: ‘Tall wheat’ and ‘Dwarf wheat’ and at two growth stages ‘St1’ and ‘St2’. LSD1 bar was used to compare between bare soil and any of the four means. LSD2 bar was used for a pairwise comparison between the four means.

The ANOVA analysis shows that there was no significant difference in porosity (%) between the wheat lines ($p = 0.385$). The total number of pores and the average pore area (mm²) were also not significantly different between the wheat lines ($p = 0.26$; $p = 0.45$, respectively). Figure 4-9 shows an X-Ray CT scan example from one of the experimental samples, where pores, roots and soil are visible.

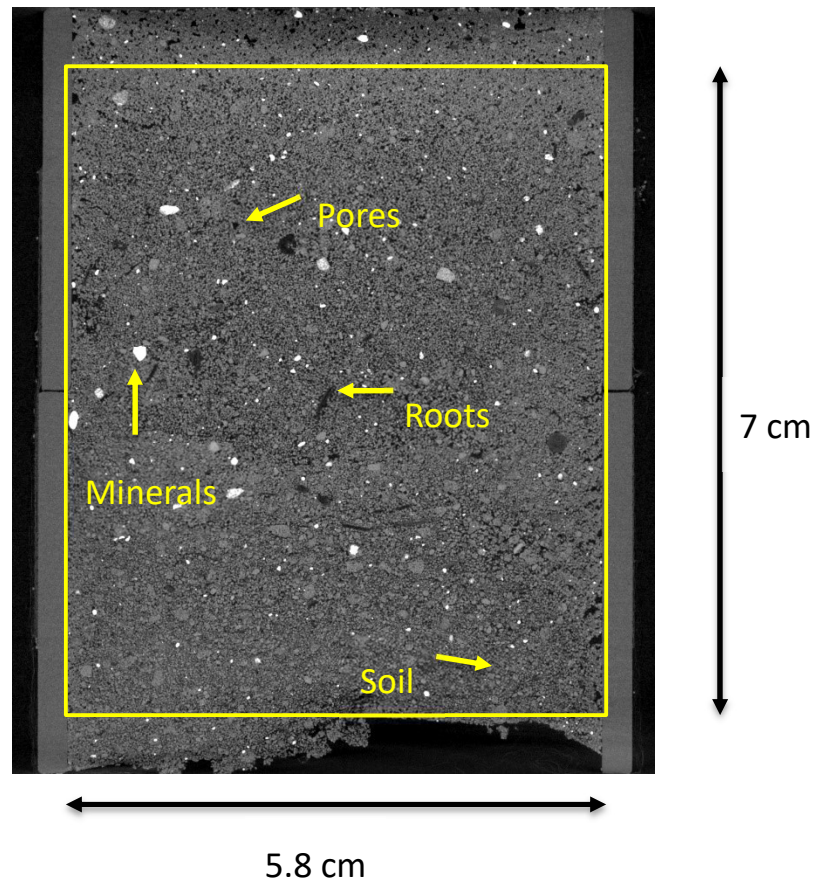


Figure 4-9 Example of an X-Ray CT scan of an experimental soil sample showing the different components in the soil (minerals in white, soil in grey, roots in dark grey and pores in black).

4.4.2 Effect of sowing densities on plant traits and soil properties

4.4.2.1 Effect of sowing density on plant traits

The higher sowing density significantly increased the canopy cover and the ground cover by 23% and 48%, respectively, compared to the lower sowing density (Figure 4-10a and Figure 4-10b). Increasing the sowing density significantly reduced the number of tillers per plant by 23% compared to the lower sowing density. But if the total number of tillers per column is considered, then this increased by 93% when the sowing density is higher. The increased canopy cover was positively affected by this increase in the total number of tillers. The higher sowing density significantly increased the fresh and dry aboveground biomass by 39% compared to the lower sowing density (Figure 4-10c and Figure 4-10d).

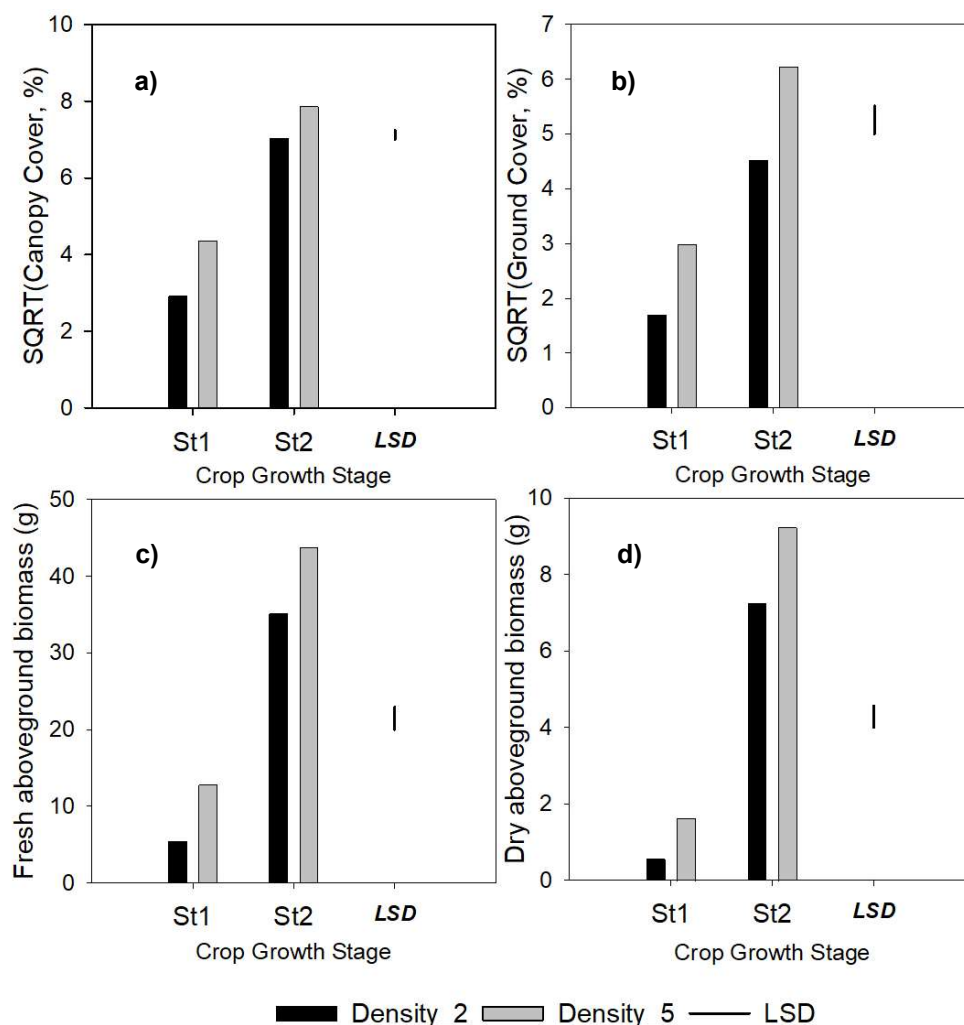


Figure 4-10 a) canopy cover, b) ground cover, c) fresh aboveground biomass, and d) dry aboveground biomass measured for both sowing densities: 2 plants per column ‘Density_2’, and 5 plants per column ‘Density_5’ at two stages of plant growth ‘St1’ and ‘St2’. LSD bar used for a pairwise mean comparison.

Increasing the sowing density from two to five plants per column resulted in a higher root length density for roots with diameters ranging from 0.05 to 0.7 mm. However, for roots with diameters greater than 0.7 mm, the higher sowing density resulted in a decreased root length density. This indicates that higher sowing density increases the proportion of fine roots compared to the lower sowing density, as evidenced by the significantly low average root diameter ($p < 0.001$).

4.4.2.2 Effect of sowing density on soil properties

There was no significant difference between sowing densities in hydraulic conductivity measured at the first stage of crop growth. However, at the second stage of plant growth, the hydraulic conductivity was 35% higher in the denser planted columns 'Density_5' than in the less dense planted columns 'Density_2' (Figure 4-11). The highest sowing density significantly increased soil cohesion compared to the lowest sowing density ($p = 0.04$) (Figure 4-12), especially at the second growth stage. At the higher sowing density, the bulk density significantly increased by 8% going from the first stage of plant growth to the second (Figure 4-13). At the second stage, the bulk density significantly increased by 6% under 'Density_5' ($LSD = 0.057$). The ANOVA analysis shows that the porosity was not significantly different between the two sowing densities ($p = 0.58$). The total number of pores and the average pore area (mm^2) were also not significantly different ($p = 0.88$; $p = 0.36$, respectively).

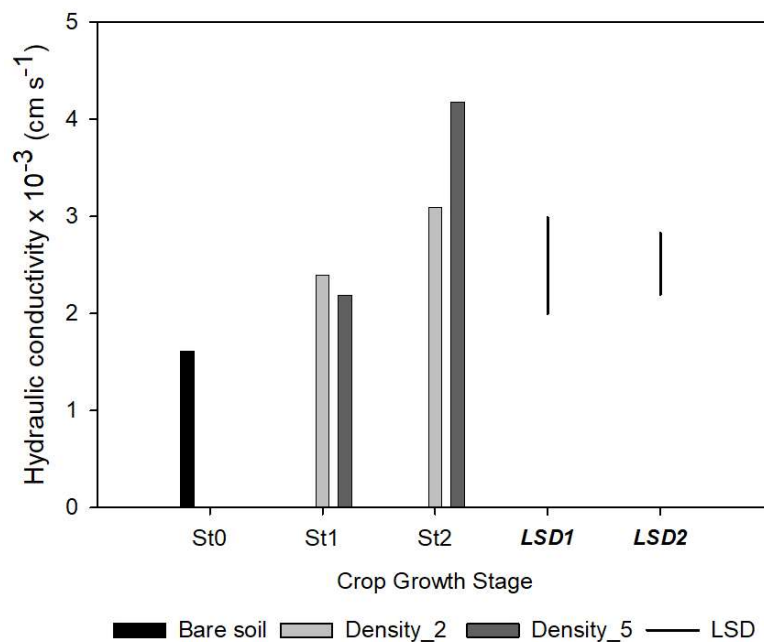


Figure 4-11 Hydraulic conductivity measured for a bare soil 'St0' and planted soil with two sowing densities: 2 plants per column 'Density_2', and 5 plants per column 'Density_5' and at two stages of plant growth 'St1' and 'St2'. LSD1 bar was used to compare between bare soil and any of the four means. LSD2 bar was used for a pairwise comparison between the four means.

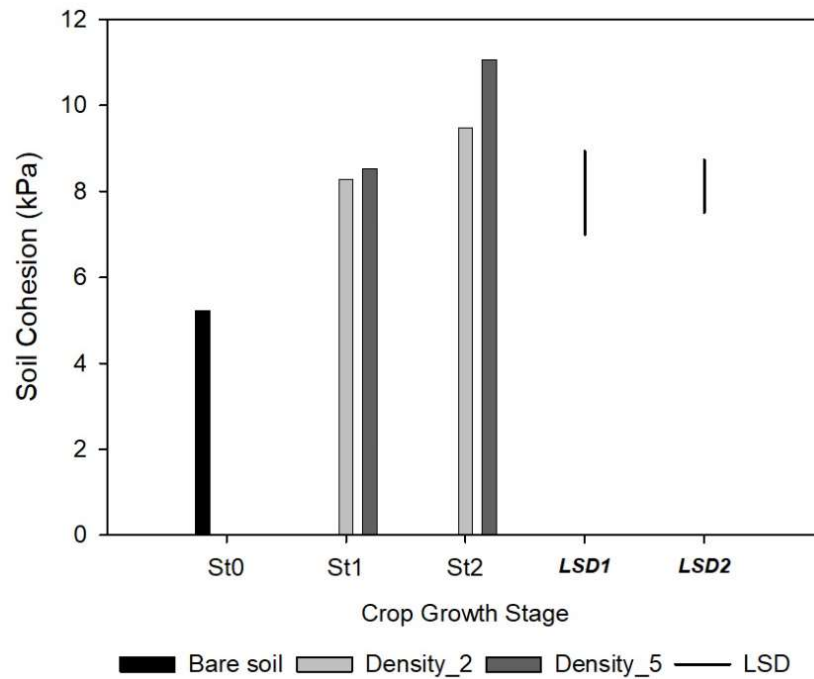


Figure 4-12 Soil cohesion measured for a bare soil ‘St0’ and planted soil with two sowing densities: 2 plants per column ‘Density_2’, and 5 plants per column ‘Density_5’ and at two stages of plant growth ‘St1’ and ‘St2’. LSD1 bar was used to compare between bare soil and any of the four means. LSD2 bar was used for a pairwise comparison between the four means.

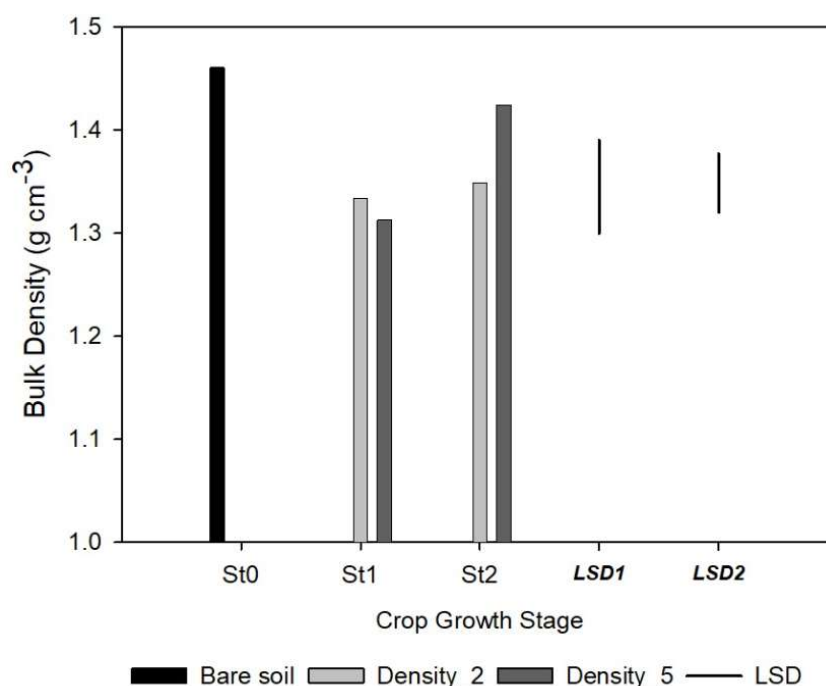


Figure 4-13 Bulk density measured for a bare soil ‘St0’ and planted soil with two sowing densities: 2 plants per column ‘Density_2’, and 5 plants per column ‘Density_5’ and at two stages of plant growth ‘St1’ and ‘St2’. LSD1 bar was used to compare between bare soil and any of the four means. LSD2 bar was used for a pairwise comparison between the four means.

4.4.3 Effect of drought on plant traits and soil properties

4.4.3.1 Effect of drought on plant traits

The lower moisture content treatments significantly reduced the canopy cover (Figure 4-14a) and the number of tillers by 11% and 30%, respectively, compared to the well-watered treatment. The fresh and dry aboveground biomass also significantly decreased under the drought treatment by 55% and 48%, respectively compared to the well-watered treatment (Figure 4-14b and Figure 4-14c). Plant height of the ‘tall’ wheat of Cadenza decreased under the drought condition by 13% compared to the well-watered condition (Figure 4-14d). However, for the ‘dwarf’ wheat, there was no difference in height between moisture regimes. Drought caused a reduced root length density compared to the well-watered treatment, with a decrease of 33%.

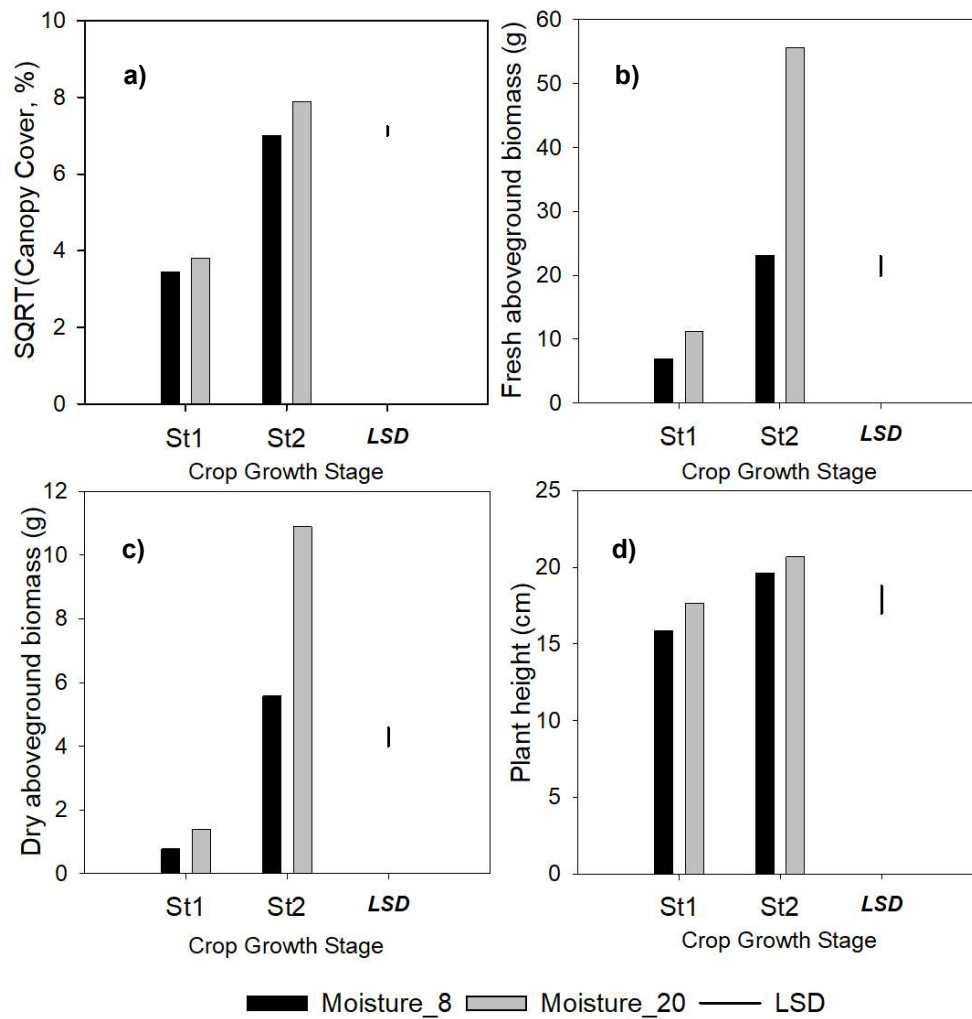


Figure 4-14 a) canopy cover, b) fresh aboveground biomass, c) dry aboveground biomass, and d) plant height measured for both moisture regimes: Drought treatment with a moisture content of 8% 'Moisture_8', and a well-watered treatment with a moisture content of 20% 'Moisture_20' at two stages of plant growth 'St1' and 'St2'. LSD bar used for a pairwise mean comparison.

4.4.3.2 Effect of drought on soil properties

There was no significant difference between moisture regimes in soil hydraulic conductivity at the first stage of crop growth (Figure 4-15). However, at the second stage of plant growth, the well-watered treatment 'Moisture_20' significantly increased the hydraulic conductivity by 37% compared to the drought treatment 'Moisture_8' (LSD = $0.627 \times 10^{-3} \text{ cm s}^{-1}$). Drought significantly increased soil cohesion by 19% compared to the well-watered treatment (Figure 4-16) ($p < 0.001$). According to Whalley et al. (2008), high soil strength and soil dryness

tend to occur together. There was no significant difference between the two moisture regimes in terms of bulk density ($p = 0.758$) and porosity ($p = 0.37$). The total number of pores and the average pore area (mm^2) were also not significantly different ($p = 0.36$; $p = 0.64$, respectively).

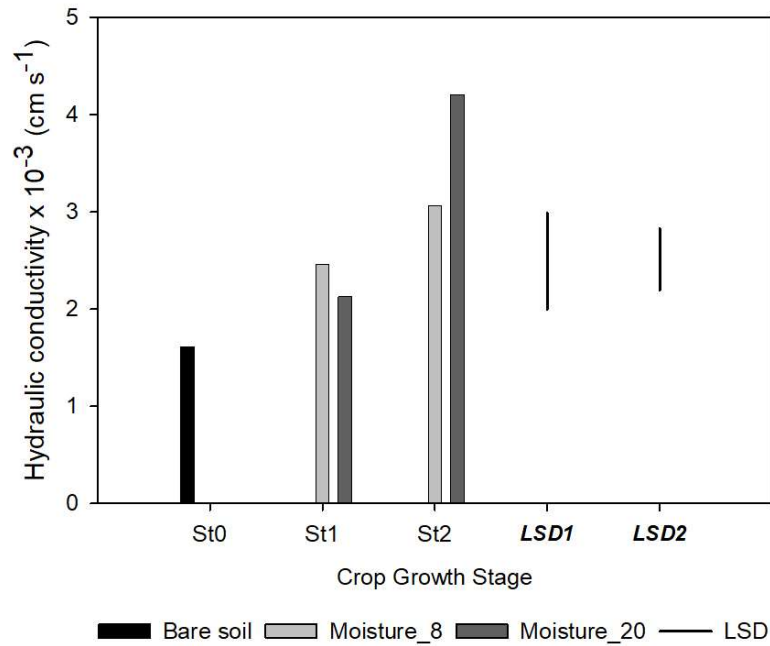


Figure 4-15 Hydraulic conductivity measured for a bare soil ‘St0’ and planted soil with two moisture regimes: Drought treatment with a moisture content of 8% ‘Moisture_8’, and a well-watered treatment with a moisture content of 20% ‘Moisture_20’ and at two stages of plant growth ‘St1’ and ‘St2’. LSD1 bar was used to compare between bare soil and any of the four means. LSD2 bar was used for a pairwise comparison between the four means.

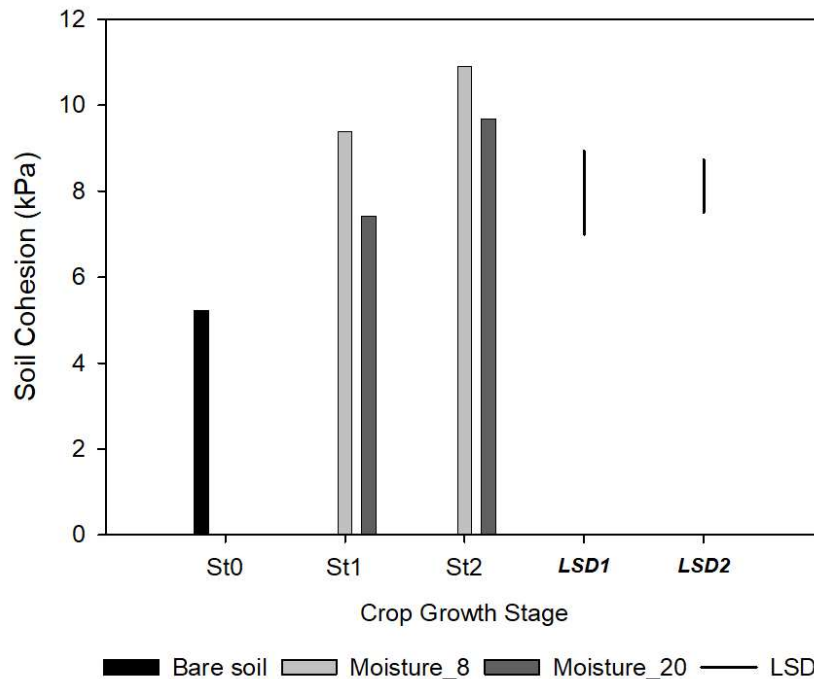


Figure 4-16 Soil cohesion measured for a bare soil ‘St0’ and planted soil with two moisture regimes: Drought treatment with a moisture content of 8% ‘Moisture_8’, and a well-watered treatment with a moisture content of 20% ‘Moisture_20’ and at two stages of plant growth ‘St1’ and ‘St2’. LSD1 bar was used to compare between bare soil and any of the four means. LSD2 bar was used for a pairwise comparison between the four means.

4.4.4 Effect of plant traits and soil properties on runoff and soil loss as predicted by the modified Morgan, Morgan & Finney model

4.4.4.1 Prediction of runoff

The total predicted annual runoff (mm) significantly decreased when plants were present in the soil ($p = 0.027$), going from 92.5 mm for bare soil to 57.6 mm when the soil was planted (when pooling data of all treatments). Figure 4-17 depicts the significant difference between both crop growth stages ($p < 0.001$). As the plants developed (i.e. from 1st growth stage to 2nd growth stage), predicted runoff volumes significantly decreased by 38%. However, the analyses show no significant differences in predicted surface runoff between wheat lines ($p = 0.594$), between sowing densities ($p = 0.383$) or between moisture regimes ($p = 0.867$). It was expected that predicted surface runoff would be reduced at a higher sowing density, but the results show no significant differences between the

sowing densities. This might be related to the fact that higher sowing density increased the soil bulk density with time through occupation of space by the roots. This would decrease the infiltration and increase the runoff. Therefore, the role of vegetation (i.e. higher sowing density) in reducing runoff was cancelled out.

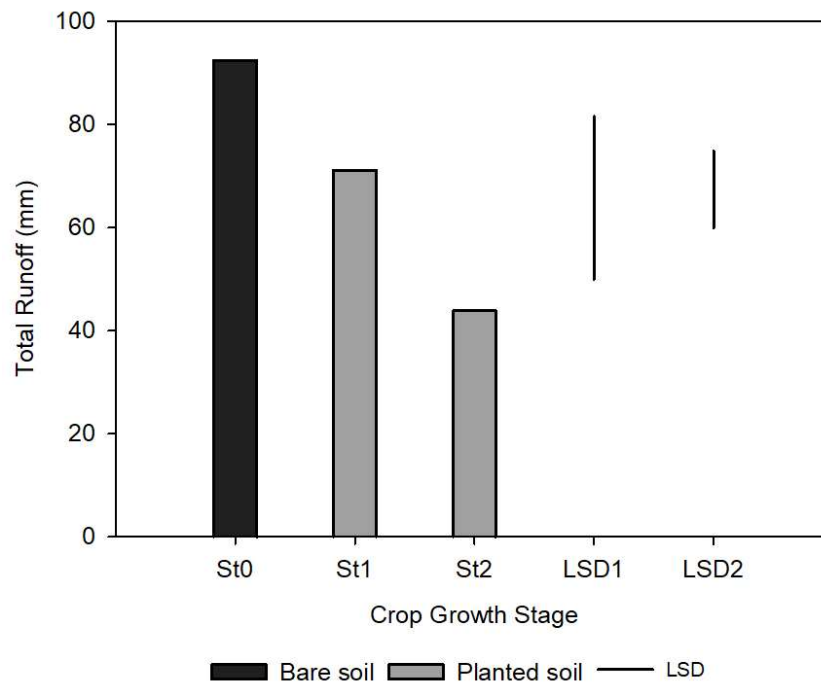


Figure 4-17 Total runoff predicted by the mMMF model at three crop growth stages: Bare soil 'St0', first stage 'St1' and second stage 'St2'. LSD1 bar was used to compare between bare soil and either of the two other means. LSD2 bar was used to compare between means of St1 and St2.

When soil is at field capacity, it means it can still absorb more water up to a certain limit before becoming saturated. So, as soil moisture content at field capacity increased, the maximum amount of water the soil can hold also increased. As a result, moisture storage capacity of the soil increased (Figure 4-18a), therefore, the predicted surface runoff decreased (Figure 4-18b). These significant relationships were picked up by regression models which were statistically significant ($p < 0.001$).

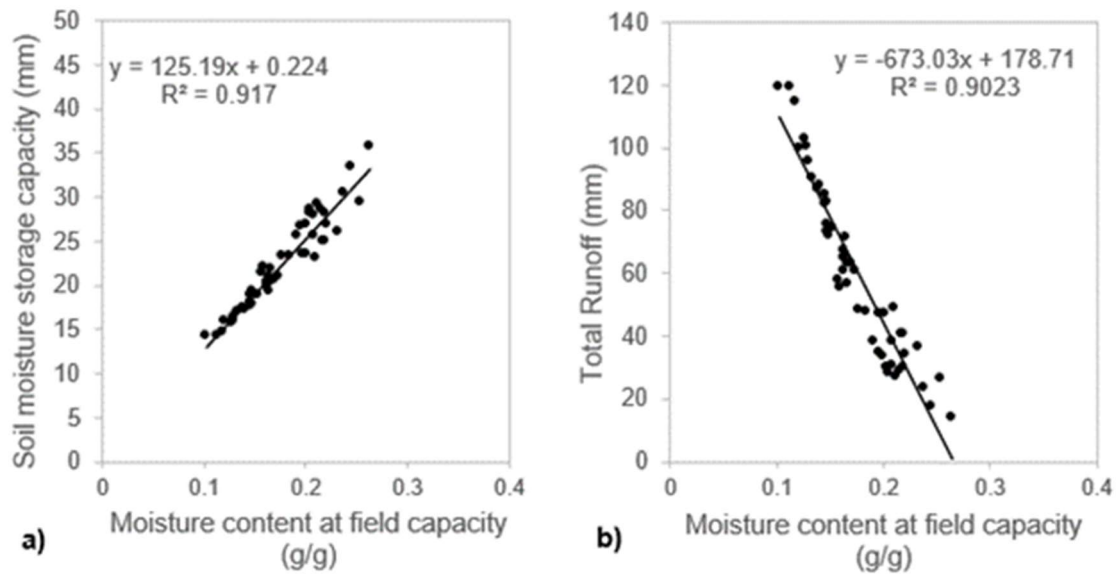


Figure 4-18 Effect of the soil moisture content at field capacity on a) soil moisture storage capacity and on b) predicted total runoff. The data points represent individual values, while the regression line illustrates the best-fit linear relationship between every two variables.

4.4.4.2 Prediction of soil loss

Plants at their first stage of growth significantly decreased predicted total soil loss by 20% compared to bare soil. The difference between both growth stages was significant ($p < 0.001$) and soil loss decreased by 62% going from the 1st to the 2nd growth stage.

The analysis indicate that there was a significant difference between the dwarf and tall wheat lines at the 2nd stage of plant growth, and the dwarf wheat significantly reduced soil loss by 25% compared to the tall wheat (Figure 4-19). This was due to the effect of wheat lines on plant traits where the dwarf wheat presented significantly more canopy cover, ground cover and root length density than the tall wheat in the 2nd growth stage.

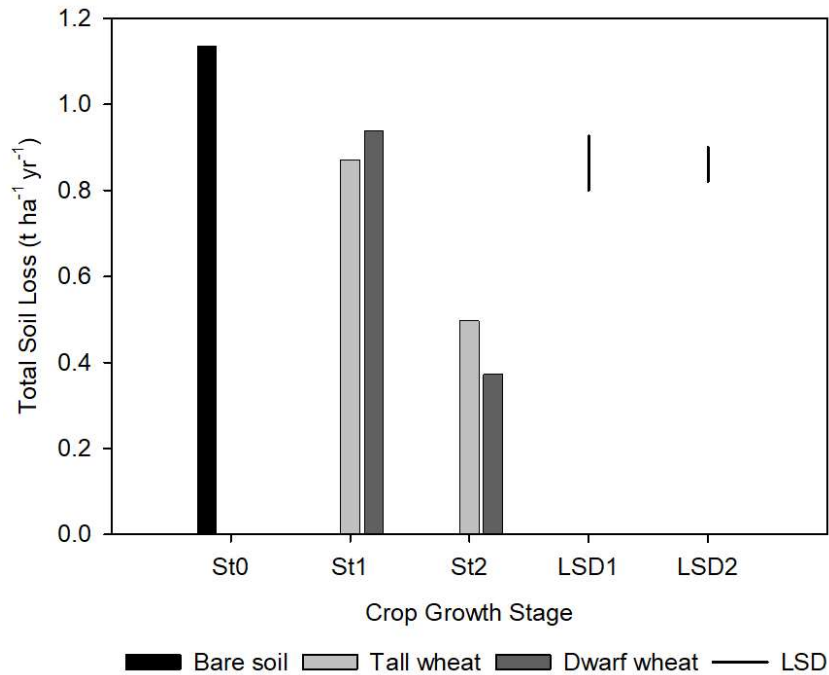


Figure 4-19 Total soil loss predicted by the mMMF model for a bare soil ‘St0’ and planted soil with two wheat lines: Tall cadenza wheat ‘Tall’, and dwarf Rht-B1c wheat ‘Dwarf’ and at two stages of plant growth ‘St1’ and ‘St2’. LSD1 bar was used to compare between bare soil and any of the four means. LSD2 bar was used for a pairwise comparison between the four means.

The results as presented in Figure 4-20 show that increasing the sowing density significantly reduced the soil loss at all stages of plant growth ($p < 0.001$). Soil loss decreased by up to 31% at the 2nd growth stage. This was expected, as increasing the sowing density has increased canopy cover, ground cover, aboveground biomass, soil cohesion and hydraulic conductivity, especially at the second growth stage.

There was a significant difference in predicted soil loss between the two moisture treatments ($p = 0.027$). The well-watered treatment reduced soil loss compared to the drought treatment. This decrease (of 23%) was significant at the 2nd stage of plant growth (Figure 4-21). This was due to the plant traits rather than the soil properties. Plant traits such as biomass, tillering, canopy cover and root length density were higher under the well-watered treatment than under the drought treatment.

The results indicate that the treatments with improved plant traits and soil properties, i.e. higher canopy cover, ground cover, soil cohesion and hydraulic conductivity significantly reduced soil loss as predicted by the erosion model. By pooling all data, the regression analyses confirmed the significant effect of these properties on predicted soil loss ($p < 0.001$). The correlation coefficients show strong negative relationships between the canopy cover and the predicted soil loss ($r = -0.95$) (Figure 4-22) and between the ground cover and the predicted soil loss ($r = -0.85$). Moderate negative relationships were found between soil cohesion and predicted soil loss ($r = -0.66$) and between hydraulic conductivity and predicted soil loss ($r = -0.62$). Root length density was also negatively correlated with soil loss as predicted by the mMMF.

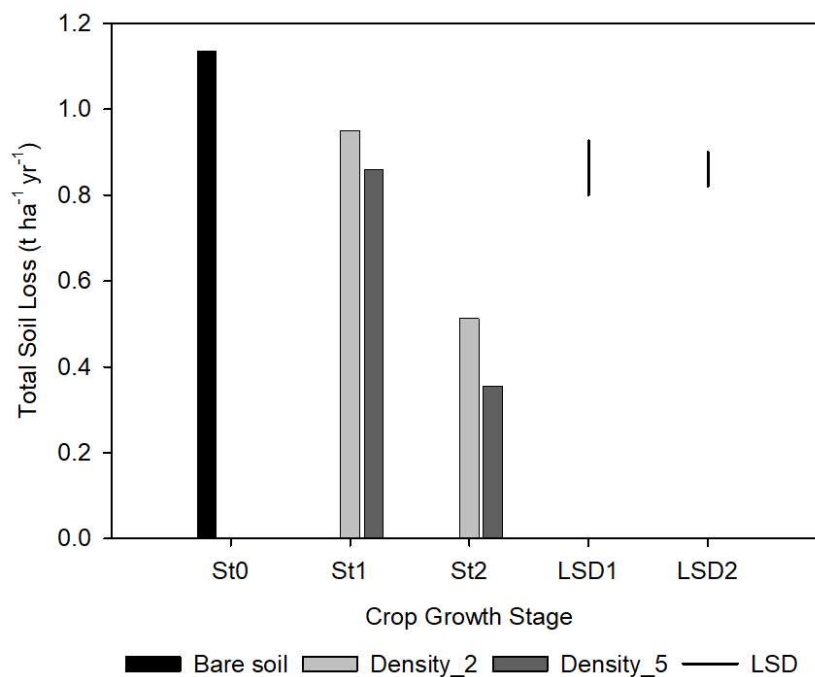


Figure 4-20 Total soil loss predicted by the mMMF model for a bare soil ‘St0’ and planted soil with two sowing densities: 2 plants per column ‘Density_2’, and 5 plants per column ‘Density_5’ and at two stages of plant growth ‘St1’ and ‘St2’. LSD1 bar was used to compare between bare soil and any of the four means. LSD2 bar was used for a pairwise comparison between the four means.

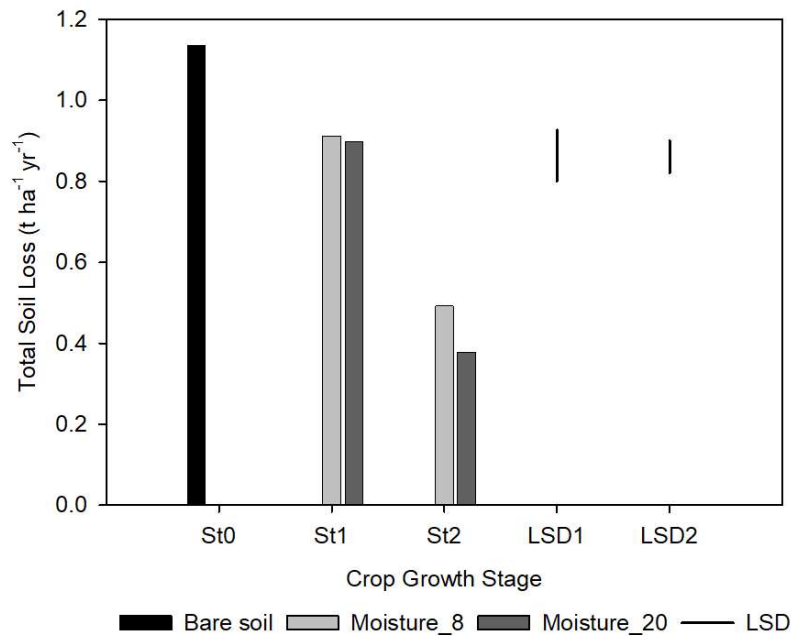


Figure 4-21 Total soil loss predicted by the mMMF model for a bare soil 'St0' and planted soil under two moisture regimes: Drought treatment with a moisture content of 8% 'Moisture_8', and a well-watered treatment with a moisture content of 20% 'Moisture_20' and at two stages of plant growth 'St1' and 'St2'. LSD1 bar was used to compare between bare soil and any of the four means. LSD2 bar was used for a pairwise comparison between the four means.

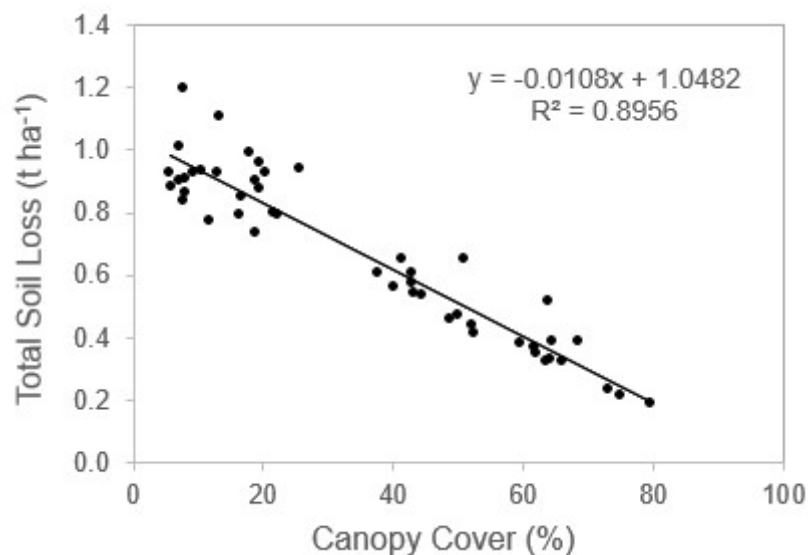


Figure 4-22 Relationship between the canopy cover and predicted soil loss. The data points represent individual values, while the regression line illustrates the best-fit linear relationship between the two variables.

4.5 Discussion

4.5.1 Effect of wheat lines, sowing densities and water regimes on plant traits and soil properties

The results show that the dwarf wheat line presented higher canopy cover, ground cover, tiller number, and root length density than the wild-type wheat. The observed differences between the tall and dwarf wheat lines in terms of plant traits highlight the influence of the genotypic variation on these properties. These variations were parameterised in the mMMF input parameters, leading to different predicted runoff and soil erosion rates, with the dwarf wheat line exhibiting better soil erosion control capabilities (i.e. lower predicted soil loss) than the tall wheat line, particularly at the second growth stage.

The results demonstrate that the higher sowing density significantly increased canopy cover and ground cover compared to the lower sowing density. However, the higher sowing density reduced the number of tillers per plant, though the total number of tillers per column increased, as also found in Szczepanek et al. (2022). The reduced number of tillers per plant at the higher sowing density can be explained by the increased competition between plants for nutrients, light and water (Casal et al., 1986; Tahir et al., 2019). Nevertheless, the total number of tillers per column significantly increased with increasing sowing density which suggests that the higher plant population was able to compensate for the reduced tillering at the individual plant level. At the higher sowing density, the root length density of finer roots with diameters ranging from 0.05 to 0.7 mm measured at the final crop growth stage was higher. This resulted in an improved soil structure over time witnessed by an increase in hydraulic conductivity which was significant at the second growth stage, resulting in reduced predicted surface runoff and soil loss. Higher root density as a result of higher sowing density also contributed to an increase in soil cohesion, significantly so at the second growth stage. This is likely due to the greater root biomass and associated soil binding effects. Although there were no significant differences between sowing densities in terms of soil porosity, root density could decrease soil porosity in the short term due to the physical occupation and compression of soil pores by roots. However, roots

could improve soil structure over time and increase the soil porosity due to roots decomposition in the long-term.

The results show that drought significantly reduced canopy cover, tiller number, plant height, aboveground biomass and the root length density of the wheat plants compared to the well-watered treatment. These reductions in plant growth and root development can be attributed to the limited availability of plant available water under drought conditions, which restricts plant physiological processes and resource allocation. This is consistent with numerous studies that have reported the negative impacts of drought stress on various growth parameters of wheat and other cereal crops (Colombi et al., 2018). Drought stress inhibits plant cell expansion and division, ultimately reducing leaf area, tiller production, and overall plant growth and development (Zahra et al., 2021). Also, drought conditions can impair the plant's ability to take up and translocate essential nutrients crucial for various physiological processes and biomass accumulation (Sallam et al., 2019). Fresh and dry biomass significantly decreased under drought stress, which aligns with the findings of Chen et al. (2021). The observed decrease in canopy cover and above-ground biomass will leave the soil vulnerable to erosive forces, as illustrated by the higher predicted soil loss observed under drought conditions. This supports the findings of Durán Zuazo & Rodríguez Pleguezuelo (2008).

The results indicate that the dwarf wheat plant (Rht-B1c) was able to maintain its height under drought conditions, unlike the taller wild-type Cadenza. This suggests that the dwarfing gene may confer some drought tolerance, which has been observed in other studies (Zhang et al., 2005). In addition to that, the dwarf wheat presented higher root density than the wild-type wheat under the dry condition at the higher sowing density. This suggests that this wheat line could enhance root growth over time, even under water-limited conditions.

The results show a strong positive correlation between tiller number and root length density, as each tiller would have developed its own roots. There was also a strong positive correlation between root length density and hydraulic conductivity. Roots can modify soil structure causing changes in water retention characteristics of the soil, leading to differences in water availability for plants

(Whalley et al., 2005). In well-watered conditions, roots play a key role in improving water availability, which supports plant growth and development. They absorb nutrients efficiently, promoting healthy growth and biomass accumulation through increased canopy cover, ground cover, plant height and number of tillers. These results underscore the importance of studying the interactions between aboveground and belowground plant traits and their effect on soil physical properties.

The soil water content exhibited significant differences between the first and second stages of plant growth with higher values found at the second growth stage. Such changes in soil water status can impact plant growth, as demonstrated by Whalley et al. (2008). The analysis of the soil water release curves and the van Genuchten model parameters provides further insights into the dynamics of soil water retention during the plant growth cycle. Accurate measurement of soil matric potential, as discussed by Whalley et al. (2013), is crucial for reliably determining these soil hydraulic properties. The residual water content (θ_r) and the pore-size distribution parameter (n) exhibited significant differences between growth stages. The residual water content represents the moisture content below which the soil can no longer supply water to plants. Its variation across growth stages could be attributed to changes in root density, distribution, and water extraction patterns (Vrugt et al., 2001). Similarly, the pore-size distribution parameter (n) governs the shape of the water retention curve and influences the soil's ability to release water (Ghanbarian-Alavijeh et al., 2010). The significant variation in n may be related to soil structural changes induced by root growth, microbial activity, and organic matter dynamics during plant development.

4.5.2 Effect of plant traits and soil properties on predicted runoff and soil erosion

The results clearly demonstrate the significant impact of plant traits on mitigating soil erosion processes. The presence of plants in the soil significantly reduced predicted total runoff and soil loss compared to bare soil conditions (Vannoppen et al., 2017). This finding aligns with previous studies that have highlighted the

crucial role of vegetation cover in protecting the soil surface from erosive forces (Durán Zuazo & Rodríguez Pleguezuelo, 2008). Notably, as the plants progressed from the first growth stage to the second growth stage, predicted runoff volumes and soil loss significantly decreased. The model accounts for increased plant cover and potentially root development through the increased effective hydrological depth over time, which will enhance soil protection and reinforcement (Arvidsson, 1998; Gyssels et al., 2005). Additionally, roots exude mucilaginous compounds that bind soil particles together, increasing soil cohesion and shear strength which can reduce the risk of soil erosion (Liang et al., 2017; B. Wang & Zhang, 2017). The correlations observed between predicted soil loss and the different plant traits and soil properties further underscores the importance of these parameters in controlling erosion processes.

Interestingly, while there were no significant differences in predicted surface runoff volume between wheat lines, sowing densities or moisture regimes, predicted soil losses did vary considerably depending on these experimental conditions. The differences between the tall and dwarf wheat lines in terms of predicted soil loss at different growth stages reflect the influence of genotypic variation on soil erosion control. At the second growth stage, the dwarf wheat line significantly reduced predicted soil loss compared to the tall wheat line, due to its higher canopy cover and ground cover which provided better soil protection. Higher sowing densities significantly reduced predicted soil loss compared to lower sowing densities at all growth stages. This can be attributed to the increased plant cover (at canopy and ground levels), stem density and root development associated with higher plant populations, which enhance soil aggregation, cohesion, and surface protection (Arvidsson, 1998; Colombi et al., 2018; Gyssels et al., 2005). The well-watered treatment reduced predicted soil loss compared to the drought treatment, particularly at the second plant growth stage. This was due to the plant traits rather than the soil properties. Plant traits such as biomass, tillering, canopy cover and root length density were higher under the well-watered treatment than under the drought treatment. This finding highlights the detrimental effects of drought stress on the development of a

protective vegetation cover, leading to increased erosion risks (Durán Zuazo & Rodríguez Pleguezuelo, 2008).

The findings of this study demonstrate that the interactions between aboveground and belowground plant traits, coupled with their influence on soil properties, collectively contribute to mitigating soil and water losses.

4.6 Conclusions

This study investigates the effects of plant growth stages, genotypic variations, management practices (sowing densities), and environmental conditions (drought) on plant traits (shoots and roots), soil properties, and ultimately soil erosion processes. The outcome of this study indicates that the presence of plants significantly reduced predicted total runoff and soil loss compared to bare soil conditions, underlining the pivotal role of vegetation in erosion control.

The results demonstrate that sowing density played a significant role in shaping plant traits and soil properties. While higher sowing density increased canopy cover and ground cover, it also reduced the number of tillers per plant due to intensified competition for resources. However, the total number of tillers per column increased with higher sowing density, suggesting compensatory mechanisms at the population level. Additionally, increased sowing density resulted in higher root length density of finer roots, improving soil structure and cohesion, thus reducing predicted soil loss.

This study shows that drought stress had detrimental effects on plant growth, significantly reducing canopy cover, tiller number, plant height, aboveground biomass, and root length density compared to well-watered conditions. Consequently, drought led to increased predicted soil erosion risks, while well-watered treatments provided better soil protection and reduced soil loss, particularly at later growth stages. This highlights the critical role of adequate water supply for plant growth and soil protection.

Genotypic variations played a crucial role, with the dwarf wheat line (Rht-B1c) exhibiting better drought tolerance than the taller wild-type Cadenza. The dwarf wheat maintained its height under water-limited conditions and demonstrated

higher root density, especially at higher sowing densities and under dry conditions. It also exhibited superior erosion control capabilities (as parameterised in the mMMF) compared to the wild-type wheat line, particularly at later growth stages, due to its higher canopy cover, ground cover, and root development, providing better soil protection. This underscores the importance of genetic traits in mitigating erosion risks.

Strong positive correlations were observed between tiller number, root length density, and hydraulic conductivity, highlighting the importance of studying aboveground and belowground plant traits and their effects on soil physical properties. Negative correlations between predicted soil loss and plant traits and soil properties further emphasize the crucial role of these factors in controlling soil erosion.

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5 Discussion

The aim of this research was to better understand the processes of soil erosion by water and wind under different tillage and agronomic measures, with a view to reduce soil and water losses, particularly in erosion-prone regions like Morocco. To achieve this aim, novel methodological approaches were developed to simulate soil surface conditions and hydrological processes, considering representative conditions in Morocco. This chapter synthesises the main findings of this research, emphasising the contribution to knowledge and proposing areas of research for future work.

5.1 Soil erosion mitigation and implications for soil conservation

5.1.1 Across-slope oriented roughness

In Chapter 2, different SSR conditions were simulated. The across-slope oriented roughness gave two contrasting results, higher and lower runoff and soil loss compared with up- and downslope oriented roughness and the smooth surface. While contour cultivation (or across-slope oriented roughness) is widely viewed as an effective technique for conserving soil and water (da Rocha Junior et al., 2018), its benefits diminish substantially on slopes steeper than 10% (Alvarez-Mozos et al., 2011; USDA, 2017). The reason is that on such inclines, runoff can concentrate in topographic lows along the cultivation ridges. This accumulated water can eventually overtop and breach the ridges, leading to increased erosion risk (Morgan, 1992). Quinton et al. (2004) recommended evaluating contour cultivation techniques in fields with varying slope configurations. They explained that on complex and multidirectional terrain, where maintaining precise contours is challenging, water can accumulate in depressions and eventually breach ridges, generating concentrated flows that erode soil due to their velocity and KE. This issue relates to how a slope's steepness impacts its surface storage capacity for water. As illustrated in Figure 5-1, the steeper the slope gradient, the lower its ability to retain surface water before runoff commences (Zhao et al., 2021). While da Rocha Junior et al. (2016) found that across-slope oriented roughness reduced runoff under light rainfall (50.8 mm hr^{-1}), it increased runoff when rainfall

was heavier (114.3 mm hr^{-1}). The researchers attributed this to the higher intensity rain potentially breaching the tilled ridges due to its greater KE.



Figure 5-1 Surface storage capacity behind contour features on a gentle slope (a) and on a steep slope (b). Stored water illustrated in blue

The effectiveness of contour tillage at controlling runoff and soil loss can be diminished by high rainfall intensity and/or steep slope gradients. In the study presented in Chapter 2, a rainfall intensity of 90 mm hr^{-1} was simulated, a value which is between the low and the high intensity values used by da Rocha Junior et al. (2016). A slope gradient of 10% was also simulated - the maximum grade where contour tillage is expected to provide adequate control (USDA, 2017). These findings point to unclear conclusions about the capability of across-slope oriented roughness in mitigating runoff and erosion under varying rainfall and topography conditions. Additional research simulating a range of intensities and slopes is recommended to better understand the limits of these conservation methods.

5.1.2 Mounds and depressions

The spatial structure of surface microrelief significantly affects sediment transportability (Wu et al., 2016). Experimental results in Chapter 3 indicated that mounds and depressions on a rough surface (RS) delayed runoff generation and reduced both runoff and soil loss compared to a smooth surface (SS). This is because during rainfall events the depressions on RS retained water and mounds acted as a physical barrier to the downslope movement of the water, increasing infiltration and delaying runoff. This aligns with the findings of Zhao et al. (2019, 2021). The soil loss also decreased in relation to the reduction in runoff volume. This soil surface roughness resembles reservoir tillage, a soil and water conservation practice used in some countries (Zhao et al., 2021).

In addition to that, the findings of this research (Chapter 3) suggest that maintaining a rough soil surface can mitigate the adverse effects of wind-driven rain (WDR) at lower wind velocities (6 m s^{-1}). This is because the mounds and depressions reduced the wind velocity and interrupted the wind-driven water flow, hence decreasing the velocity of surface runoff. However, at higher wind velocities (10 m s^{-1}), this mitigation effect of the RS was cancelled out, suggesting that additional in-field measures may be necessary to protect the soil from erosion risks. The findings from this research have practical implications for soil conservation. For example, adopting soil surface roughness management techniques, such as reservoir tillage, can be a valuable approach to reduce soil and water losses, especially in erosion-prone areas with heavy rainfall with moderate wind exposure. Nevertheless, it is important to note that the effectiveness of SSR in mitigating soil erosion and runoff is influenced by various factors that should be considered, such as slope gradient, rainfall intensity and wind velocities. Furthermore, the spatial scale at which surface roughness is measured and evaluated can also play a role in determining its impact on erosion processes. At smaller scales, dominant erosion processes such as splash detachment, transport and deposition (Morgan, 2005) take place. However, while roughness may be effective at smaller spatial scales, its influence on erosion control at larger scales should be studied, where other factors, such as topography (slope gradient) and vegetation cover, become more dominant.

5.1.3 Vegetation and soil properties

Findings presented in Chapter 4 demonstrated that vegetation, both aboveground (shoots) and belowground (roots) mitigate soil erosion processes as predicted by the mMMF model. As plants progressed through growth stages, and at a higher sowing density, the increased plant cover and root development gave enhanced soil protection and reduced erodibility, as demonstrated by significantly lower runoff volumes and soil loss according to the mMMF model predictions. These results are consistent with previous research emphasising the vital role of vegetation in soil protection against erosion (Durán Zuazo & Rodríguez Pleguezuelo, 2008). The roots facilitated water infiltration, reducing surface runoff and associated soil losses. Whalley et al. (2005) reported that root

systems have the ability to alter soil structure, resulting in changes to the soil's water retention properties, which consequently affects the availability of water for plant uptake.

The findings of this research also demonstrate that the dwarf wheat genotype (Rht-B1c) presented higher root length density and higher canopy cover, ground cover and number of tillers compared to the wild-type wheat. In addition to that, this wheat line was able to maintain its height under drought conditions, unlike the wild-type that experienced a reduced plant height when subjected to water-limited conditions, suggesting that the dwarfing gene may confer some drought tolerance. This confirms findings in other studies (Zhang et al., 2005). These variations, when included in the mMMF model input parameters, exhibited superior erosion control capabilities of the dwarf wheat compared to the wild-type wheat, explained by the lower predicted soil loss, particularly under higher sowing densities and advanced growth stages. This demonstrates an opportunity to use genetic traits for effective soil conservation.

Recent work by Hudek et al. (2022) has highlighted the potential of root traits and cover crops in improving soil physical properties. However, further research is needed to expand this approach to a broader range of plant species and genotypes to identify those with optimal aboveground and belowground traits for soil conservation purposes. This could involve screening and selecting plant varieties with extensive root systems, dense canopy cover, and favourable biomass production, as well as evaluating their performance under different environmental conditions and management practices.

5.2 Increased rainfall erosivity due to wind

One of the key findings from this research is the significant impact of wind-driven rain (WDR) on accelerating runoff generation and increasing soil loss compared to windless rain (WLR). Results from Chapter 3 demonstrate that this is particularly evident under higher wind velocities, where the rainfall erosivity is amplified by the wind, leading to greater detachment and transport of soil particles. The altered trajectory and increased inclination of raindrops due to wind resulted in increased velocity and KE of raindrops, enhancing their erosive

potential to detach and transport soil particles. These findings align with previous research demonstrating higher soil losses under wind-driven rain conditions for a range of wind velocities (Erpul et al., 2009, 2013), rainfall intensities (Arshad et al., 2019; Mahmoodabadi et al., 2021), slope gradients (Erpul et al., 2002, 2003) and soil types (Mahmoodabadi et al., 2021; Marzen et al., 2017).

5.3 Soil Surface Roughness dynamics

This research also highlighted the dynamic nature of SSR and its evolution in response to rainfall and wind conditions. The findings in Chapter 2 and Chapter 3 show that SSR is not a static property but evolves in response to rainfall and wind velocities. Windless rain and WDR can both increase and decrease SSR, depending on the initial surface conditions. For initially smooth surfaces, the impact of raindrops dislodges, transports and redeposits soil particles, creating a microrelief at the soil surface, resulting in an increase in SSR (Figure 5-2). However, for initially rough surfaces, rainfall causes a decrease in SSR. This decrease can be attributed to the detachment of soil particles from the mounds and ridges present on the rough surfaces. These dislodged particles were subsequently transported and deposited in the lower-lying depressions and furrows. Wind-driven rain exacerbated these changes in SSR. Consequently, these processes collectively contribute to an accelerated alteration in soil surface roughness (SSR) during wind-driven rainfall events compared to situations without wind. The combined effects of enhanced raindrop and runoff erosivity facilitated by wind result in more rapid modifications of the soil surface microtopography.

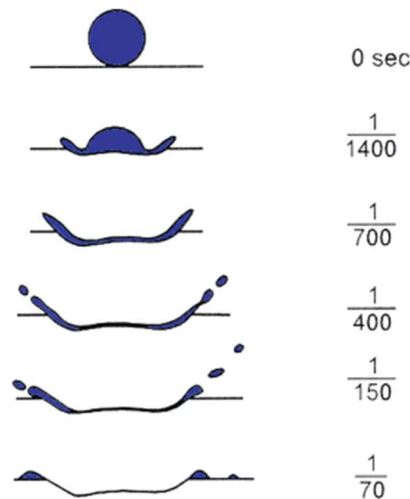


Figure 5-2 Impact of a raindrop splash at different timing (fraction of a second) leading to deformation of an erodible soil surface. Source: Environmental Soil Physics, (Hillel, 1998).

5.4 Soil erosion in the context of climate change

Climate change is projected to bring about changes in precipitation patterns, including an increase in the frequency and intensity of extreme rainfall events interspersed with longer dry periods, as well as shifts in wind patterns and velocities. These changes can have profound implications for soil erosion processes and the effectiveness of soil conservation measures, particularly in regions with sparse vegetation cover and susceptible soil types.

5.4.1 Rainfall, wind and SSR patterns

The outcome from Chapter 2 and 3 showed that rainfall and wind-driven rainfall significantly changed the initial SSR. Furthermore, wind increased the rainfall erosivity, leading to greater soil and water losses compared to WLR conditions. As climate change intensifies, the likelihood of experiencing more frequent and intense rainfall events, coupled with stronger wind conditions, may increase the occurrence of WDR events (Bourcet et al., 2023). This could exacerbate soil erosion rates, particularly in areas prone to high winds during rainfall. With more intense wind-driven rainfall events in the context of climate change, the changes in SSR may be amplified, potentially altering the effectiveness of soil erosion

control measures that rely on maintaining specific SSR orientations or magnitudes.

5.4.2 Drought and Vegetation

The findings from Chapter 4 show that drought significantly impaired plant growth, reducing canopy cover, tillering, plant height, biomass, and root length density, leading to increased predicted erosion risks. Well-watered conditions promoted plant growth and soil protection, which gave rise to predictions of lower runoff and soil erosion rates. These results align with projections that climate change is expected to increase the frequency and intensity of droughts in many regions, posing significant threats to soil health and erosion control (Dai, 2013). Dai (2013) projected that droughts will intensify over the years in most land areas due to decreased precipitation and increased evapotranspiration driven by global warming. This is particularly relevant for Morocco, where climate projections indicate a significant decrease in annual precipitation of 10-20% by 2050, with more frequent and severe drought events expected across the country's agricultural regions (Schilling et al., 2012). Climate change-induced droughts and shifts in precipitation patterns may adversely affect vegetation growth and soil health properties, reducing the effectiveness of these in controlling soil erosion control.

5.5 Critical evaluation of methodologies

5.5.1 Rainfall erosivity

Rainfall erosivity describes the potential of rainfall to detach and transport soil particles. It is quantified by calculating the rainfall KE, which is determined by the mass and velocity of the raindrops. The laser optical disdrometer (LOD), also known as the parsivel disdrometer, has been widely used to measure these rainfall characteristics (Johannsen et al., 2020; Zapata et al., 2018, 2021). However, the method has certain shortcomings. The LOD measures the fall velocity of raindrops, which is a combination of the terminal fall speed and vertical air motion. Consequently, strong winds can alter the distribution of drop sizes and fall velocities. Therefore, the Parsivel is particularly prone to measurement errors

in the presence of strong winds and turbulence, potentially leading to discrepancies (Kim & Song, 2018). Friedrich et al. (2013) examined how strong winds affect the particle size distributions measured by Parsivel disdrometers, and observed that particles not falling perpendicularly to the sampling area at high wind velocities can lead to misclassification of the particle sizes. For these reasons, some studies (Tilg et al., 2020) found that rainfall KE calculated from the vertical fall speed of raindrops decreased significantly with increasing wind velocities, which is not expected. These authors explain that the measurement approach neglects the horizontal component added by wind, leading to increasing uncertainty and an underestimation of the overall KE as wind speeds rise. In the experiments reported in Chapter 2, the use of the LOD was suitable, as the rainfall events were windless. In the experiments reported in Chapter 3, the LOD wouldn't be ideal for wind-driven rain conditions. Measuring the KE of WLR and WDR was crucial to understand the rainfall erosivity dynamics. Therefore, another method was used to measure the raindrop characteristics which is adapted to windy conditions. The method includes using a laser diffraction (Oxford Laser Visisizer N60) that also measures the raindrop impact angle, essential for the calculation of the resultant velocity and KE of the WDR. Using the appropriate device, it was found in this study that wind increases the rainfall KE, hence the rainfall erosivity, leading to more erosion. The findings align with those of Erpul et al. (2003, 2005, 2008, 2009). However, Tilg et al. (2020) highlighted that high KE does not necessarily cause more soil erosion. Factors such as the impact angle, the drop shape, and the soil type play an important role in the drop impact and, consequently, in the erosion process.

5.5.2 Soil surface roughness

One of the methods widely used to quantify SSR is the chain method proposed by Saleh (1993) and Morgan et al. (1993) (Equation (C-1) and Equation (C-2) in Appendix C.2). This method has been used by several authors (Hösl & Strauss, 2016; Idowu et al., 2001, 2002; Morgan et al., 1998; Thomsen et al., 2015; Zhao et al., 2014). Analysis on the equation proposed by Saleh (1993) undertaken in the current study suggests that its parameters are suitable in the field where the whole chain length could be considered on a large area of the ground, but its use

is limited in the laboratory using erosion trays which have a smaller area compared to a field, especially when simulating roughness at different orientations (Chapter 2). One of the objectives of Chapter 2 was to assess the changes in SSR due to the rainfall events. To achieve this, measuring the SSR should be done before and after the rainfall event. Analysis on the equation proposed by Morgan et al. (1993) is that the denominator in Equation 2 should be the same value in both measurements before and after the rainfall event, for a fair comparison between initial and final SSR. Therefore, for the experiments of this research, a slight modification to the equation proposed by Morgan et al. (1993) was made so that the denominator is the straight-line distance between the two points (X), as presented in Equation (C-3) of appendix C.2.

The limitation of the chain method is that it does not cover the whole surface area of the tested soil. Therefore, a 3D method to quantify the soil surface roughness was used to overcome this shortcoming. It is a laser scanner (Creaform EXAScan 3D Handscanner) and an integrated 3D scanning software, XVelements. The 3D soil surface areas were computed to obtain a calculated surface area using Geomagic Studio® software. This was done before and after each WLR and WDR event and a ratio was calculated to obtain the soil surface roughness (%). The results obtained aligned with those of the chain method which were also represented as a ratio (%). However, the laser scanning method could be further developed by analysing the Digital Elevation Models (DEMs), extracting several valuable metrics. These include changes in surface elevation to quantify soil loss or deposition across the different roughness types, rill network development, and flow path analysis, which can help understand how water moves across both smooth and rough surfaces. Furthermore, the data could be used to calculate the storage capacity for each roughness type, improving the assessment of how topography influences erosion patterns. Ultimately, integrating DEM data into hydrological and erosion models could enhance simulations of water flow and erosion dynamics, providing a comprehensive understanding of soil erosion processes across varied surface conditions.

5.5.3 Soil erosion modelling

In the study presented in Chapter 4, different wheat lines, sowing densities, water regime and plant growth stages were simulated to study their effect on different plants traits and soil properties. For practical reasons, direct soil erosion measurement was not possible to conduct. Therefore, the modified Morgan-Morgan-Finney (mMMF) model was employed to predict runoff and soil loss as affected by the different aforementioned treatments. This model is easy to use and has modest data requirements, which is a significant advantage, unlike the other erosion models that are too complex and data-hungry (Choi et al., 2017a). MMF has been successfully used in diverse environments such as the Mediterranean basin (López-Vicente et al., 2008), Sub-Saharan Africa (Shrestha & Jetten, 2018; Vigiak et al., 2005), East Asia (Li et al., 2017; Morgan, 2001), South-East Asia (Besler, 1987; Shrestha & Jetten, 2018) and Central America (Febles-González et al., 2012). It also demonstrated the capacity to predict hydrogeological risk in delicate ecosystems of Mediterranean regions (Zema et al., 2020).

The mMMF have some limitations. In Chapter 4, it was shown that the different simulated treatments affect the different plant traits (including root length density) and soil properties (including soil cohesion and hydraulic conductivity). The different simulated treatments also affected the soil loss as predicted by the mMMF. However, the belowground plant traits and soil properties are not explicitly considered as input parameters in the mMMF model. In addition to that, the standard guidance input values in the model only have one category of Wheat, whereas our results show that different wheat lines, sowing densities and water regimes affected the predicted soil erosion rates. Furthermore, in Chapter 2 and 3, it was shown that SSR affects hydrological and soil erosion processes. In addition to that, WLR and WDR events change the conditions of the initial SSR. However, SSR evolution over time is not explicitly considered as input parameters in the model.

The model is very sensitive to the effective hydrological depth (EHD). This parameter is likely to be determined by hydrological properties including water

retention, and saturated and unsaturated hydraulic conductivity. Such level of detail is currently not explicit in the estimation of EHD in the mMMF, which has more an empirical basis. Whereas a coupling between actual (measured) soil physical properties and the mMMF operating functions might lead to over parameterisation in the estimation of EHD, more physically-based models could be used to calculate how these soil physical properties directly affect effective hydrological depth. This might allow for a more accurate evaluation of the effect of soil physical properties, such as those measured in Chapter 4, on runoff generation and subsequent soil erosion.

Previous authors pointed the limitation of MMF as an “mean annual” based model so fails to account for seasonal or diurnal variability in hydrology, climate and land cover. Brunner et al. (2023) proposed changes to the Revised and Modified MMF to enable the assessment of runoff and soil loss based on individual rainfall events. Peñuela et al. (2018) also proposed a modification to the model to function on a monthly basis. Choi et al. (2017b) suggested changes in the model’s temporal scale to function on a daily basis. Also, Shrestha & Jetten (2018) adapted the model to a daily basis, as some parameters will vary day-by-day, such as soil moisture, and the runoff component of the model is based on the available daily storage of the effective hydrological depth (EHD). These authors concluded that the modifications to the temporal scale of the model would be suitable to predict soil loss in semi-arid regions with occasional extreme rainstorms, such as Morocco. However, there might be some criticism of these studies because the mMMF model was not designed for use with these smaller timesteps, and some of the model's operating functions assume annual timesteps.

5.6 Contributions to knowledge

This research has advanced our understanding of soil erosion processes and the factors influencing them, achieving the objectives set forth. By presenting the findings from multiple novel and complementary experiments, it has provided valuable insights into the effects of:

- different configurations of soil surface roughness (SSR) on hydrological and erosion processes;
- different wind velocities on rainfall erosivity;
- different rainfall events (windless and wind-driven rain) on initial SSR;
- plant traits (as determined by wheat lines, sowing densities and water regimes) and soil properties on estimations of runoff and soil erosion using a semi-empirical erosion prediction model; and
- different experimental methodologies on measuring soil properties associated with hydrological and erosion processes.

These contributions have important implications for soil erosion modelling, soil conservation strategy development, and sustainable soil management practices.

5.7 Implications of experimental findings to a larger scale

Several challenges and considerations need to be addressed to scale the experimental results to a larger scale in the field. Scaling up can introduce variability in factors such as soil type, topography, climate, and land management practices, which may affect the dominant erosion processes observed in small-scale experiments. For example, processes like overland flow might become more pronounced at larger scales, while the effects of soil surface roughness or vegetation cover might differ in their influence on runoff and erosion. Additionally, heterogeneity in land use and spatial patterns of rainfall distribution could complicate direct extrapolation of findings. Models play a crucial role in scaling by integrating small-scale data with broader environmental and landscape characteristics, allowing for predictions at larger scales. However, model accuracy depends on the availability and quality of input data, and scaling can introduce uncertainties, particularly in accounting for interactions between local processes and larger-scale dynamics. Therefore, careful consideration is needed when applying findings beyond the experimental setup to ensure reliability and relevance at larger scales.

The findings of this research provide insights that are particularly applicable to Morocco, where soil erosion driven by both water and wind presents ongoing challenges to sustainable agriculture. The effectiveness of surface roughness,

specifically in the form of mounds and depressions, demonstrated a reduction in runoff and soil loss, suggesting that conservation practices such as rough surface management or reservoir tillage could be valuable in Morocco's variable rainfall conditions. Additionally, the results underscore the impact of wind-driven rain in enhancing rainfall erosivity, suggesting that Moroccan farmers would benefit from implementing wind control measures, such as windbreaks, alongside soil roughness management. Given Morocco's heavy reliance on wheat as a primary crop, this research further highlights the importance of exploring wheat genotypes, particularly dwarf varieties, which have shown improvements in plant growth characteristics even at dry conditions which help reduce erosion risks. Higher sowing densities have also been associated with greater canopy cover and root development, enhancing soil stability and reducing surface runoff. Together, these findings emphasise that a combined approach - using strategic soil surface roughness, protective wind barriers, and optimised wheat cultivation practices - could provide effective, locally tailored solutions for soil conservation in Morocco under current and projected climate challenges.

5.8 Future work

The findings from this study can be used to inform future research. The aim would be to develop more effective and comprehensive soil conservation strategies based on a sound understanding of the hydrological and erosional processes operating. To achieve this, future research efforts should focus on the following:

1. Conduct comprehensive studies to investigate the effectiveness of across-slope oriented surface roughness under a wide range of rainfall intensities and slope gradients. These studies should aim to establish the limits and optimal conditions for the successful implementation of this soil conservation method.
2. Explore the influence of spatial scale on the impact of surface roughness on soil erosion control. While some roughness types, such as mounds and depressions, may be effective in the laboratory at smaller scales ($< 1\text{m}$), their role in the field and at larger spatial scales ($> 10\text{m}$), where topography, environmental conditions and vegetation cover become more dominant, should be quantified.

3. Expand research efforts to evaluate a diverse range of plant species and genotypes, with a focus on identifying those with optimal aboveground and belowground traits for soil erosion control and soil conservation purposes, as well as conducting long-term field experiments under varying environmental conditions and management practices.
4. Investigate the incorporation of a wider range of soil properties and root traits (and their interactions) into the operating functions of soil erosion models, such as the modified Morgan-Morgan Finney (mMMF) model. Refinement and validation of these well-parameterised operating functions could improve the accuracy of soil erosion rate predictions by explicitly accounting for factors like soil cohesion, hydraulic conductivity, and root length density, which have been shown to significantly affect soil loss.
5. Develop soil erosion models that would incorporate the dynamic nature of soil surface microtopography and its evolution over time, as well as the synergistic effects of wind and rainfall conditions on soil erosion processes. These considerations could lead to more accurate predictions of soil erosion risks, particularly in areas with diverse tillage practices, and in regions prone to high winds during rainfall events.
6. Explore event-based modelling to capture seasonal and diurnal variability in weather, hydrology, and land cover, which can influence erosion processes.

5.9 References

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APPENDICES

Appendix A Ethical Approval Letter



28 March 2020

Dear Miss Bahddou ,

Reference: CURES/9751/2020

Title: Technical and practical innovations to reduce soil and water losses by improving soil physical properties

Thank you for your application to the Cranfield University Research Ethics System (CURES).

We are pleased to inform you your CURES application, reference CURES/9751/2020 has been reviewed. You may now proceed with the research activities you have sought approval for.

If you have any queries, please contact CURES Support.

We wish you every success with your project.

Regards,

CURES Team

Appendix B Supplementary Material for Chapter 1

B.1 Sediment collectors

There are several devices used to collect eroded material under the effect of wind, whether in field experiments or in wind tunnels. The most important characteristic of these devices is their efficiency in collecting eroded sediment which depends on the collector design (size and shape), the speed of the wind relative to the air speed at the sampler orifice, the size of the particles, and the total time of sampling (Goossens & Offer, 2000). Aeolian sand samplers can be stationary or rotating: the stationary samplers that are usually used in a wind tunnel are always oriented to a single direction, while the rotating samplers that are needed in field measurements are able to change their direction in response to the changing wind direction (Dong et al., 2004). A list of some sediment collectors, also called samplers or catchers, is presented in (Table B-1).

Table B-1 Different sediment collectors (wind erosion), their characteristics, efficiencies, strengths and shortcomings.

Sampler	Author	Wind velocity	Soil type and particle size	Efficiency	Process	Strengths	Shortcomings
BSNE (Big Spring Number Eight)	Fryrear (1986)	10.4, 13.0 and 15.7 m s ⁻¹	D ₅₀ : 177, 185 and 249 µm	Between 86% and 93%	Saltation/suspension. Airborne sand collected at a height of 12 cm above the ground (Goossens et al., 2000). Airborne dust collected at a height of 23.5 cm and 1 m above the wind tunnel floor and the field surface respectively (Goossens and Offer., 2000)	-Can be used in the field as well as in wind tunnels. In the field, a wind vane at the rear of the device assures the sampler to be turned to the wind. -Applicable for dust and sand catching. -Higher efficiency. For sand, average values for many studies were around 90%. -Efficiency varies only slightly with wind speed (Goossens and Offer, 2000).	-The efficiency drops with wind speed (Fryrear, 1986; Shao et al., 1993; Goossens et al., 2000) and for fine particles (Goossens et al., 2000)
	Fryrear (1986)		< 63 µm	Between 96 and 165%			
	Shao et al. (1993)	9.0, 10.5 and 12.0 m s ⁻¹	D ₅₀ : 176 µm	Between 86% and 95%			
	Shao et al. (1993)		< 10 µm	40%			
	Goossens and Offer (2000)	From 1 to 5 m s ⁻¹ .	Dust: 95% silt (2-63 µm) and 5% clay (< 2 µm), median diameter of 30 µm	Between 35 and 45%			
	Goossens et al. (2000)	Between 6.6 and 14.4 m s ⁻¹	Sands between 132 and 287 µm	-Between 90 and 120 % for sand grain size ~ 200 µm			
	Shannak et al. (2014)	From 1 to 5.5 m s ⁻¹	Polystyrene sphere of 0.5 mm and 1 mm.	81-85%			
MWAC (Modified Wilson And Cooke)	Sterk (1993)	9.9, 10.4 and 11.0 m s ⁻¹	D ₅₀ : 222 µm.	between 43% and 66%	Saltation/suspension. Airborne sand collected at a height of 12 cm above the ground (Goossens et al., 2000). Airborne dust collected at a height of 23.5 cm and 1 m above the wind tunnel floor and the field surface respectively (Goossens and Offer., 2000)	-Can be used in the field as well as in wind tunnels. In the field, it can be attached to a mast provided with a wind vane. -The efficiency remains constant in the wind velocity range investigated (Goossens et al., 2000) -No relationship between the efficiency of the MWAC catcher and the velocity of the wind (Sterk, 1993; Pollet, 1995).	-The device is very small, notably the inlet pipes.
	Bakkum (1994)			50–55%			
	Pollet (1995)			42–56%			
	Goossens and Offer (2000)	From 1 to 5 m s ⁻¹ .	Dust 30 µm	Over 75% -75% at a speed of 1 m s ⁻¹ -More than 90% for wind speed between 2 and 5 m s ⁻¹			
	Goossens et al. (2000)	Between 6.6 and 14.4 m s ⁻¹	Sands between 132 and 287 µm	Between 90 and 120 %			
	Shannak et al. (2014)	From 1 to 5.5 m s ⁻¹	Polystyrene sphere of 0.5 mm and 1 mm.	65%			
POLCA (Pollet Catcher)	Pollet (1995), Pollet et al. (1998)	6, 7, 8.5 and 9.5 m s ⁻¹	D ₅₀ : 270 µm	between 27% and 39%	Saltation. Airborne sand collected at a height of 12 cm above the ground (Goossens et al., 2000).		-The efficiency drops with wind speed and for finer sediments (Goossens et al., 2000)
	Goossens et al. (2000)	Between 6.6 and 14.4 m s ⁻¹	Sands between 132 and 287 µm	Between 80 and 120 %			
	Shannak et al. (2014)	From 1 to 5.5 m s ⁻¹	Polystyrene sphere of 0.5 mm and 1 mm.	70-75%			
SUSTRA (Suspended)	Goossens and Offer (2000)	From 1 to 5 m s ⁻¹ .	Dust 30 µm	15%	Saltation/suspension. Airborne sand collected at a		-The efficiency drops with wind speed and for fine

Sampler	Author	Wind velocity	Soil type and particle size	Efficiency	Process	Strengths	Shortcomings
sediment trap)	Goossens et al. (2000)	Between 6.6 and 14.4 m s ⁻¹	Sands between 132 and 287 µm	>90 % for sand grain size ~ 200 µm and wind speeds < 11 m s ⁻¹	height of 12 cm above the ground (Goossens et al., 2000). Airborne dust collected at a height of 23.5 cm and 1 m above the wind tunnel floor and the field surface respectively (Goossens and Offer., 2000)		particles (Goossens et al., 2000). But Goossens and Offer (2000) found the opposite for dust. -Not efficient for dust, 15% (Goossens and Offer, 2000) and difficult to install several samplers in a vertical array
	Shannak et al. (2014)	From 1 to 5.5 m s ⁻¹	Polystyrene sphere of 0.5 mm and 1 mm.	< 72%			
Saltiphone	Goossens et al. (2000)	between 6.6 and 14.4 m s ⁻¹	Sands between 132 and 287 µm	10–17%. for the finest sand. 30–74% for the medium-sized sand. 100–500% for the coarsest sand.	Saltation. Airborne sand collected at a height of 12 cm above the ground (Goossens et al., 2000).	The efficiency remains constant in the wind velocity range investigated (Goossens et al., 2000)	-Efficiency extremely low (10-17%) for the finest sand (Goossens et al., 2000)
WDFG (Wedge Dust Flux Gauge)	Hall et al. (1993)	3 and 8 m s ⁻¹	Dust 59 µm	80%			-Efficiency drops with increasing wind velocity (Goossens and Offer, 2000)
	Hall et al. (1993)	3 and 8 m s ⁻¹	Sand 136 µm	90-95%			
	Goossens and Offer (2000)	From 1 to 5 m s ⁻¹ .	Dust 30 µm	50-60% at low wind speeds (< 3 m s ⁻¹). < 30% for winds > 4 m s ⁻¹ maximum efficiency of 63% at 2 m s ⁻¹			
	Shannak et al. (2014)	From 1 to 5.5 m s ⁻¹	Polystyrene sphere of 0.5 mm and 1 mm.	60-68%			
SIERRA	Goossens and Offer 2000	From 1 to 5 m s ⁻¹ .	Dust 30 µm	Over 75%		Efficient for Dust (Goossens and Offer, 2000)	
	Shannak et al. (2014)	From 1 to 5.5 m s ⁻¹	Polystyrene sphere of 0.5 mm and 1 mm.	63-67%			
ICE (International Centre for Eremology)	Cornelis (2003)	From 6.4 to 16 m s ⁻¹	Sand 250.2 µm	75%	Particles in creep (bedload) and saltation	-Efficiency of 75%, high value compared to other samplers (MWAC and POLCA) used in the same wind tunnel and under comparable conditions (Cornelis, 2003). -Non-selective sampler	-The sampler is not separated. Particles that stick to the walls of the sampler by electrostatic or cohesion forces are not weighed. -The efficiency drops with wind speed (Cornelis, 2003).
WITSEG (Segmented sand sampler for wind tunnel test)	Dong et al. (2004)	From 8 to 22 m s ⁻¹	Sand 0.18 mm	91%	Saltation/Suspension. Segmented sampler collecting the sediment at different heights. The bottom of the lowest opening of the sampler was set flush with the tunnel floor (so, it can collect bedload).	-Good for measuring aeolian sand flux. Efficiency of 91% (Dong et al., 2004) -Collect the sediment flux at different heights. Useful in studying flux profiles. -Can be used in field if a rotating device is provided.	

B.2 Soil erosion models

Over the years, researchers have developed various models to estimate and predict soil erosion rates, each with its unique strengths and limitations:

The Universal Soil Loss Equation (USLE) and its revised version, the Revised Universal Soil Loss Equation (RUSLE), are among the earliest and most widely used empirical models for estimating soil erosion. These models were developed based on extensive data from standard field plots and are primarily designed for sheet and rill erosion estimation in agricultural lands, east of the Rocky Mountains in the US (Renard et al., 1997; Wischmeier and Smith, 1978). However, these models have limitations. According to Kinnell (2010), parameterising the model with appropriate values requires considerable effort, and at hillslope scales, the model lacks sufficient sensitivity to account for spatial variations in soil, vegetation and runoff patterns. According to Pandey et al. (2021), RUSLE overpredicts higher erosion rates when compared to the measured sediment yield. These limitations raise concerns about RUSLE's performance, especially when extrapolated beyond its original plot-scale development and application.

The Water Erosion Prediction Project (WEPP) model is a process-based model that simulates various erosion processes, including sheet and rill erosion, as well as ephemeral gully erosion (Flanagan et al., 2001). WEPP incorporates advanced physical principles and can be applied to a wide range of conditions, making it a powerful tool for erosion prediction. However, its complexity and data requirements can be challenging, particularly in data-scarce regions (Pandey et al., 2021). The model's complexity can make it difficult to apply, particularly for users without extensive training or experience with the model. According to Alewell et al. (2019), although the WEPP model has the advantage of including explicit consideration of runoff (unlike the USLE and RUSLE models), its effectiveness in predicting soil losses in the USA is no better than that of the USLE or the RUSLE.

The European Soil Erosion Model (EUROSEM) is a physically-based model developed for simulating erosion processes at the field and catchment scales (Morgan et al., 1998). It combines empirical and physical equations to estimate soil erosion rates and can account for various factors, including vegetation cover, soil properties and slope topography. EUROSEM is particularly useful for assessing the effect of management practices and land use on soil erosion. However, the key shortcomings identified by Smets et al. (2011) are the tendency to overpredict sediment discharge, inability to account for sediment deposition processes, need for better surface roughness representation, and potential improvements needed for runoff/sediment discharge predictions, especially with repeated rainfall events. Moreover, this model is data-hungry which can prove challenging if data of variables are not available.

The Morgan-Morgan-Finney (MMF) model (Morgan et al., 1984) is a widely used soil erosion model that predicts mean annual soil loss based on the processes of detachment and transport of soil particles. It uses the Meyer and Wischmeier (1969) concept in which the detachment and transport capacities of rainfall and runoff are compared. The model has undergone several revisions to improve its accuracy and applicability. The Revised MMF (Morgan, 2001) incorporated flow detachment and plant height effects, while the Modified MMF (Morgan & Duzant, 2008) added soil particle-size selectivity in detachment, transport and deposition processes, sediment deposition, and more detailed soil surface and vegetation cover effects. In addition to rainfall, soil and slope factors affecting erosion, the Modified MMF specifically enables the effects of vegetation on runoff and erosion dynamics to be expressed through measurable plant parameters. The model evaluates the amount of soil particles dislodged by rainsplash and surface runoff (detachment), and the quantity of sediment that can be transported by the runoff flow (transport capacity) and compares these two values and selects the lower one as the annual rate of soil loss ($\text{kg m}^2 \text{ yr}^{-1}$). This approach identifies whether the detachment process or the transport capacity acts as the limiting factor in determining the overall soil loss.

Appendix C Supplementary Material for Chapter 2

C.1 Rainfall characteristics

In the experiments conducted in this thesis, the target rainfall intensity was 90 mm hr⁻¹ for a 15- and 30-min duration rainfall event. This is estimated to occur once in 30 and 150 years respectively. The intensity was calculated based on the Montana formula $i(t,T) = a * t^{-b}$ where $i(t,T)$ is the rainfall intensity at a determined duration t (min) and a return period T (years) expressed in mm/hr; and a and b represent the Montana coefficients which vary depending on the region and the return period. The Montana coefficients database was acquired from the Hydraulic Basin Agency of Loukkos region in the north of Morocco (Table C-1).

Table C-1 Rainfall intensities obtained from Montana parameters for different storm return periods and rainfall durations. The values in bold are the targeted rainfall intensity (90 mm hr⁻¹) at two durations (15 and 30 minutes) representing rainfall events occurring once in 30 and 150 years, respectively.

Region	Return period T (years)	Montana coefficients		Duration t (min)						Rainfall intensity (mm/hr)
		a (mm/min)	b	5	10	15	20	25	30	
Tangérois & Loukkos	2	3.59	0.59	83	55	44	37	32	29	
	5	4.46	0.55	111	76	61	52	46	42	
	10	4.99	0.53	129	89	72	62	55	50	
	20	5.49	0.51	146	103	84	72	64	59	
	50	6.11	0.49	168	120	98	85	77	70	
	100	6.56	0.47	184	133	110	96	86	79	
	150	Extrapolated		200	147	122	108	98	90	
	200			217	160	135	118	107	98	
	250			235	175	147	130	117	108	

C.2 Chain method for SSR measurement

One of the methods widely used to quantify SSR is the chain method. In the method proposed by Saleh (1993), a chain of a given length (L1) is placed across

the surface, and the horizontal distance covered by the chain (L2) will decrease as the roughness increases. The chain length reduction caused by the surface irregularities is taken to represent the soil surface roughness (SSR, %) expressed in Equation (C-1):

$$SSR = \left(1 - \frac{L2}{L1}\right) \cdot 100 \quad \text{(C-1)}$$

The parameters of the equation are suitable in the field where the whole chain length could be considered on a large area of the ground, but the limitation of this equation is that it is not applicable in the laboratory using erosion trays with a limited area, especially when simulating roughness at different orientations (Chapter 2). In the method proposed by Morgan et al. (1993), the soil surface roughness (SSR, cm/m or %) is defined as the ratio of the straight-line distance between two points on the ground (X) to the actual distance measured over all the microtopographic irregularities (Y). It was expressed in Equation (C-2).

$$SSR = \frac{Y - X}{Y} \cdot 100 \quad \text{(C-2)}$$

One of the objectives of Chapter 2 was to assess the changes in SSR due to the rainfall events. To achieve this, measuring the SSR should be done before and after the rainfall event. For a fair comparison between initial and final SSR, the denominator of the SSR Equation (C-2) should be the same value in both measurements before and after the rainfall event. Therefore, a slight modification of Equation (C-2) was made so that the denominator is the straight-line distance between the two points (X), which is a fixed value (Equation (C-3)).

$$SSR = \frac{Y - X}{X} \cdot 100 \quad \text{(C-3)}$$

Appendix D Supplementary Material for Chapter 3

Modifications to one of the wind tunnels in the School of Aeronautics, Transport and Materials (SATM) at Cranfield University to include equipment simulating soil erosion by rainfall and wind was designed. The tunnel had a cross section of 39.5 cm wide and 31 cm height. A description of the proposed design is presented in Figure D-1. The Modified Wilson And Cooke “MWAC” sampler was judged by Goossens et al. (2000) to be the most efficient device among five aeolian sand traps they tested. However, this is not always ideal for wind-driven rain studies (Cornelis et al., 2004). The design of the facility could not be realised, therefore a combined wind and rainfall simulator was designed, built and calibrated (Chapter 3) to study the effect of wind on rainfall erosivity.

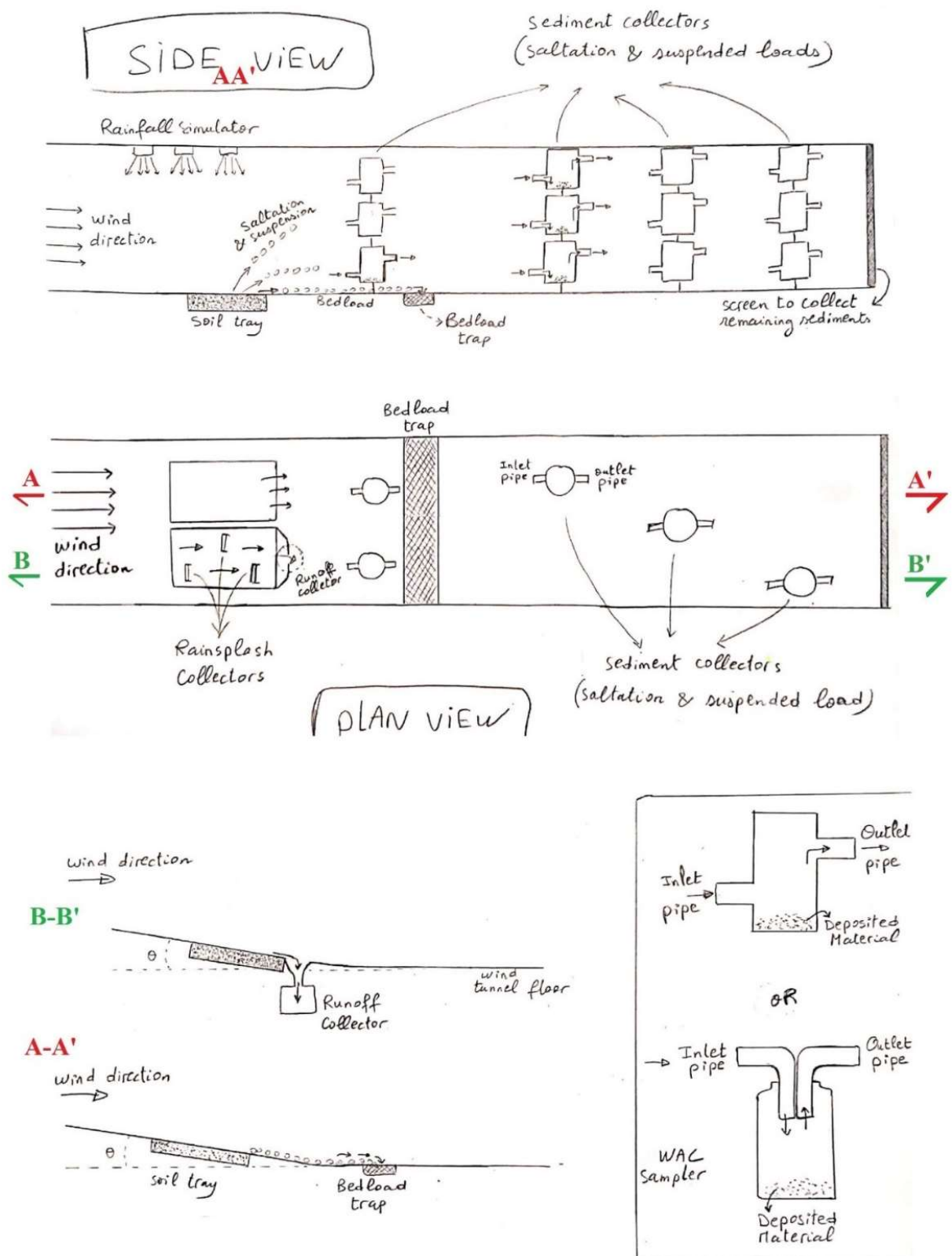


Figure D-1 Sketch of wind tunnel combined with rainfall simulator for soil erosion purposes

Description:

The bed load can be collected in a trap that is embedded into the wind tunnel floor at a certain distance from the soil tray.

- The soil tray should be flush with the bed of the wind tunnel to allow bedload to travel from the tray to the wind tunnel floor.

- It is hard to separate sediments in saltation from the suspended load because they are both airborne and are function of particle size and wind velocity that changes from one experiment to another. To keep it simple, they can be collected together in the same sediment collector: a set of jars/bottles with inlet and outlet pipes (e.g. Wilson And Cooke "WAC" sampler, judged by Goossens et al. (2000) to be the most efficient device among 5 aeolian sand traps tested). The collectors are offset and put at different heights and lengths, after the bedload trap.

- An additional set of bottles put before the bed load trap to collect the saltating particles and suspended load preventing them from being mixed with the collected bed load.

- Set up a screen at the end of the tunnel to collect the remaining sediments. Consider the mesh size to be able to capture the smallest sediment, but at the same time make sure to avoid any air turbulence generated from the air flow in contact with the small mesh screen.

- Considering both wind erosion and water erosion (runoff, rainsplash) using 2 adjacent trays, one for runoff collection and the other one for wind eroded material. A long tray is needed to give us high surface area to erode (around 50 cm, but depends on how long the wind tunnel will be).

- Choosing a leeward slope (the runoff going down the slope at the same direction as the wind) because interest lies in the increased erosivity under the combined effect of water and wind, to have a synergy effect from the 2 processes operating together with no conflicts between their energies. Also, this makes the mechanism of collecting eroded sediment easier.

- Pilot experimental runs are needed to have an idea about the amount of sediment collected which depends on the wind speed, the particle size and the

soil moisture content. If the system is not efficient and does not collect enough material, a plan B is needed (e.g. set of layers in heights that covers the whole breadth of the test area, or a part of it).

Appendix E Supplementary Material for Chapter 4

Table E-1 The modified Letcombe's stock solution - Micronutrients and macronutrients

Micronutrient Stock	Stock Conc. (mM)	Final Conc. (μM)	
CuCl ₂ x 2 H ₂ O	3	9	
H ₃ BO ₃	60	180	
MnCl ₂ x 4H ₂ O	21.6	64.8	
Na ₂ MoO ₄ x 2H ₂ O	0.6	1.8	
ZnCl ₂	15	45	
Stock Solution	Stock Conc. (M)	Final Conc. (mM)	Vol. per 1L Sol. (mL)
1M Ca(NO ₃) ₂ x 4H ₂ O	1	9	9
1M KNO ₃	1	36	36
1M CH ₄ N ₂ O	1	9	9
1M MgSO ₄ x 7H ₂ O	1	9	9
1M KH ₂ PO ₄	1	6	6
1M K ₂ HPO ₄			
50 mM Fe EDTA	0.05	0.5	10
Micronutrient Stock			3

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