Water erosion process on sloping cropland in Central Vietnam – A case study in A Luoi district, Thua Thien Hue province

Le Dinh Huy

2022

Acknowledgments

First of all, I would like to express my deepest gratitude to Professor FUNAKAWA, Professor of Kyoto University for all the scientific guidance, encouragement, and support throughout my study. I would like to greatly thank Dr. SHIBATA, Mrs. Yuko Ogawa, and Associate Professor, Dr. Nguyen Ho Lam, Associate Professor of Hue University for their guidance and support during my PhD research.

I would like to sincerely thank Associate Professor Dr. Hitoshi Shinjo, Associate Professor of Kyoto University, Associate Professor Dr. Tetsuhiro Watanabe, Associate Professor of Kyoto University, and Dr. Shigeru Araki, Professor Emeritus of Kyoto University for their scientific advice and recommendation, and helpful words of encouragement that I received from them.

My sincere thanks also go to Dr. Yuri Ichinose, Dr. Jinsen Zheng, Mrs. Reiko Okuda, Mr. Ajay Kumar Mishra, Dr. Athuman Mahinda, and Mr. Shinichi Watanabe for their help, warm encouragement, and valuable discussions. I would like to thank Mr. Ho Van Thua for his sincere help during the experiment.

Finally, I am extremely grateful to my family, my wife and daughter, for their companionship.

This research was financially supported by Grants from JSPS KAKENHI.

Le Dinh Huy

Contents

Contents

List of Tables

List of Figures

Chapter 1

General introduction

1.1. Problems statement

Soil erosion by water, wind, and tillage is the greatest threat to soil health and soil ecosystem services in many regions of the world including Africa, Asia, Latin America, the Near East and North Africa, and North America. The trend for soil erosion was becoming progressively worse in the first four of those regions. Only in Europe, North America, and the Southwest Pacific, the trend for erosion was improving (Pennock, 2019). Water erosion is one of the main forms of land degradation. Researchers reported that one-sixth of the world's soils are affected by water erosion. In mountain areas of developing countries, soil erosion constraints rural development and aggravates poverty by decreasing the productive capacity of highland agriculture and livestock raising (Zimmerer, 1993; Lal, 2001; Carlos, 2005)

In water erosion, the detachment of soil from the soil layers occurs in two ways: from the impact of raindrops splash on the soil surface and from eroding forces by runoff (Kinnell, 2006; Matsumoto et al., 2016). Transport of the detached sediment by flowing water first occurs in thin sheets of runoff (sheet erosion). Then runoff water is concentrated in small channels (rill erosion) or deeper incisions (gully erosion); in both of these types of channels, the erosive forces of the flow are significantly boosted. The rill and gully erosion cause visible signs of erosion operating in the landscape. In most cases, the runoff and sediment are carried to a stream system and are removed entirely from the landscape. In some cases, vegetation settles the sediment and runoff water by decreasing the velocity of the water flow (Pennock, 2019). Water erosion is originally a natural process; it is also accelerated by human activities such as slash and burn practices, mass grazing, and abandoned plantation forest (Mizugaki et al., 2008; Pham, 2015). Wischmeier and Smith (1978) investigated the driving factors of water erosion by analyzing data from fieldwork. These factors, including rainfall pattern, soil type, topography, crop system, and management practices, were computed to the Universal Soil Loss Equation (USLE). The family of USLE models, including the original Universal Soil Loss Equation (USLE), the Revised Universal Soil Loss Equation (RUSLE), the Revised Universal Soil Loss Equation version 2 (RUSLE2), and the

Modified Universal Soil Loss Equation (MUSLE), were developed and applied worldwide for aiding land management by clarifying the areas vulnerable to water erosion in the baseline scenario, the potential water erosion rates, and possible causes of water erosion. Still, some researchers reported that the most significant limitation of the USLE family of models is their low applicability to regions outside the United States of America (Aksoy and Kavvas, 2005; Naipal et al., 2015; Sadeghi et al., 2014). Wischmeier and Smith (1978) have also clarified that the extrapolation error will be occurred if the family of USLE models is applied to conditions different from the agricultural conditions that the model was formulated. Rubianca et al. (2018) reviewed studies that compared the soil loss rates calculated by the family of USLE models to observed data and reported that the amount of soil loss predicted by the USLE family is from 0.04 to 5 times higher than the observed values. The inability of USLE models to calculate the gully erosion and massive events is one of the reasons for underpredicted soil loss (Thorne et al., 1985; Dabney et al., 2012; Gaubi et al., 2017). An integrated field assessment-modeling approach is essential for predicting the long-term annual soil loss rate (Evans and Boardman, 2016).

In Vietnam, much of the natural forest damaged during the war was further degraded by people looking for food and land for crops in the 1970s and 1980s (Pham, 2000). Large forests and protected areas were deforested, leading to decreasing land cover and rapidly declining soil quality (Mai, 2007; Nguyen et al., 2008). Natural forest cover was 19 Mha in 1945, 12 Mha in 1980, 9.6 Mha in 1985, and 9.3 Mha in 1992 (Mai, 2007). Vezina (2006) reported that water erosion is the most serious degradation problem in Vietnam. The degraded area covered 13 million ha, accounting for 40% of the total land area of the country. Thai and Nguyen (1994, 1998) reported that annual soil loss of 70-100 Mg ha^{-1} in an upland rice and cassava cultivation area and 7-88 Mg ha^{-1} in a heavy textured soil area. These cause a considerable loss of nutrients annually, including 5,600 Mg of organic matter, 199.2 kg of nitrogen, 163.2 kg of phosphorous, and 33 kg of Ca and Mg. Annually, water washes away about 250 million Mg of fertile alluvial to the sea (Socialist Republic of Viet Nam, 2018). As a result, soil loss was the major cause of reducing crop yield (Vu, 2015).

In the northern and central highlands of Vietnam, water erosion has been well investigated using both field assessment and modeling approaches, especially in parts of the highlands affected by timber harvesting, shifting cultivation, and forest clearance (Douglas, 2006; Sidle et al., 2006; Vezina et al., 2006). Annual soil loss under forests is estimated at 3–12 Mg ha^{-1}, under coffee and tea 22–70 Mg ha^{-1}, and under cassava and hill rice 175–260 Mg ha^{-1} (Tran, 1995; Vu, 1999; Tran, 2001). Based on the results of water erosion research, scientists have developed and adapted soil erosion control methods to agricultural farming on sloping land with outstanding efficiency. The practical techniques are planting trees along contour lines, planting trees in ditches (e.g., tea, sugarcane, pineapple); planting trees in holes (e.g., coffee, rubber, citrus, avocado), covering the soil with green manure plants, rice straw, sugarcane leaves, grass residue, polyethylene, or rootstock; plowing and weeding along contour lines; crop rotation, intercropping, and overlapping crops; arranging appropriate planting and harvesting times; using a sloping land-farming model; and minimal farming (Nguyen and Thai, 1999). Nguyen and Pham (2018) reported that for coffee planted on the following contour lines, the amount of soil loss annually was 63.37 Mg ha^{-1}. On the coffee cultivation following level top bench terrace, the soil loss was only 39.55 Mg ha^{-1}. Compared to traditional methods, planting more grass strips and intercropping soybean with the main crops reduced the amount of soil loss by 71% and 63–76%, respectively. For the annual crop (maize), compared to traditional methods, using the stems of maize as mulching material after harvesting to cover lands following contour lines and terraces, and intercropping with legumes decreased the amount of soil loss by 38–59% and 50–68%, respectively.

Central Vietnam is usually suffered from tropical storms and extreme weather. The highland areas with a complex topography and steep slopes occupy more than 75% of the total land area in the central part of Vietnam, thus, frequently suffering from the harsh climate that causes water erosion (Le, 1998). However, the studies on water erosion mostly applied the modeling approach, but not the field assessment approach (Pham, 2008; Truong et al., 2012; Nguyen and Nguyen, 2014; Tran et al., 2014; Pham et al., 2018; Huynh et al., 2020). The water erosion process and its seasonal risks have not been well investigated. The efficiency of water erosion mitigation solutions has not been tested. Therefore, these studies suggested ambiguous recommendations for water erosion mitigation to local land managers and farmers but no specific solutions.

1.2. Objectives

To increase insight into the water erosion processes in central Vietnam and to support local government and farmers in land use management, my study pursued the following objectives:

1) To clarify the site-specific conditions in rainfall and soil characteristics and their interaction that contributes to the water erosion generation processes.
2) To make specific practical recommendations to local land managers to mitigate water erosion risks.

Chapter 2

Site description

Central Vietnam is one of the three geographical regions within Vietnam. It includes 1 municipality and 18 provinces, is separated into 3 administrative regions named North Central Coast, South Central Coast, and Central Highlands. The North Central Coast is 5.15 million ha and contains 6 coastal provinces (Thanh Hoa, Nghe An, Ha Tinh, Quang Binh, Quang Tri, and Thua Thien Hue) in the northern half of Vietnam's narrow central part. All provinces stretch from the coast in the east to Laos in the west. The South Central Coast is 4.44 million ha and contains 1 municipality (Da Nang) and 7 coastal provinces (Quang Nam, Quang Ngai, Binh Dinh, Phu Yen, Khanh Hoa, Ninh Thuan, and Binh Thuan) in the southern half of Vietnam's central part. One province shares a border with Laos. The Central Highlands is 5.46 million ha and contains 5 mountainous provinces (Kon Tum, Gia Lai, Dak Lak, Dak Nong, and Lam Dong) to the west of south-central Vietnam. There are a significant number of ethnic minorities in this region. One province is along Vietnam's border with Laos, and four share a border with Cambodia (Le, 1998; General Statistics Office, 2017).

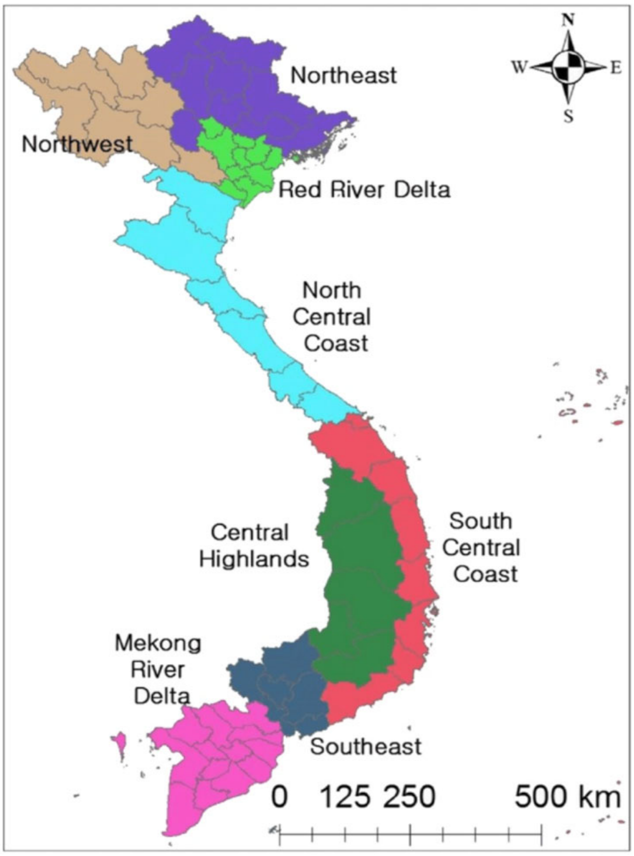


Figure 2.1. Regions in Vietnam. Source: Lee et al., 2017.

2.1. Geography

The north of Central Vietnam borders the Red River Delta and the Northwest. The south borders provinces of Binh Phuoc, Dong Nai, and Ba Ria - Vung Tau. It borders Vietnam east sea in the east and borders Laos and Cambodia in the west. The plains are surrounded by the Truong Son range along the west and the sandy coastal along the east. The terrain of Central Vietnam has a lower elevation in the northwest to southeast directions. The western North Central Coast region is medium and low mountains. The altitude of the mountainous area of Thanh Hoa province is 1000 to 1500 m above sea level. The mountainous area of Nghe An and Ha Tinh provinces is the headwater of the Truong Son range and is very rugged terrain. Most of the high mountains are scattered there. The plains have a total area of about 0.62 million ha, of which the Thanh Hoa delta, which is accreted by alluvial sources from the Ma and Chu rivers, accounts for nearly half of the area and is the most expansive plain of the Central region. The Central Highlands locate to the west of the Truong Son range. Its terrain is diverse and complex, mainly plateaus with high mountains at an altitude of 250 – 2500 m. The South Central Coast consists of a coastal plain and low mountains. There is a system of short and steep rivers, a deep coastline with many bends, and a narrow continental shelf. The western mountains spread along the north-south direction, gradually approaching the sea and progressively narrowing the area. The plains are small and are accreted by rivers and seas, following the foothills of the mountains (Le, 1998; Le, 2009).

2.2. Geology

The territory of Vietnam is divided into five structural blocks: Northeast, Northwest, Truongson, Kontum, and Nambo. The Central locate in Truongson and Kontum blocks. The Truongson block is regarded as northwest - southeast trending Paleozoic folded system filled with thick Paleozoic formations (> 12000 m). Precambrian strata are widespread in the Kontum block. Archean rocks are found only in the Kontum block, which is regarded as a stable massif without Paleozoic sedimentary rocks (Tran, 1995).

The Archean granulites in the Kontum massif are grouped into the Cannak complex, which is the oldest stratigraphic unit in Vietnam. They are found in close connection with autochthonous plutons of alkali - charnokites (orthopyroxene-bearing granites). The thickness of the complex has been estimated to be > 4000 m. Lower

Proterozoic rocks found in the Kontum massif are placed into different complexes under local names. The general thickness of the complexes has been estimated to be 2500–3000 m. Upper Proterozoic metamorphic rocks with a strata thickness of 1000–1200 m are widespread and form a 50–60 km wide belt bordering the Kontum massif (Thi, 1985 cited from Tran, 1995).

Paleozoic strata in Central Vietnam are widespread in the Truongson blocks but are absent in the Kontum blocks. In the Truongson block, the 1300 - 2000 m thick Middle Cambrian - Lower Ordovician strata that consist mainly of limestone, mudstone, and sandstone are named the Changpung types. The Changpung type has been regarded as a member of the Eastern Asia-Australia paleobiogeographical province. The 3000–3500 m thick Upper Ordovician - Lower Silurian formations are largely distributed in the Truongson block. Rocks are terrigenous flysch in character and contain graptolite assemblages. The 2000–3500 m thick Upper Silurian formations covering large areas in the Truongson block contain many fossils such as graptolites, brachiopods, trilobites, and acritarchs (Ngan et al, 1986 cited from Tran, 1995). The Lower Devonian strata are characterized by a 2000 m thick formation of shale and sandstone. The Middle Devonian strata are characterized by a 1200 m thick terrigenous formation in the lower part and a 500 m thick carbonate formation in the upper part. The thin Upper Devonian strata are composed of two facies: the carbonate facies contain Frasnian-Famennian stromatoporoids and conodonts distributed in the north part of the block; the clastic facies of the tidal-littoral zone is only Frasnian in the south part (Thanh et al., 1986 cited from Tran, 1995). The Carboniferous - Permian formations widely distributed in the Truongson block are composed of Lower Carboniferous shale, sandstone, conglomerate, limestone, and Carboniferous–Permian limestone containing abundant assemblages of foraminifers. The total thickness of the Carboniferous-Permian strata has been estimated to be 1800–2200 m (Hung and Tien, 1986 cited from Tran 1995).

2.3. Climate

Central Vietnam is located in the tropical belt and is hot and humid throughout the year. It forcefully suffers from the Asia monsoon regime, mainly as northeast and southeast monsoon. In the North Central Coast, the impact of the northeast monsoon is powerful, causing two distinct seasons in the region: the hot season is from May to October, and the cold season lasts from November to coming April. On the other hand, the South Central Coast and Central Highlands are mainly affected by the southeast monsoon with heat and wetness the whole year. Due to the region's varied terrain, Central Vietnam has several sub-climate regions. For instance, Lam Dong Province in the Central Highlands has a temperate climate. Ninh Thuan province has a tropical savanna climate. The average annual temperature is from 26–27^{0}C, the average rainfall is 700–800 mm in Phan Rang city, the air humidity is from 75 to 77% (Le, 1998; Socialist Republic of Viet Nam, 2004; Babatunde et al., 2016). Central Vietnam suffers from 6 to 10 storms and tropical depressions that cause heavy rain and flood. Storms and tropical depressions often occur from June to November but mainly in September and October (Socialist Republic of Viet Nam, 2004).

2.4. Vegetation

Vietnam is one of the 25 high biodiversity countries. It contains many types of ecosystems and biological species, and it is rich and endemic in genetic resources. The total forest area, as well as forest cover, increased –from 2015 to 2020. In 2020, the total forest area was 14.7 million ha, the natural forest area was 10.3 million ha, the plantation forest area was 4.4 million ha, and forest cover occupied 42% of Vietnam's total land area. Natural forests are mainly timber, bamboo forests, and mixed forest of wood and bamboo with approximately 8.9 million ha, 0.24 million ha, and 1.14 million ha, respectively. The areca-coconut forest occupies a very small area, less than 5000 ha (Vietnam Ministry of Natural Resources and Environment, 2021).

Central Vietnam consists of a large part of Vietnam's forest area and occupies 3 out of 8 forest ecological zones on the mainland of Vietnam. The forest coverage rates in the Central Highlands, South Central Coast, and North Central Coast are 45.9%, 50.4%, and 57.4%, respectively (Vietnam Ministry of Agriculture and Rural Development, 2021a). In 2020, the natural forest area in Central Vietnam was 6.0 million ha (2.2 million ha in the North Central Coast, 1.6 million ha in South Central Coast, and 2.2 million ha in Central Highlands). The plantation forest area in Central Vietnam was 2.2 million ha, occupying 50% of those in the whole country. The plantation forest area distributed in North Central Coast, South Central Coast, and Central Highlands is 0.92 million ha, is 0.87 million ha, and is 0.38 million ha, respectively. Acacia forest (1.35 million ha) was the largest plantation forest in the central region and the mainland of

Vietnam. This forest is mainly developed in the South Central Coast (0.7 million ha) and North Central Coast (0.55 million ha) (To et al., 2021; Vietnam Ministry of Agriculture and Rural Development, 2021a).

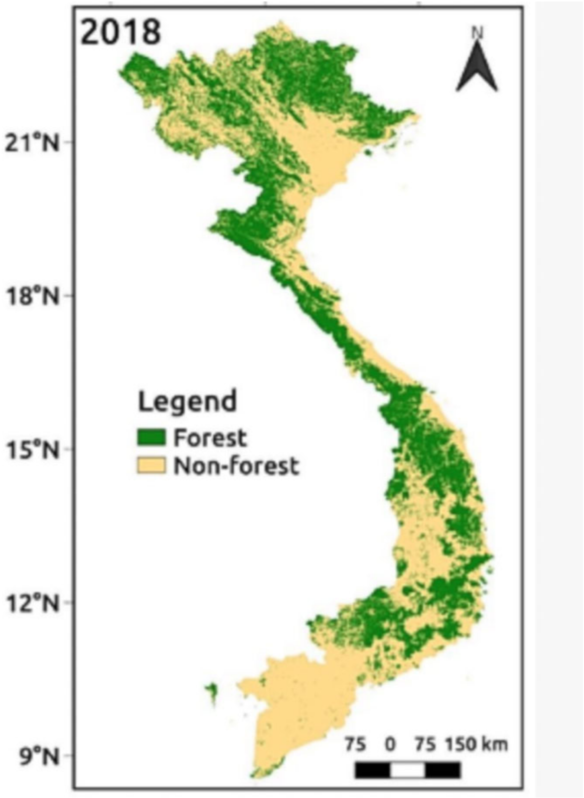


Figure 2.2. Forest – Non-Forest map in Vietnam. Source: Truong et al., 2019.

In Vietnam, forest biodiversity is concentrated mainly in special-use forests and protection forests that play a vital role in watershed protection and biodiversity conservation, contributing to climate change response. According to the purpose of biodiversity protection and conservation, special-use forests are classified into (i) national parks; (ii) nature reserve; (iii) species - habitat conservation areas; (iv) landscape protection zones (forests preserving historical-cultural relics, scenic spots); (v) forest of beliefs; (vi) urban environmental protection forests, industrial zones, export processing zones, economic zones, high-tech zones; (vii) scientific research and experimental forests; (viii) national botanical garden and (ix) national seed forest (Vietnam Ministry of Natural Resources and Environment, 2021). By 2020, the central region has 14 national parks, 24 nature reserves, 7 species, and habitat conservation areas, and 21 landscape protected areas, occupied by 50%, 42.8%, 58.3%, and 39.6% of the total of those in Vietnam, respectively. The special-use forest area of the three ecological regions is 0.61 million ha in the North Central Coast, 0.28 million ha in the South Central Coast, and 0.48 million ha in the Central Highlands, respectively (Vietnam Ministry of Agriculture and Rural Development, 2021b). The protection forests distributed in the three ecological regions of the central region is 1 million ha in the North Central Coast; 1.16 million ha in the South Central Coast, and 0.64 million ha in the Central Highlands, respectively (Vietnam Ministry of Natural Resources and Environment, 2021).

2.5. Soils

Viet Nam soils include 14 groups and 31 soil units. In the mountainous and hilly areas, the largest soils groups are Acrisols (20 million ha) followed by Ferrasols (3 million ha). These soils rapidly degrade and tend to be acidic with low fertility. However, they are suitable for forestation and perennial and fruit crops cultivation (Nguyen and Thai, 1999). Those in the deltas are mostly alluvial soils (3.4 million ha), marine sandy soils (0.5 million ha), and gley soils (0.5 million). Except for sandy soils, these soils are mostly very fertile and can cultivate effectively intensively. (Babatunde et al., 2016).

In Central Vietnam, Acrisols are developed from clay shale, metamorphic, sandstone, igneous rock, and ancient alluvium. They are found at altitudes from 25 m to 900m above sea level in the North Central Coast, 50 m to 900 m in the South Central Coast, and less than 1000 m in the Central Highlands. Soil properties vary according to the parent rock type. The leaching process leads to clay particles accumulating in the B horizon, and the soil becomes acidic due to the loss of alkaline substances. Quantitative results of the B layer, according to the quantitative classification method of FAO - UNESCO, show that the B layer of Acrisols meets the standards of B.Argic (Nguyen and Thai, 1999; Vietnam Soil Science Association, 2000). Ferrasols are found almost entirely in Central Highlands. They locate at high elevations, on sloping or gentle terrain, or strongly dissected. The typical parent rock is basalt. In addition, there are other parent rocks such as shale, metamorphic rock, and limestone. The weathering process of parent rocks happens intensively (Nguyen and Thai, 1999).

Alluvial soils in Vietnam are divided into 3 units: alluvial soils in the Red River system, those in the Mekong River system, and the other rivers system. Generally, the alluvial soils of the Red River and Mekong River systems are good. Those of the other rivers system have lower soil fertility because of their relatively poor chemical properties. Dystric Fluvisols occupy most of the alluvial soils in the central region. Their main characteristics are: they have a base saturation of less than 50%; there is no potential or active alum layer in the soil profile from the soil surface to a depth of 125cm; the soil is usually light brown; acidic (pH_{KCl} = 4.5 – 5); active aluminum content is moderate-high; Soil organic and nitrogen content are moderate; Soil total and available phosphorus are poor; Soil total potassium content and the exchangeable potassium content are moderate (NISF and DSTPQ, MARD, 2002). The marine sandy soils area in the Central Coast provinces is 0.34 million ha comprising 63 % of Vietnam's sandy soils. In spite of their small area, they play an essential role in regional economic growth (Hoang et al., 2010). The Umbric Gleysols are the only units of Gley soils distributed in the central region. These soils cover an area of more than 43,000 ha, to be found almost entirely in the North Central region. They are often flooded, and waterlogged the whole year cause there is no A layer, the soil has no structure, and gleying occurs strongly in the entire profile. These soils are usually very rich in organic matter and humus (OM% is often 3-4%), but this is mainly in the coarse humus form because of the slow mineralization of carcass of aquatic organisms. The soils are very acidic ($pH_{KCl} < 4.4$). They significantly contain reducing substances such as Fe^{2+}, H_2S..., and are poor to very poor in phosphorus and potassium (Vietnam Soil Science Association, 2000).

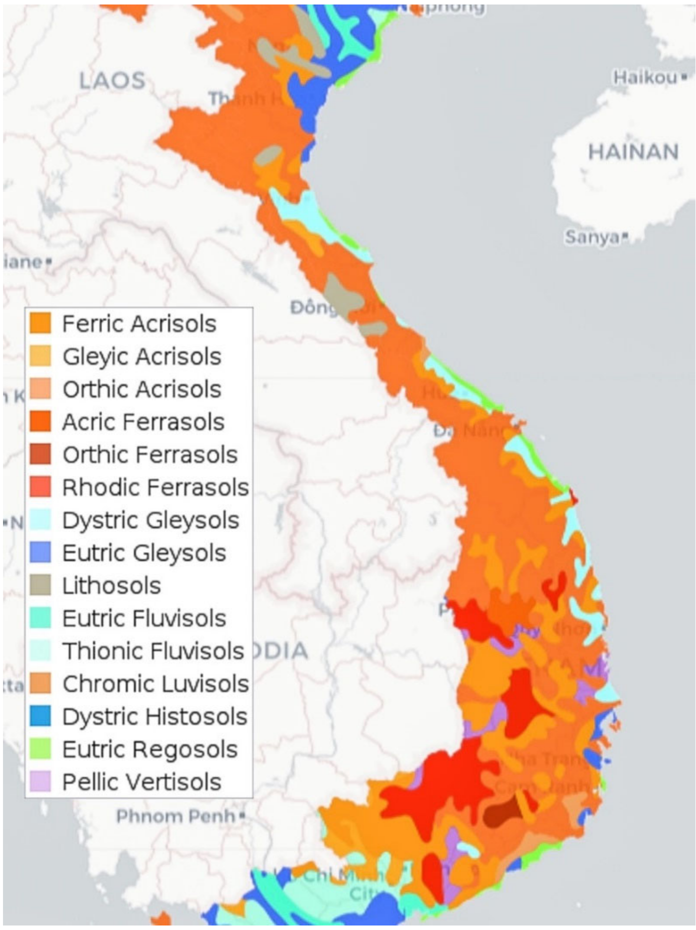


Figure 2.3. Soil types of Central Vietnam. Source: Open Development Mekong Source: https://data.opendevelopmentmekong.net.

Chapter 3

Analysis of the processes that generate surface runoff and soil erosion using a short-term water budget on a mountainous sloping cropland in central Vietnam

3.1. General

Water erosion is one of the most severe soil degradation phenomena worldwide (Lai, 1998; Pimentel, 2006; Mekonnen et al., 2015). It is the most hazardous phenomenon to soil productivity in five regions of the world: Africa, Asia, Latin America, Near East and North Africa, and North America (FAO & ITPS, 2015; Pennock, 2019), and can reduce the annual global crop yield by up to 0.4 % (FAO, 2015). Field measurement and modeling are two major approaches for water erosion assessment worldwide (Pennock, 2019). Wischmeier and Smith (1978) identified the factors affecting the intensity of soil erosion through analyzing data from fieldwork and computing these data to the Universal Soil Loss Equation (USLE). At a regional scale, the family of USLE models is suitable for testing hypotheses of the water erosion process, building scenarios, and assisting managers in policy setting, but not for an accurate measure of the soil loss rate (Panagos et al., 2016). Applying these models outside the United States of America requires researchers to establish local field measurements for models equation calibration (Kinnell, 2016). Evans and Boardman (2016) stated that an integrated field assessment-modeling approach will greatly benefit modeling efforts.

In Vietnam, much of the natural forest damaged during the war was further degraded by people looking for food and land for crops in the 1970s and the 1980s (Pham, 2000). Many migrants moving into the highlands had no choice but to settle on land that was not suitable for agriculture due to low fertility. When such land is not covered, it often becomes subject to severe erosion and a rapid decline in fertility (Nguyen et al., 2008). Vezina (2006) reported that water erosion is the most serious degradation problem in Vietnam. The degraded area encompasses 13 million ha, accounting for 40 % of the total land area of the country. In highland areas, soil loss is the leading cause of reductions in crop yields (Vu, 2015).

The Thua Thien Hue Province is situated along the tropical typhoon belt and thus frequently suffers from typhoons and floods. The highlands account for more than 75 %

of the total land area (Thua Thien Hue People's Committee, 2005; Duc et al., 2012), and are often affected by a harsh climate that causes water erosion. Additionally, the highland area is the home to minority ethnic groups, which together account for over 70 % of the total population, with agricultural production being maintained primarily for self-sufficiency. Furthermore, the land use and management practices of local governments and farmers mainly rely on exploiting natural soil fertility. Thus, they do not pay adequate attention to soil protection or focus on improving soil fertility.

In the northern and central highlands of Vietnam, a wide range of studies have been undertaken on soil erosion at the plot and watershed scales, particularly in parts of the highlands affected by timber harvesting, shifting cultivation, and forest clearance (Douglas, 2006; Sidle et al., 2006; Vezina et al., 2006). Fallow land with 10–15 % ground cover loses 223 t ha^{-1} $year^{-1}$ of soil, and a year-old coffee plantation intercropped with shade trees loses 44–59 t ha^{-1} $year^{-1}$ of soil. Extensive annual crop cultivation has caused a loss of 250–300 t ha^{-1} $year^{-1}$ of soil (Environment Database Division, 2002 cited by Nguyen, 2008). In spite of this, only two soil erosion studies were conducted in the highlands of Thua Thien Hue Province by Tran et al. (2014) and Pham et al. (2018). They used the family of USLE and a geographical information system (GIS) to predict soil loss rates, but they lack actual measurement data in the field, such as surface runoff volume, sediment yield and the rainfall erosivity factor (R) corresponding to the climatic conditions of the study area, and the cropping management factor (C).

Besides, their studies did not focus on the seasonal erosion risk, the dual impact of rainfall and coverage on soil loss, or the impact of rainfall on land cover, despite the fact that it is necessary for land managers to be aware of seasonal variations in water erosion risks (Kulikov et al., 2016). Thus, it is unclear how environmental conditions, such as rainfall characteristics and soil properties, interact to generate water erosion in different land-use types in the highlands of Thua Thien Hue Province. To compensate for the shortcomings of the afore-mentioned erosion studies, a plot scale study was undertaken, in which detailed water movement including the infiltration and runoff generation during rainfall events could be analyzed at short intervals. The results were demonstrably useful for improving our understanding of the factors contributing to rainfall characteristics, soils, and the erosion process at regional scales; in regions such as northern and northeastern Thailand (Funakawa et al., 2007), the Uluguru Mountains in Tanzania (Nishigaki et al., 2017), and eastern Cameroon (Nishigaki et al., 2017). Those researches that applied the short-term water budget have successfully clarified the integrated impact of rainfall characteristics and initial volumetric soil water content of each rainfall event on the water erosion generation process. Using this approach, the main objectives of the present study were to 1) clarify the site-specific conditions in rainfall and soil characteristics that contribute to the processes generating surface runoff and soil erosion; and 2) apply the results obtained to make recommendations that will decrease soil erosion risks at local farmers' practices.

3.2. Materials and methods

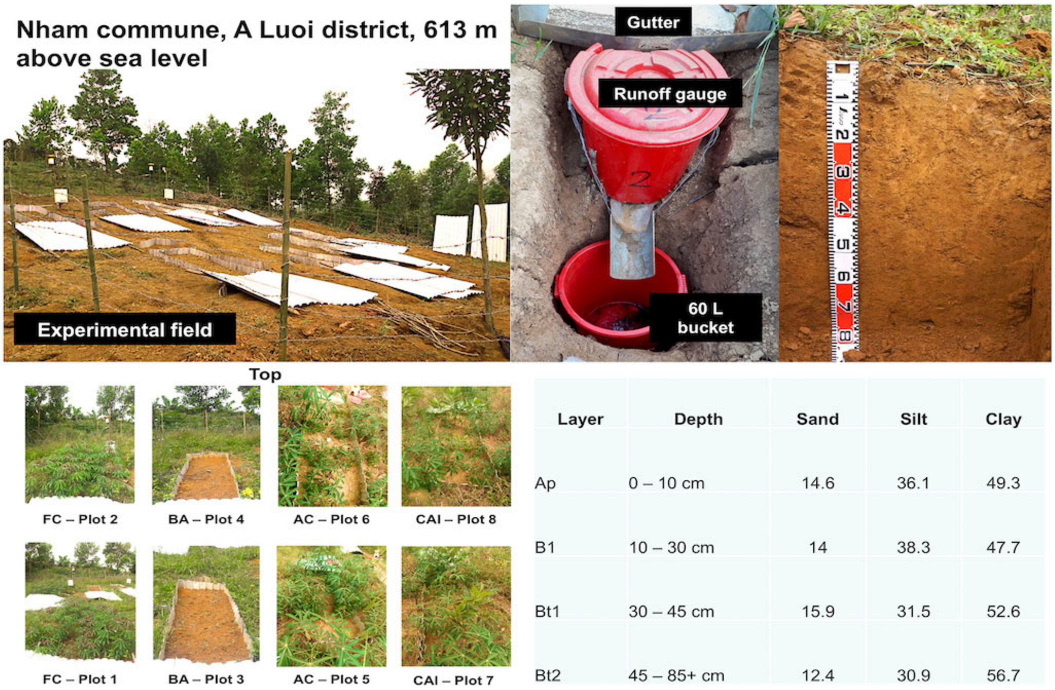
3.2.1. Site description

The research was conducted in the Nham commune, which is located at 16°1343″N, 107°1059″E, A Luoi District, Thua Thien Hue Province, Vietnam, where four ethnic minority groups (Pa Kô, Tà Ôi, Ka Tu, and Pa Hy) comprise more than 90 % of the total district population. The agricultural land is mainly situated on slopes ranging from 10–20°, at elevations of 600–800 m above sea level. The climate is characterized by a tropical monsoon climate, and the average annual rainfall and air temperature from 1984 to 2013 were 3808 mm (SD = 1027.8) and 21.7 °C (SD = 0.42), respectively. The major rainy season occurs from August to December, and rainfall is concentrated mainly in October and November, whereas the minor rainy season occurs from March to July. The soils at the study site are derived mainly from sedimentary rocks and/or felsic igneous rocks. Hence, they are strongly acidic and classified as Ferralic Acrisols and Dystric Cambisols, according to the FAO-UNESCO soil classification system (Thua Thien Hue People's Committee, 2005).

Food crop cultivation is the main livelihood for the local people. They typically follow traditional slash-and-burn cultivation, which is a nomadic farming style. However, since the 1980s, locals have cultivated two paddy rice (*Oryza sativa*) crops annually; the first is called fifth-month rice, which is grown from February to May, and the second is called tenth-month rice, which is grown from June to September. One upland rice crop is also cultivated between May and November. Maize (*Zea mays* L.) is planted as a monocrop or is intercropped with upland rice. Cassava (*Manihot esculenta*) is grown as a monocrop from February to October and from April to November or intercropped with *acacia* hybrid (*Acacia mangium* × *Acacia auriculiformis*). The success of crops depends mostly on the natural condition of the land, and locals generally do not care about applying fertilizer to the soil to enhance their crops (Ha & Hoàng, 2012). Animals such as buffalo, cattle, and goats are grazed in the forest, whereas pigs and poultry are kept within gardens. The raising of animals is focused around religion and meat as a food source or for sale in markets, and they are not used for labor and manure. Their work tools consist of large knives, diggers, rakes, and sticks for pricking holes.

3.2.2. Experimental setting

This study applied an experimental setting similar to that described by Nishigaki et al. (2017). Four treatments were established, each with two replicates: February cassava plot (FC), bare land plot (BA), April cassava plot (AC), and April cassava + September acacia intercropping plot (CAI). The plot size was 0.8 × 2.4 m and was small enough to calculate the water budget within the plot during rainfall events, and to minimize the impact of microtopography on runoff dynamics (Funakawa et al., 2007; Nishigaki et al., 2017). In FC, cassava was planted at the end of February and harvested on October 30, 2017, and 2018. In the AC and CAI, cassava was planted on May 1 and harvested on November 30, 2017, and 2018. Acacia was planted on September 5, 2017, in the CAI. The soil surface within all plots was kept free of weeds by hand throughout the experimental period, which was conducted once every two weeks. Fertilizers were not applied to crops.



Layer	Depth	Sand	Silt	Clay
Ap	0 – 10 cm	14.6	36.1	49.3
B1	10 – 30 cm	14	38.3	47.7
Bt1	30 – 45 cm	15.9	31.5	52.6
Bt2	45 – 85+ cm	12.4	30.9	56.7

Figure 3.1. Experimental design and soil profile at the experimental field A Luoi district.

The plots were surrounded by iron sheets on a slope ranging from 11.7–17.0° after they were cleared of natural vegetation (Figure 1). Each plot had one tipping bucket installed to collect runoff for later recording; the volume of water per tip was approximately 65 mL (0.03385 mm per plot). One large (60 L) bucket was used to collect the soil lost from each plot. For plots 2, 4, 6, and 7, three time-domain reflectometry moisture sensors were installed (CS616) at 0–15, 15–30, and 30–60 cm to determine the soil moisture. Tipping bucket rain gauges (TE525MM) and CS215 sensors were used to record the rainfall and air temperature, respectively. All sensors were connected to two CR1000 data loggers, and data were recorded every 10 min, except for the atmospheric temperature, which was taken at 30-min intervals.

3.2.3. Measurements of experimental components

A rainfall event was identified by the following rules: if any adjacent rainless period was shorter than the rainfall period, it was incorporated into the rain event; rainless periods <1 h were always included within a longer event; and rainless periods >6 h were always used as separators between two successive events (Veneziano & Lepore, 2012).

The average intensity of rainfall events was indicated as I_{1hrs}, which was defined as the ratio of the total rainfall volume to the duration of the rain event. The maximum rainfall intensity was denoted by I_{10max}, which is the total rainfall volume recorded at 10-min intervals. Rain showers were classified as light, moderate, or heavy rain, with rates of approximately 0–2.5, 2.6–7.6, and >7.6 mm h^{-1}, respectively (Linsley, 1977). Runoff water was collected twice per month or when the volume of runoff water was approximately two-thirds of the bucket volume and was weighed and used to calibrate the runoff gauges.

At depths of 0–5, 5–10, 20–25, and 40–45 cm, five replicates of undisturbed soil core samples of 100 cm^3 (5 cm height) were collected from the soil profiles. These samples were used to measure bulk density (Gross & Reinsch, 2002) and saturated hydraulic conductivity (Ks) using the constant-head and falling-head methods (Klute, 1965). The soil moisture constants of core samples at depths of 5–10, 20–25, and 40–45 cm were determined following the procedures of Klute (1986) and Dane and Hopmans (2002). The volume of the large pores was calculated using the gap between the saturated and wilting points. Sediments trapped in the large buckets were collected every two weeks, air-dried, and weighed.

3.2.4. Data analysis

All experimental data including air temperature, soil volumetric water content, rainfall, runoff volume and sediment amount was monitored during the period from February 27, 2017, to December 9, 2018. Sediment concentration was calculated as the ratio of the total sediment trapped in large buckets, and the total runoff volume was recorded by runoff gauges over the same period. The daily soil loss during this period was then computed by multiplying the sediment concentration and the daily runoff volume. To assess how the initial volumetric water content (VWC) affected runoff generation and water movement, rainfall events were grouped based on the initial VWC of the top layer (0–15 cm) at the beginning of each event (Nishigaki et al., 2016). Soil was considered wet when the initial VWC was greater than the field capacity ($\Psi m = -9.8$ kPa), dry when the initial VWC was lower than the wilting point ($\Psi m = -1{,}500$ kPa), and moist when the initial VWC was between the two water constants.

To evaluate the effect of environmental parameters on soil loss and runoff generation, multiple regression models were constructed using stepwise backward selection procedures ($P < 0.05$) (Rawlings et al., 1998; Funakawa et al., 2007; Prats et al., 2012 cited by Nishigaki et al., 2016). In advance to the analysis, the rainfall volume was log-transformed to restore normality. The runoff volume was then recalculated using the following equation:

$$\textit{Runoff volume} = \log(\textit{rainfall}) \times \textit{runoff coefficient of rainfall event}/100 \quad (1)$$

In addition, in many rainfall events, precipitation volume dropped off significantly within 1 or 2 h, and it continued to rain at a lower intensity for many hours, causing the I_{1hrs} of those events to be underestimated. Consequently, instead of I_{1hrs}, I_{10max} was selected as the independent variable that impacted runoff generation. The model equations used in the analysis are as follows:

$$RO_{volume} = a + b \times R + c \times I_{10max} + d \times VWC_{initial}, \quad (2)$$

$$SL_{volume} = a + b \times I_{10max} + c \times RO_{volume}, \quad (3)$$

where RO_{volume} (mm) is the runoff volume that was recalculated based on the logarithm of rainfall volume and SL_{volume} (Mg ha^{-1}) is the soil loss volume that was recalculated by applying the following equation: $SL_{volume} = RO_{volume} \times$ sediment concentration in runoff water/100. The rainfall volume (R), I_{10max}, and initial VWC ($VWC_{initial}$) were selected as independent variables that could explain runoff volumes

($\text{RO}_{\text{volune}}$), and the volume of soil loss ($\text{SL}_{\text{volume}}$) could be explained by the I_{10max} and $\text{RO}_{\text{volume}}$ generated during a rainfall event.

A two-way analysis of variance (ANOVA) with replication and Tukey's honestly significant difference (HSD) test ($\alpha = 0.05$) were used to evaluate the impact of coverage status on soil loss and runoff generation. All statistical analyses were performed using Microsoft Excel software.

3.3. Results

3.3.1. Soil physical characteristics

Bulk density generally increased as clay content increased, and decreased with increasing soil depth. The saturated hydraulic conductivity (Ks) was highest at the surface layer. The volume of large-sized pores was high, which contributed to the high Ks of the surface layer (0–10 cm) at the beginning of the experiment. The value of Ks was significantly lower 21 months later (Table 3.1, Figure 3.1).

Table 3.1. Soil water and physical properties at different depths

Depth	**Bulk density (Mg m^{-3})**	**Saturated hydraulic conductivity (mm h^{-1})**		**Volumetric water content at saturated point (L L^{-1})**	**Field capacity[1] (L L^{-1})**	**Wilting point[2] (L L^{-1})**	**Volume of larger-sized pores[3] (L L^{-1})**
		Before experiment	**After experiment**				
0–5 cm	1.03	7.3×10^2 (5.6×10^2)	3.6 (7.7)				
5–10 cm	1.03	51.5 (52.1)	0.2 (0.3)	0.514 (0.01)	0.425 (0.02)	0.302 (0.02)	0.212
20–25 cm	1.18	4.3 (2.3)	0.1 (0.1)	0.523 (0.01)	0.461 (0.02)	0.344 (0.02)	0.179
40–45 cm	1.24	0.2 (0.2)		0.526 (0.04)	0.471 (0.02)	0.345 (0.03)	0.181

Value shown in parentheses are standard deviations

[1] VWC at −9.8 kPa of matric potential (pF 2).

[2] VWC at −1,500 kPa of matric potential (pF 4,2).

[3] The difference in VWC between the saturated point and wilting point.

3.3.2. Rainfall characteristics and temporal dynamics of soil moisture contents

There were no differences in the monthly average temperatures between 2017 and 2018, but the total rainfall volume in 2018 accounted for only half of that in 2017, being 1354.5 and 2761 mm, respectively (Figure 3.2). Differences were observed mainly in July, September, and November; no typhoons affected Vietnam's central region in 2018, whereas in 2017 there were typhoons on July 25–26, September 14–15, and November 3–5, producing rainfall volumes of 97.8, 158.2, and 443.1 mm, respectively. These results demonstrate the extreme effect of typhoons on the research site, as well as on Thua Thien Hue Province as a whole. The third typhoon created a massive flood on flat land and caused landslides and erosion in the highland area. Based on climate data collected from 1984 to 2013 by the Thua Thien Hue Hydrometeorological Forecasting Center, the abnormally low rainfall in 2018 had not been observed before in the A Luoi District (the previous lowest rainfall volume was 2351 mm in 2012). However, some unusual phenomena were observed in the Thua Thien Hue Province, as follows: in Hue City in 1988 and 1989, the rainfall volumes were 1426 and 1751 mm, respectively, while in Nam Dong (another highland district of the province) in 2012, the rainfall volume was 1806 mm.

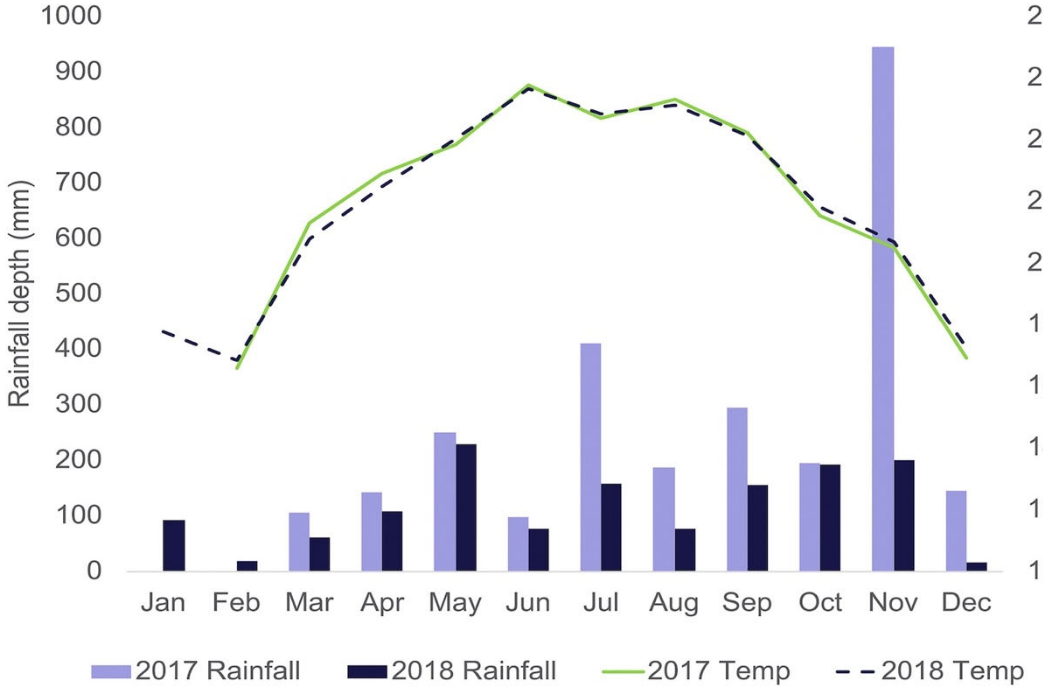


Figure 3.2. Monthly rainfall and temperature in 2017 and 2018.

During the experimental period, from February 27, 2017, to December 9, 2018, 205 rain events accounted for more than 95 % of the rainfall volume observed (the remaining volume comprised drizzle events). In 2017, 111 events occurred, comprising 49 events in the minor rainy season and 62 events in the major rainy season. Ninety-four events occurred in 2018, and 54 and 40 events occurred in the minor and major rainy seasons, respectively. While the proportion of heavy, moderate, and light rain events clearly differed between the minor and major rainy seasons in 2017 and 2018 (Figure 3.3) and the rainfall volume in the major season was significantly higher than that in the minor season in 2017, the difference in rainfall volume between the minor and major rainy seasons in 2018 was not large (Table 3.2). The heaviest event occurred over 54 h on November 3–5, 2017, with a rainfall volume of 443.1 mm. The I_{10max} recorded during the experimental period on July 12, 2017, was 17.1 mm (Figure 3.4).

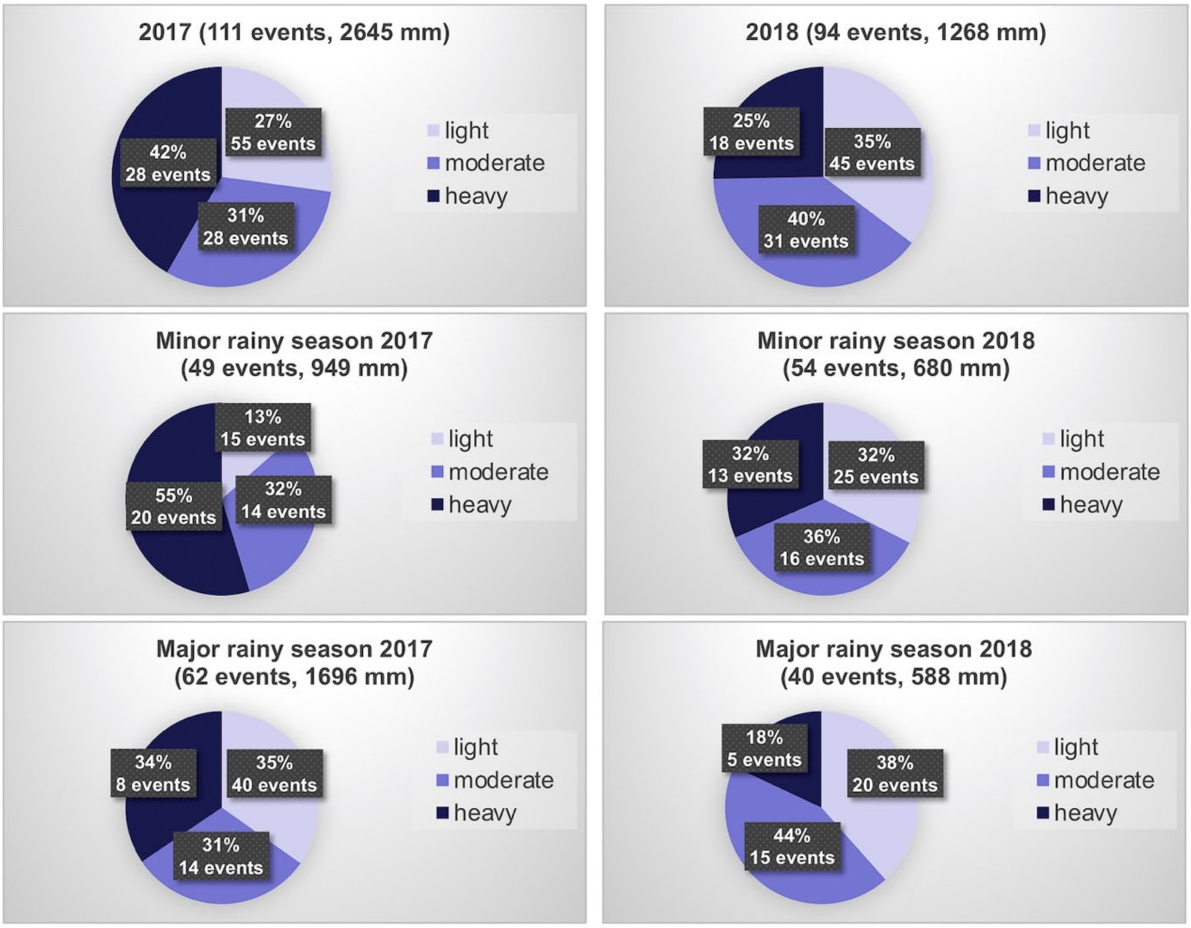


Figure 3.3. Proportion of amount of rainfall with different average rainfall intensities in 2017 and 2018.

The results of the I_{1hrs} classification showed that the I_{1hrs} values of rain events in the 2018 rainy seasons were much lower than those in 2017 (Figure 3.3). While the proportion of heavy rain events decreased sharply, the opposite trend was observed in the proportions of moderate and light rainfall events. There were 46, 59, and 100 events classified as heavy, moderate, and light rain, respectively. Heavy rainfall events were distributed mainly in the minor rainy seasons, light rainfall events occurred mostly in the major rainy seasons, and moderate rainfall events were distributed equally between the minor and major rainy seasons (Figure 3.3).

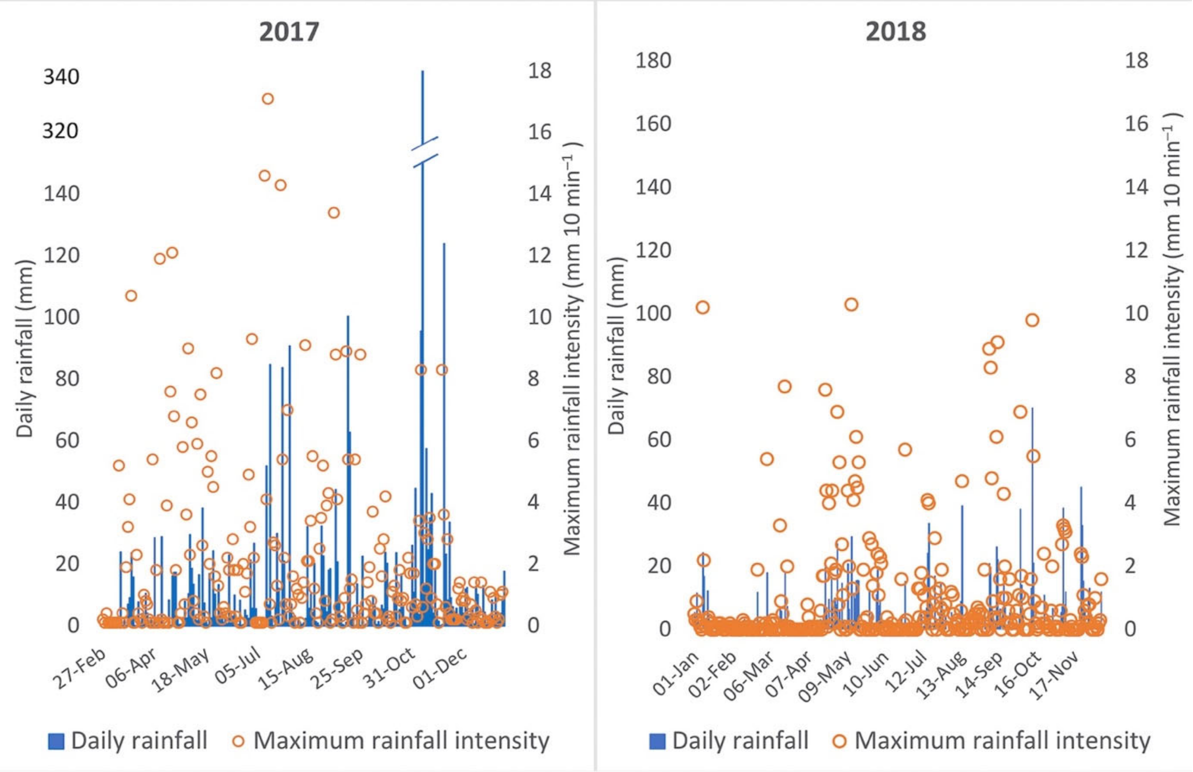


Figure 3.4. Daily rainfall and maximum 10-min intervals of rainfall intensity during the experiment period.

The daily soil moisture content differed considerably among treatments. Generally, the soil moisture content in the treatments was in the order of AC > CAI > FC > BA (Figure 3.5). However, because of the significant reduction in rainfall in 2018, a change in the soil moisture content in the soil layers occurred (Figures 3.5 and 3.6). That is, the number of days during which the soil was in the dry condition increased, and the number of days that the soil was in the wet condition decreased in 2018, compared to 2017. Indeed, the number of wet days in 2017 was 143, 106, 235, and 187 in FC, BA, AC, and CAI, respectively, and in 2018, the number of wet days was 66, 37, 87, and 70 in FC, BA, AC, and CAI, respectively. In contrast, in 2017, the number of dry days was 10 and 11 in FC and BA, respectively. There were no dry days in AC and CAI, and in

2018, the number of dry days was 59, 104, 34, and 21 in FC, BA, AC, and CAI, respectively.

Analyzing the daily VWCs at 0–15, 15–30, and 30–60 cm depths for the four treatments over the experimental period indicated that the VWCs were much lower in 2018 than in 2017, in not only the top layer but also in the sub-layers. In 2017, the VWCs in the sub-layers of all treatment plots were rarely lower than 0.40 cm^3 cm^{-3}. In 2018, however, the VWCs in the sub-layers fell below 0.35 cm^3 cm^{-3} (Figure 3.6).

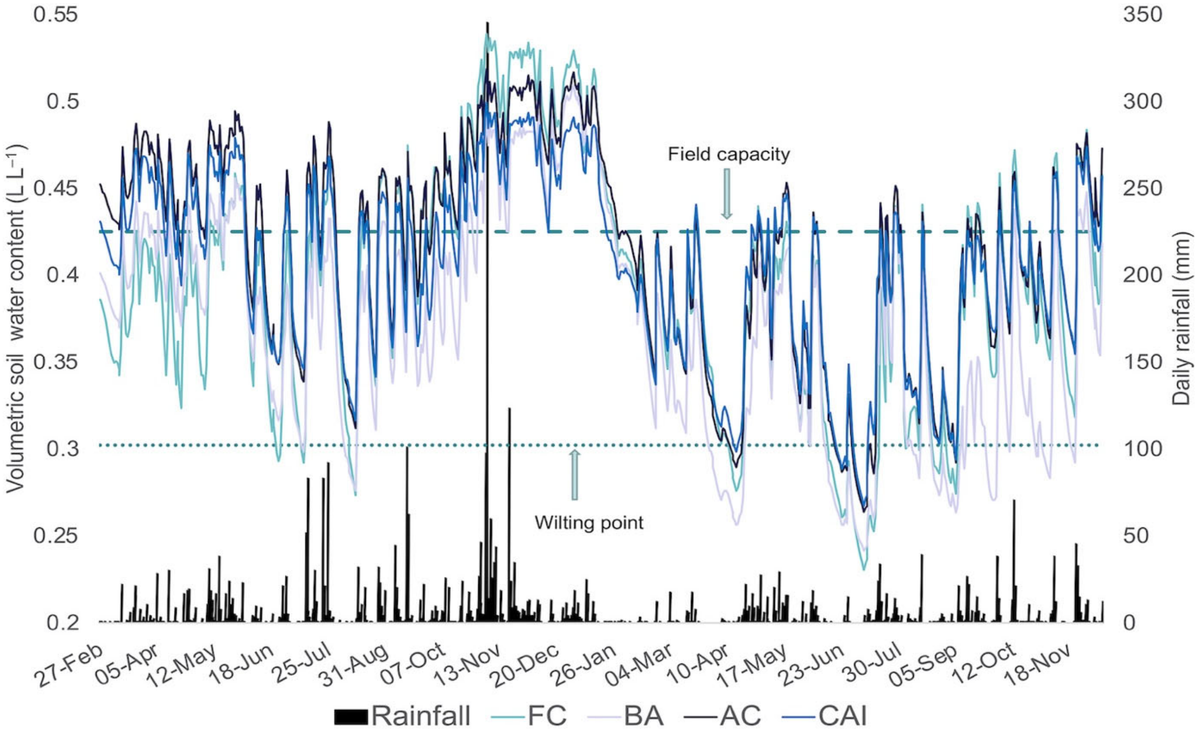


Figure 3.5. Daily rainfall and average soil moisture content at the surface layers during the experimental period.

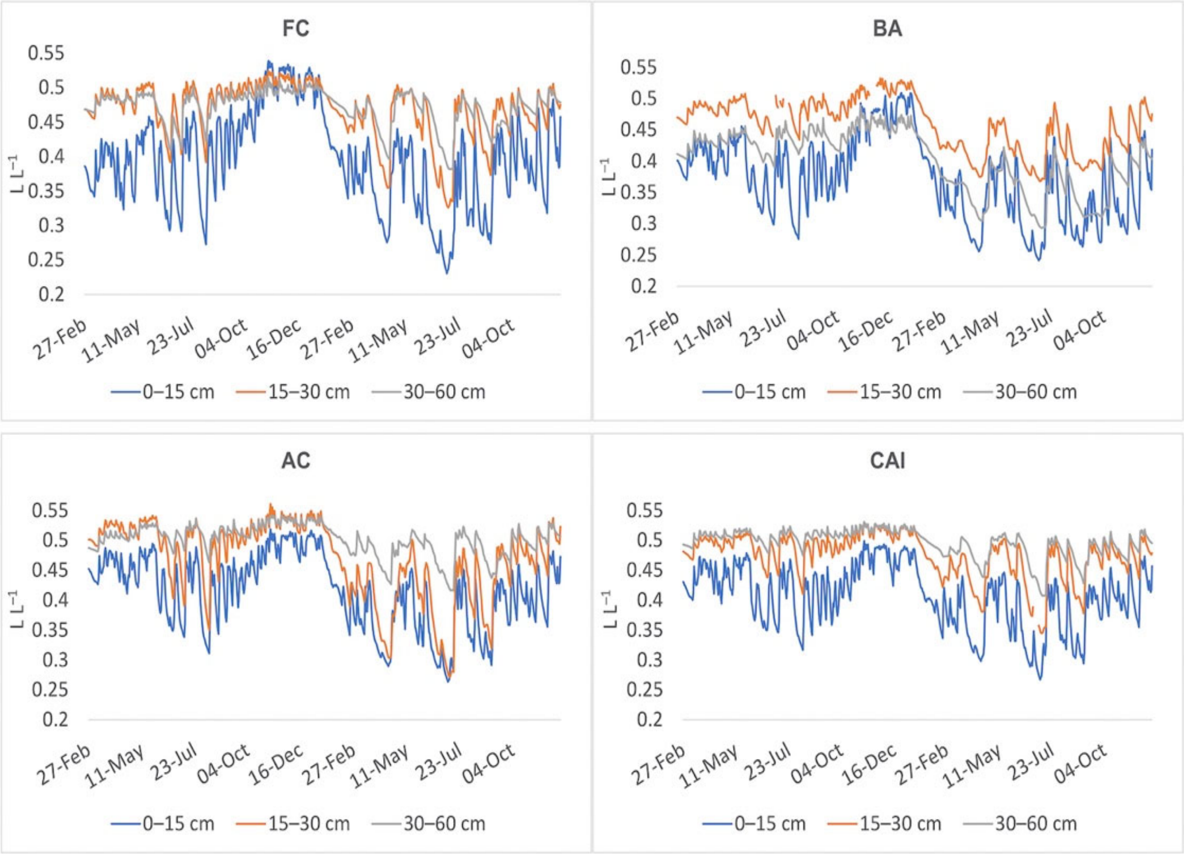


Figure 3.6. Daily volumetric water content at four treatments over the experimental period.

3.3.3. Runoff, soil loss volume, and sediment concentration in runoff water

The rainfalls, runoffs, and soil losses, runoff coefficients, and sediment concentrations in runoff water during the experimental period (from February 27, 2017, to December 09, 2018) are shown in Table 3.2. The differences in the runoff volumes, soil loss volumes, and runoff coefficients were significant among the plots: the runoff volumes, soil loss volumes, and runoff coefficients in BA were more than twice as high in FC and 1.5 times higher in AC and CAI.

According to Table 3.2, the soil loss volume in FC was significantly lower than that in AC, mainly because of the significantly lower runoff coefficients during the early three terms (8.2 and 15.5 % in Mar–Jul 2017, 16.9 and 23.7 % in Aug–Dec 2017, and 8.3 and 12.0 % in Jan–Jul, respectively). Early planting of cassava was considered advantageous for decreasing soil loss due to the early development of soil surface coverage. On the other hand, acacia intercropping (CAI) did not seem to be effective in suppressing surface runoff and soil loss relative to monocropping of cassava (AC), at least under the present conditions (April cassava + September acacia; in the first year).

Figure 3.7 shows the daily and cumulative soil losses during the experimental period. In the four treatments, soil loss accumulated substantially when heavy and large rain events occurred. In FC and BA, the highest soil losses occurred on November 5, 2017, when a typhoon (November 3–5) produced 443.1 mm of rain mostly on that day, while the soil surface was uncovered. In contrast, AC and CAI achieved their highest losses on May 19, 2018, when a series of heavy rain events occurred after the soil surface had been disturbed for April cassava crop cultivation.

In the 2017 minor rainy season, when the soil surface was not covered in BA or the coverage areas in cropping treatments were small (Figure 3.1), the I_{1hrs} values of many events were vigorous (Figure 3.3). Consequently, the soil aggregates were destroyed and the sediment eroded easily from the surface layers. This caused total soil loss, except in BA, and the sediment concentrations in runoff water from all treatments in the minor rainy season were much higher than those in the major rainy season. In the 2017 major rainy season, because of the much higher rainfall volumes (Figure 3.4) and VWCs in the surface layers (Figure 3.5), there were significant increases in the runoff volume and coefficients of all treatments, compared to those in the 2017 minor rainy season. This could explain why, in comparison between the minor and major rainy seasons in BA, the sediment concentration in runoff water was significantly reduced but the soil loss volume was slightly increased (Table 3.2). In contrast, in 2018, there was little difference in rainfall volumes and VWCs in the surface layers between the two rainy seasons (Table 3.2), which, combined with the steady decrease in heavy rain events (Figure 3.3), caused not only less soil loss and lower sediment concentrations, but also significantly reduced runoff volumes and coefficients for all treatments in the major rainy season, compared to those in the minor season (Table 3.2).

Analysis of the runoff coefficients indicated that the VWC at the surface layers and coverage status at the beginning of events differed between treatments. Thus, the difference in runoff coefficients was obvious. The runoff coefficients of the treatments decreased in the order BA > AC, which was almost equal to CAI > FC. However, in some periods, the order was different. In the 2017 minor rainy season, for instance, the VWCs at the surface layer in AC and CAI at the beginning of the rain events were significantly higher than in BA, and the crop coverage areas were insignificant. Consequently, the runoff coefficients did not differ among BA, AC, and CAI. In the later part of the major rainy season in 2018, when the February–October cassava crop was harvested, the lack of coverage caused the runoff coefficient in FC to be higher than those in AC and CAI (Table 3.2).

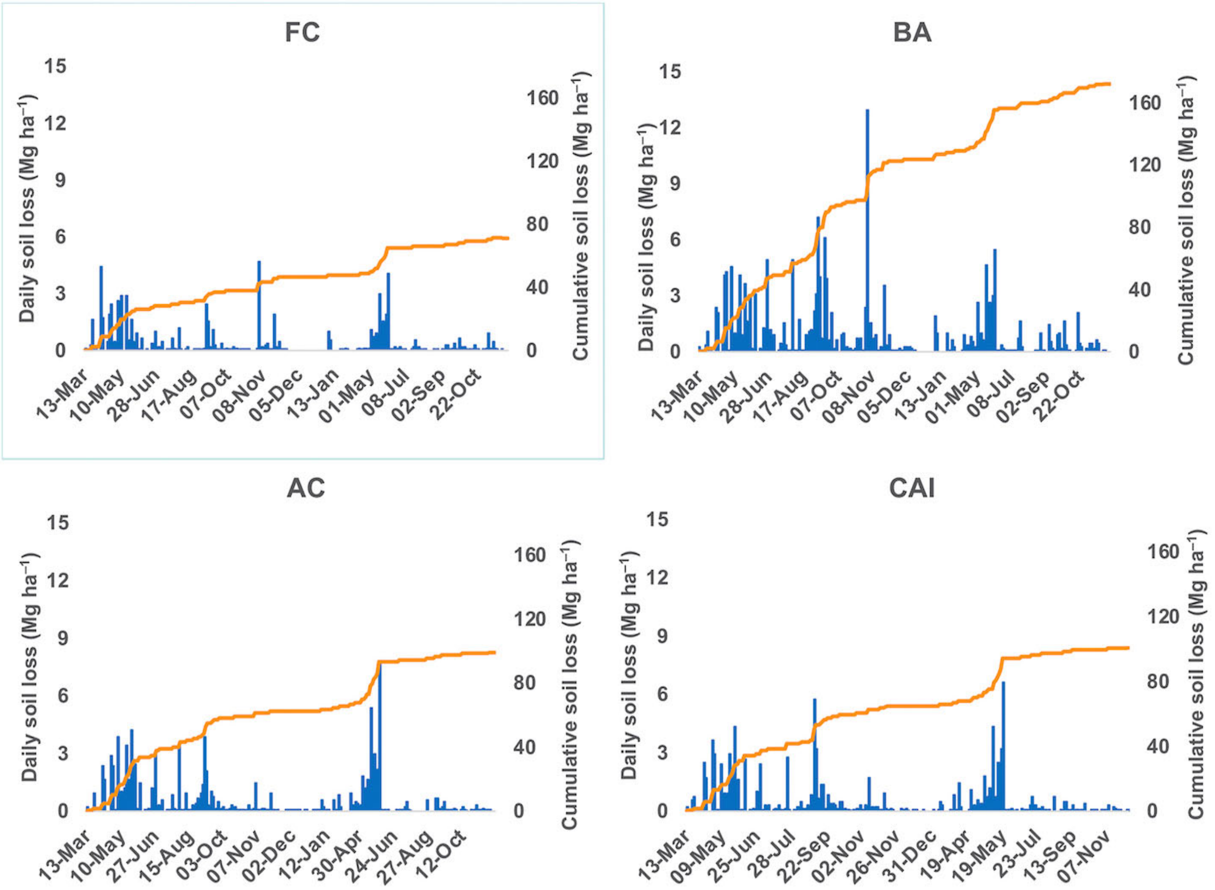


Figure 3.7. Daily and cumulative soil loss in the four treatments.

Two-way ANOVA with replication showed that the differences in soil losses, runoff volumes, and runoff coefficients among treatments and rainy seasons were statistically significant. A significant difference in sediment concentrations was found between the rainy seasons, but not within treatments ($P < 0.05$). Tukey’s HSD test ($\alpha = 0.05, 0.1$) indicated that the runoff coefficient and runoff volumes generated during the 2017 major rainy season were significantly higher than those in other rainy seasons. In AC and CAI, the runoff coefficients in the 2018 major rainy season was significantly lower than those in the other rainy seasons. While the differences in runoff volumes and runoff coefficients between bare land and cropping treatments was statistically significant, no significant difference in runoff volume and coefficient among cropping treatments was found. A non-significant difference in the volume of soil loss was found only between AC and CAI (Table 3.2).

Table 3.2. Rainfall characteristics and differences among treatments in runoff and soil loss amounts, runoff coefficient, and sediment concentration in surface runoff water

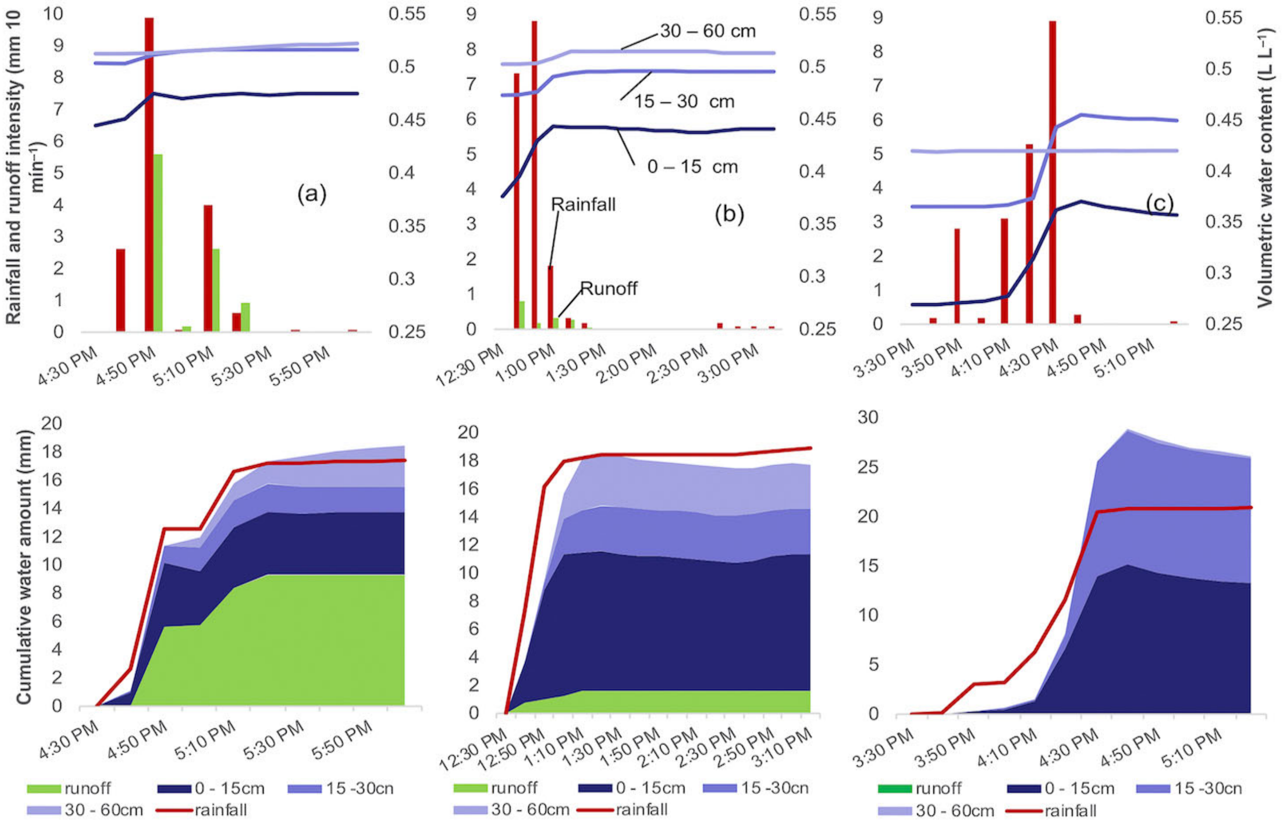
Treatment	**Period**	**Total rainfall (mm)**	**Number of rainfall events**	**Total runoff (mm)**	**Total soil loss (Mg ha^{-1})**	**Runoff coefficient (%)**	**Sediment concentration (g L^{-1})**
		A		**B**	**C**	**100 × B/A**	**100 × C/B**
1st Feb Cassava - FC	Mar–Jul 2017	1016	49	83.5 b	33.6 a	8.2 b	40.2 a
	Aug–Dec 2017	1745	62	294.4 a	15.8 c	16.9 a	5.4 c
	Jan–Jul 2018	714	54	58.9 b	21.6 b	8.3 b	36.7 a
	Aug–Dec 2018	640	40	29.9 b	6.7 d	4.7 b	22.5 b
	Total	**4115**	**205**	**466.7 B**	**78.7 C**	**11.3 B**	**16.9 NS**
2nd Bare land - BA	Mar–Jul 2017			140.6 b	57.1 b	13.8 b	40.7 a
	Aug–Dec 2017			643.4 a	67.5 a	36.9 a	10.5 c
	Jan–Jun 2018			123.8 b	35.9 c	17.3 b	29.0 b
	Aug–Dec 2018			78.2 b	13.5 d	12.2 b	17.3 c
	Total			**986.0 A***	**174.0 A**	**24.0 A**	**17.7 NS**
3rd Apr Cassava - AC	Mar–Jul 2017			157.9 b	45.4 a	15.5 b	28.8 b
	Aug–Dec 2017			414.4 a	19.4 c	23.7 a	4.7 c
	Jan–Jun 2018			85.7 bc	32.8 b	12.0 b	38.3 a
	Aug–Dec 2018			21.0 c	5.1 d	3.3 c	24.4 b
	Total			**678.9 B***	**102.7 B**	**16.5 B**	**15.1 NS**
4th Apr Cassava – Sep Acacia Intercropping - CAI	Mar–Jul 2017			150.1 b	42.3 a	14.8 b	28.2 a
	Aug–Dec 2017			394.1 a	23.6 c	22.6 a	6.0 c
	Jan–Jun 2018			108.1 b	36.0 b	15.1 b	33.3 a
	Aug–Dec 2018			17.3 c	3.4 d	2.7 c	19.4 b
	Total			**669.6 B***	**104.3 B**	**16.3 B**	**15.6 NS**
			HSD$_{0.05}$	**81.8**	**3.65**	**5.91**	**5.43**
			HSD$_{0.1}$	**71.1**			

Different letters indicate significant differences at $P < 0.05$ by Tukey's honestly significant difference test for two factors with two replicates (different capital letters indicate significant differences, NS indicates no significant difference among treatments, and different lowercase letters indicate significant differences among rainy seasons). * indicates a significant difference at the $P < 0.1$ level.

3.4. Discussion

3.4.1. Factors influencing runoff generation and water movement

Generally, surface runoff can be generated via two different mechanisms: saturation excess runoff (i.e., runoff is generated only when the soil moisture content exceeds the saturated point) and infiltration-excess runoff (i.e., runoff is generated when the surface water input exceeds the infiltration capacity of the surface layer) (Tarboton, 2003; Yang et al., 2015). Some studies have indicated that runoff ratio is controlled by initial soil moisture content (Penna et al., 2011) and total rainfall, but not by average rainfall intensity (Hino et al., 1988). Infiltration-excess runoff is rare in most humid regions (Tarboton, 2003), and soil moisture condition at the beginning of events significantly affects discharge rates (Meyles et al., 2003).



CAI - Plot 7
January 8 2018

CAI - Plot 8
September 25 2017

FC - Plot2
September 6 2018

Figure 3.8. Water balance during events with different initial volumetric water contents. Upper graph shows the intensity of rainfall and surface runoff (mm 10 min $^{-1}$) and volumetric water content at each depth. Lower graph shows cumulative water amount derived from rainfall in each proportion. (a) Rainfall event when initial surface moisture condition was wet. (b) Rainfall event when initial surface moisture condition was moist. (c) Rainfall event when initial surface moisture condition was dry.

The rainfall-runoff analysis in our study showed that when rainfall increased, the rain-free period shortened. Consequently, the soil moisture content increased, and wet conditions were more frequently observed. Moreover, the runoff coefficients in all treatments increased as rainfall increased (Table 3.2), and the soil surface was wetter

(Figure 3.5). This indicates that if rainfall volume of events are similar, a higher risk of runoff generation in wetter soil conditions could be observed (Figure 3.8)[1]. When surface soil was wet at the beginning of a rainfall event, rainfall infiltrated soil layers more slowly, and if soil layers became saturated, rainfall became runoff water (Figure 3.8a). In the case where the surface layer was in a moist condition, part of the rainfall infiltrated moderately into the soil layer, and the remaining ran off intermediately (Figure 3.8b). In contrast, when the soil was initially dry, most of the rainfall quickly infiltrated the soil layers, and only a small volume became runoff water (Figure 3.8c).

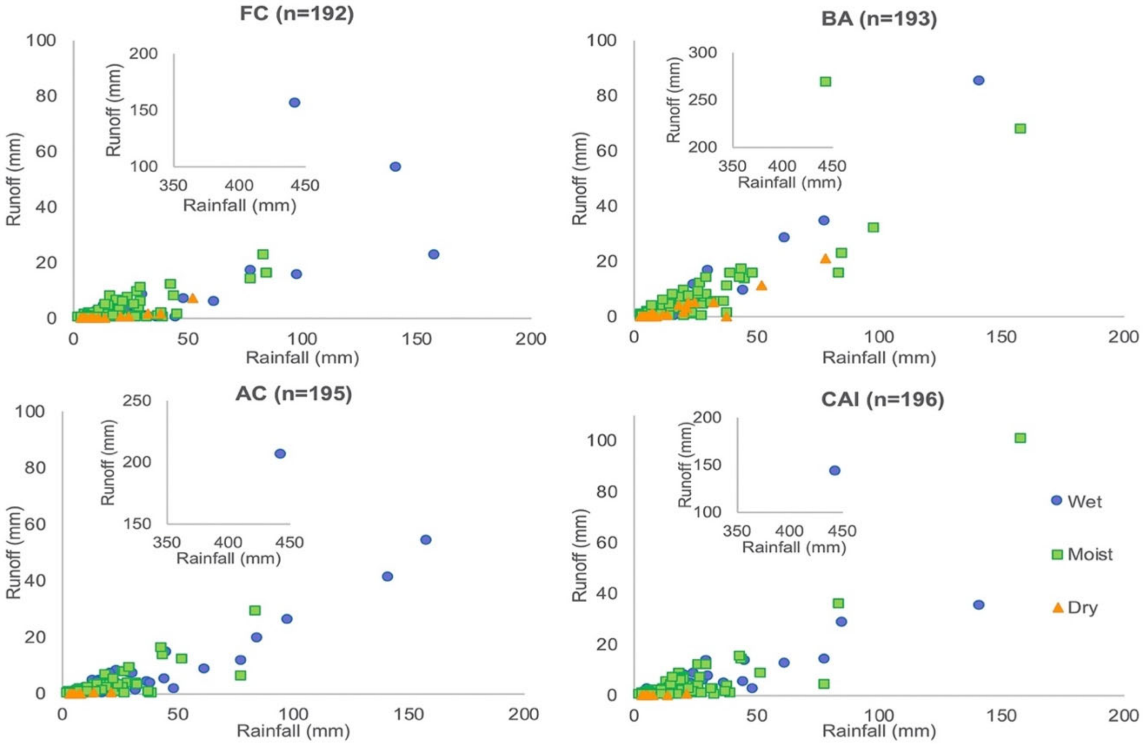


Figure 3.9. The relationship between rainfall and runoff in each event for the four treatments.

Analysis of the rainfall event runoff coefficients showed that in some events, surface runoff was generated even if soil moisture content did not exceed the saturated point (VWC = 0.514 L L^{-1}), even under dry conditions (VWC < 0.302 L L^{-1}) (Figure 3.9). This indicates that there were mechanisms reducing soil layer infiltration capacity

---

[1] At some rainfall events, the sum of runoff and volumetric soil water content at each depth did not equal the rainfall amount. The reasons are 1) high rainfall intensity causes error of rain-gauge measurement, and 2) spatially-uneven distribution of soil moisture especially under rapid water infiltration into the soil would hinder accurate measurement by TDR probes.

that were unaccounted for. Table 3.1 shows that the Ks values of all soil layers were significantly reduced after the 21-month experiment. This could have occurred because a series of heavy rain events occurred in the beginning period of the experiment when the soil surface was not covered or when coverage areas were small. The size of soil aggregate particles was reduced, topsoil that contained organic matter was eroded away, infiltration capacity was reduced, and consequently, infiltration-excess runoff occurred (Tarboton, 2003). In addition, the results from previous studies indicated that although the average rainfall event intensity did not exceed the infiltration capacity of the soil layers, if the rainfall intensity exceeds the infiltration capacity of the surface layer once in a given period, a runoff would be generated via infiltration-excess runoff (Xue et al., 2007; Yang et al., 2015). Horton (1945, cited from Kirkby and Chorley, 1967) assumed that, during the long-lasting rainfall events of constant intensity, the infiltration capacity of soil layers decreases continuously to a certain constant low value. When the infiltration capacity is lower than the rainfall intensity, at any time, overland flow begins all over the hillslope. Moreover, at near the base of the slope, overland flow can occur if soil water draining down the slope is forced to the surface by the complete saturation of the soil lower down the slope (Kirkby and Chorley, 1967). Overland flow generated in this condition could happen at restricted areas of the hillslope at much lower rainfall intensities than are required for common Hortonian overland flow. Whipkey (1965, cited from Kirkby and Chorley, 1967) reported that overland flow occurs immediately at lower slopes as half of the soil surface layer is saturated.

Previous studies reported that an increase in vegetation density caused a decrease in runoff discharge during a rainfall event (Torri and Poesen, 2014). Vegetation coverage slows down the formation of surface seals. Plant roots increase the volume of large-size pores and hence increase the infiltration rate, thereby decreasing runoff volume (Gyssels et al., 2005). In this study, the runoff volumes and runoff coefficients in bare land were significantly higher than those in cropping treatments (Table 3.2).

Pearson's correlation coefficients between the runoff volumes and environmental parameters for all treatments and the matrix correlations among the environmental parameters that impact runoff generation were built (Table 3.3). Relatively high positive correlations were found between the runoff volume and log(rainfall) or I_{10max} for all treatments (mostly at the $P < 0.05, 0.01$), while only weak correlations were detected between the runoff volume and rain duration or initial VWC (Table 3.3).

Table 3.3. Matrix correlation among environmental factors impacting runoff generation and soil loss

FC (n = 192)	Duration	Log(rainfall)	I_{10max}	Initial VWC	Runoff amount	Soil loss
Duration	1					
Log(rainfall)[1]	0.42***	1				
I_{10max}	–0.14**	0.63***	1			
Initial VWC	0.36***	0.14*	–0.15**	1		
Runoff amount[2]	0.13*	0.63***	0.64***	0.15**	1	
Soil loss[3]	–0.13*	0.32***	0.52***	0.01	0.66***	1
BA (n = 193)	Duration	Log(rainfall)	I_{10max}	Initial VWC	Runoff amount	Soil loss
Duration	1					
Log(rainfall)	0.43***	1				
I_{10max}	–0.13*	0.64***	1			
Initial VWC	0.31***	0.09	–0.13*	1		
Runoff amount	0.24***	0.76***	0.57***	0.22***	1	
Soil loss	–0.11	0.47***	0.61***	0.12*	0.59***	1
AC (n = 195)	Duration	Log(rainfall)	I_{10max}	Initial VWC	Runoff amount	Soil loss
Duration	1					
Log(rainfall)	0.46***	1				
I_{10max}	–0.14**	0.62***	1			
Initial VWC	0.33***	0.13*	–0.11	1		
Runoff amount	0.18**	0.70***	0.66***	0.15**	1	
Soil loss	–0.18**	0.33***	0.54***	0.04	0.54***	1
CAI (n = 196)	Duration	Log(rainfall)	I_{10max}	Initial VWC	Runoff amount	Soil loss
Duration	1					
Log(rainfall)	0.48***	1				
I_{10max}	–0.15**	0.62***	1			
Initial VWC	0.29***	0.11	–0.1	1		
Runoff amount	0.1	0.66***	0.69***	0.12*	1	
Soil loss	–0.19**	0.33***	0.55***	0.06	0.63***	1

[1] The rainfall amount was log transformed to restore normality. [2] The runoff amount was recalculated using the following equation: runoff amount = log(rainfall) × runoff coefficient of rainfall event/100. [3] Soil loss was recalculated by applying the following equation: soil loss = runoff amount × sediment concentration in runoff water/100. I_{10max} is the maximum 10-min interval rainfall intensity. *** Positive correlation at the $P < 0.01$ level; ** positive correlation at the $P < 0.05$ level; * positive correlation at the $P < 0.1$ level.

To clarify further how well the selected independent variables and coverage status interacted with runoff generation, multiple regression model was carried out using the equation (2). According to the results shown in Table 3.4, in minor rainy seasons, it was notable that $VWC_{initial}$ was usually appropriate as an explanatory variable, in addition to I_{10max} and/or R, except for BA. A total of 60 % of the variance in runoff volume was explained by the R and I_{10max} of the rainfall events, while in FC, the I_{10max} and $VWC_{initial}$ of rainfall events explained 59 % of the variance in runoff volume. The I_{10max}, R, and $VWC_{initial}$ values of rainfall events explained 72 and 73 % of the variance in the runoff volume in AC and CAI, respectively. The cumulative R^2 of the selected variables in AC and CAI were higher than those from BA and indicated higher risks of runoff generation if conditions were initially wetter.

In contrast, in major rainy seasons, $VWC_{initial}$ was not suitable as an explanatory variable during the stepwise regression for cropping treatments, and 48, 51, and 44 % of the variance in runoff could be explained by the R and I_{10max} of rainfall events in FC, AC, and CAI, respectively. In BA, 70 % of the variance was explained by the $VWC_{initial}$, R, and I_{10max} of rainfall events. The reduction in the cumulative R^2 of selected variables in the major rainy season for cropping treatments indicated that the coverage status strongly impacted runoff generation.

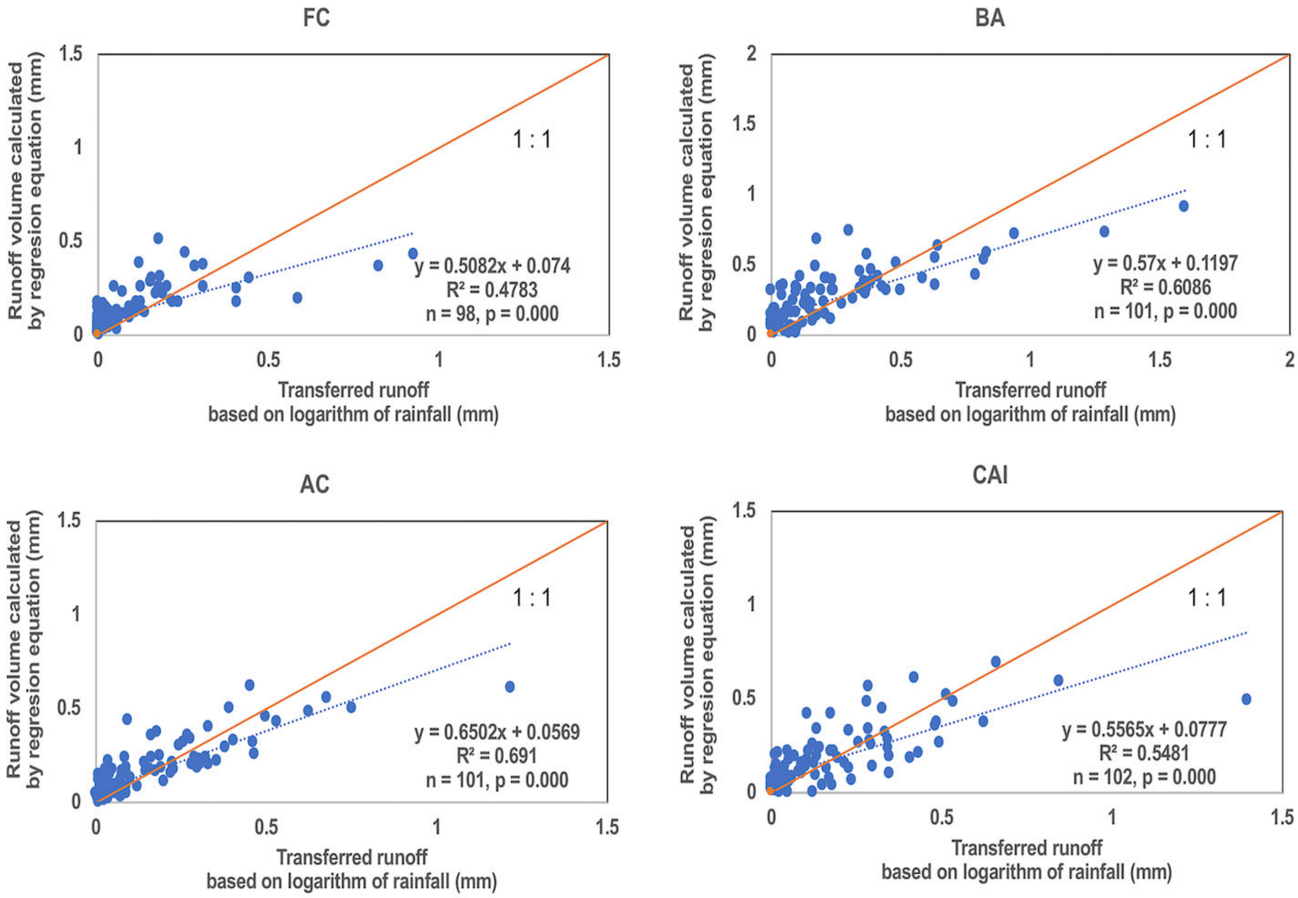


Figure 3.10. Comparison of runoff volume recalculated based on the logarithm of rainfall and those calculated by the regression equation in the four treatments in 2017.

To test the applicability of the regression models, we compared the runoff volume that was calculated by the regression equation (2) and that measured actually after logarithmic transformation for each of the plots. According to these figures, there is a bias that the equations tended to underestimate the runoff volume when it was high and the opposite trend was found when it was low, in spite of apparent high values of R^2. Hence, this approach could be applied only for estimating possible factors but may have a limitation for simulating actual runoff volumes (Figure 3.10).

To summarize, the results of regression model analysis of surface runoff partly proved the contribution of the Hortonian mechanism (infiltration-excess runoff) in runoff generation. During the experimental period, the factors that determined runoff generation in all treatments were the rainfall volume and I_{10max}. In addition, $VWC_{initial}$ was often a driving factor for outcome variables in the cultivated plots during the minor rainy season. The higher the I_{10max}, the greater the rainfall event, and the wetter the $VWC_{initial}$ at the surface layer, the more runoff will be generated. Furthermore, coverage status, by decreasing the effects of environmental factors, had a substantial impact on runoff generation.

Table 3.4. Multiple stepwise regression of runoff amount using log(rainfall)[1], I_{10max}, and initial VWC as explanatory variables

Treatments	**Variables**	**Whole rainy season**		**Minor rainy season**		**Major rainy season**	
		Coefficient	*P*-value	Coefficient	*P*-value	Coefficient	*P*-value
FC		**n=192**		**n=100**		**n=92**	
	Constant	–0.28		–0.23		–0.18	
	log(Rainfall)	0.12	1.2E–05			0.2	1.2E–07
	I_{10max}	0.023	3.9E–11	0.032	5.1E–19	0.012	0.029
	Initial VWC	0.41	7.7E–04	0.55	1.4E–03		
	Cum. R^2	0.53		0.59		0.48	
BA		**n=193**		**n=96**		**n=97**	
	Constant	–0.52		–0.17		–0.73	
	log(Rainfall)	0.38	3.3E–20	0.26	3.3E–20	0.39	4.0E–12
	I_{10max}	0.016	1.0E–03	0.018	1.0E–03	0.032	7.5E–05
	Initial VWC	0.70	1.1E–04			1.16	1.5E–05
	Cum. R^2	0.62		0.6		0.7	
AC		**n=195**		**n=94**		**n=101**	
	Constant	–0.36		–0.29		–0.24	
	log(Rainfall)	0.21	3.3E–11	0.16	5.6E–05	0.27	2.2E–08
	I_{10max}	0.024	6.5E–10	0.025	5.9E–09	0.02	4.3E–03
	Initial VWC	0.43	6.4E–03	0.42	8.3E–03		
	Cum. R^2	0.59		0.72		0.51	
CAI		**n=196**		**n=97**		**n=99**	
	Constant	–0.36		–0.34		–0.19	
	log(Rainfall)	0.17	2.2E–07	0.15	1.0E–03	0.23	1.7E–06
	I_{10max}	0.031	5.7E–14	0.034	3.1E–12	0.017	0.012
	Initial VWC	0.52	7.7E–03	0.55	0.01		
	Cum. R^2	0.58		0.73		0.44	

[1] The rainfall amount was log transformed to restore normality. The runoff amount was recalculated using the following equation: runoff amount = log(rainfall) × runoff coefficient of rainfall event/100.

3.4.2. Impact of environmental factors on soil loss

Many studies have shown that in tropical regions where annual average precipitation is often over 2500 mm, heavy rains and/or squalls are the main factors determining water erosion (Hamanaka et al., 2014). Rainfall intensity, rain duration, and raindrop energy are the drivers forcing the degree of soil loss (Römkens et al., 2002). The results shown in Table 3.2 and Figure 3.4 indicate that higher rainfall event intensity correlated with greater severe soil sediment loss in all treatments.

Water erosion progresses through the following stages: soil aggregates are broken apart by energy from raindrops and soil fractions are detached from the ground, transported by surface runoff, and deposited downhill (Kinnel, 2006; Matsumoto et al., 2016). Water erosion not only requires the detachment of soil fractions via high-energy rain drops but a high volume of surface runoff for transporting the loose components. This theoretical perspective was validated in our experiment. Analyzing the daily and cumulative soil loss across the four treatments indicated that soil loss from events during the later parts of the 2017 and 2018 minor rainy seasons and the 2018 major rainy season were low despite heavy rains (Figures 3.4, and 3.7).

Pearson's correlation between soil loss volume and environmental parameters indicated that soil loss was positively correlated with I_{10max}, log(rainfall), and runoff volume generated during rainfall events in all treatments ($P < 0.01$). A statistical correlation between soil loss and initial VWC was only found in BA, and statistically negative correlations between soil loss and rainfall duration were found in the cropping treatments. In addition, log(rainfall), runoff volume, and I_{10max} were strongly correlated with each other ($P < 0.01$) (Table 3.3).

Table 3.5 shows the results of stepwise regression for the whole year, major, and minor rainy seasons separately. In the minor rainy seasons, I_{10max} was rejected for all treatments, and only the RO_{volume} was selected as an explanatory variable for soil loss. A total of 67, 59, 55, and 59 % of the variance in soil loss was explained solely by the RO_{volume} at FC, BA, AC, and CAI, respectively. In major rainy seasons, the contribution of I_{10max} was definitive, with an accessory impact from RO_{volume}. In AC, the RO_{volume} was rejected as an explanatory variable, and 36 % of the variance in soil loss was explained only by I_{10max}. A total of 48, 57, and 36 % of the variance in soil loss was explained by I_{10max} and RO_{volume} in FC, BA, and CAI, respectively. The reduction in the cumulative R^2 of selected variables occurred in major rainy seasons for cropping treatments but not for bare land, and the cumulative R^2 values of selected variables in AC and CAI were much lower than those in FC and BA, indicating how effectively the coverage status reduced soil loss.

To test the applicability of the regression models, we compared the soil loss volume that was calculated by the regression equation (3) and that measured actually after logarithmic transformation for each of the plots. Like in the model equations for runoff volume, a similar bias was observed for the equations for soil loss, though data is not presented here, indicating the limitation of this approach.

Table 3.5. Multiple stepwise regression of soil loss using I_{10max} and runoff amount[1] as explanatory variables

Treatments	**Variables**	**Whole rainy season**		**Minor rainy season**		**Major rainy season**	
		Coefficient	*P*-value	Coefficient	*P*-value	Coefficient	*P*-value
FC		**n=192**		**n=100**		**n=92**	
	Constant	–0.001		0.001		–0.004	
	$I_{10\ max}$	0.002	0.025			0.003	1.2E–09
	Runoff amount	0.16	3.9E–13	0.31	1.5E^{-}25	0.03	8.4E–03
	Cum. R^2	0.45		0.67		0.48	
BA		**n=193**		**n=96**		**n=97**	
	Constant	–0.002		0.002		–0.004	
	$I_{10\ max}$	0.01	4.2E–09			0.01	1.0E–10
	Runoff amount	0.1	1.1E–07	0.33	4.8E–20	0.04	9.0E–03
	Cum. R^2	0.46		0.59		0.57	
AC		**n=195**		**n=94**		**n=101**	
	Constant	–0.002		0.003		–0.004	
	$I_{10\ max}$	0.005	2.8E–05			0.005	2.9E–11
	Runoff amount	0.09	5.4E–05	0.3	1.1E–17		
	Cum. R^2	0.35		0.55		0.36	
CAI		**n=196**		**n=97**		**n=99**	
	Constant	–0.001		0.003		–0.005	
	$I_{10\ max}$	0.004	5.1E–03			0.005	9.7E–06
	Runoff amount	0.14	1.2E–09	0.27	6.0E–20	0.04	0.03
	Cum. R^2	0.42		0.59		0.36	

The rainfall amount was log transformed to restore normality. [1]The runoff amount was recalculated by using the following equation: runoff amount = log(rainfall) × runoff coefficient of rainfall event/100. Soil loss was recalculated by applying the following equation: soil loss = runoff amount × sediment concentration in runoff water/100.

During the experimental period, the rainfall duration did not have an impact, and the runoff volume and I_{10max} were the primary factors controlling soil loss in all treatments. The coverage status strongly affected soil loss. During the minor rainy seasons, the driving force of soil loss might be the volume of runoff generated during rainfall events. In contrast, in the major rainy seasons, I_{10max} was the main factor controlling soil loss in all treatments.

3.4.3. Comparison of our findings to previous studies

Previous studies that applied the same experimental settings have been undertaken in northern Thailand (Funakawa et al., 2007), Tanzania (Nishigaki et al., 2016), and Cameroon (Nishigaki et al., 2016). Similar to our findings, these studies reported that runoff generation was limited and water quickly infiltrated into deeper layers when the initial VWC of the top layer was low. The Ks of the soil layers play an important role in runoff generation. Furthermore, rainfall intensity is the main factor controlling soil loss. Our results are considered to confirm several past achievements obtained by different approaches as well. For example, Dunin (1976, cited from Cerdà, 1998) reported that higher soil moisture content caused lower infiltration rates and higher runoff generation. The runoff coefficients were higher in the wet seasons and low in the summer when the catchments became dryer (Merz and Blöschl, 2009). Rainfall intensity is one of the main factors that trigger runoff and water erosion generation (Mathys et al., 2005; Abu Hammad et al., 2006, Hao et al., 2018).

In addition, we found that crop cover had a substantial influence on soil loss and runoff generation, and the seasonal changes in soil erosion mechanisms were significant. Indeed, in the minor rainy seasons, when the coverage area was unremarkable, the portion of heavy rain was vigorous, and the fluctuation in soil moisture was significant, the integrated impact of I_{10max} and/or rainfall volume and initial VWC activated surface runoff. Soil loss occurred only if the runoff was powerfully generated. In the major rainy seasons, the soil was mostly in wet conditions, with high clay content that caused the soil surface to be very sticky and plastic, and the percolation rate of water was limited. Hence, most of the rainfall could run off. Furthermore, the I_{10max} of most rainfall events was low. Soil aggregates were only slightly disrupted, and only a small volume of sediment was detached from the soil surface. Thus, soil loss was generated only if the I_{10max} was high.

3.4.4. Recommendation for local farmers to decrease soil erosion loss

According to our findings, there were two periods of the year during which a high risk of soil loss was observed. The first lasted from the middle of April to the end of May, when the heavy rains were concentrated and while the coverage of crop was trivial. The second was the typhoon season from the end of October to the end of November, during which time the soil surface was vulnerable to erosion after cassava harvesting. In contrast, the lowest risk of soil loss was observed between the middle of December and the end of February, when rainfall comprised light rain and drizzle events.

In terms of cropping management, early cassava planting in February had the advantage of decreasing the risk of surface runoff and soil loss relative to April planting, while acacia intercropping was not effective in the initial year of cropping. To understand the practical effects of intercropping, it is necessary to monitor field conditions for at least two to three years.

To reduce the soil loss rate, we recommend two optional modifications: 1) an effective utilization of plant materials as mulch either after weeding or harvesting, to increase the soil surface coverage at the start of the new cropping season or after harvesting, respectively; and 2) re-arranging the cropping calendar to bring cassava seeding forward or delay harvesting.

3.5. Conclusion

Our research has shown that tropical storms strongly affect the rainfall regime of sloping croplands in Thua Thien Hue province, Central Vietnam. Using the short-term water budget in a small scale plot, the processes and mechanisms of runoff generation and soil loss could have been successfully analyzed. Although the coverage status strongly impacted surface runoff and soil loss, the mechanisms of accelerated runoff generation and water erosion on agricultural land in A Luoi district, Thua Thien Hue Province, were different in minor and major rainy seasons; in minor rainy seasons, in addition to I_{10max} and/or rainfall volume, $VWC_{initial}$ was the primary factor controlling runoff generation. The volume of soil loss was driven by the volume of runoff generated during rainfall events. However, in the major rainy seasons, rainfall volume and I_{10max} were decisive factors for runoff generation, and I_{10max} was the key factor controlling soil loss. To decrease the risk of surface runoff and soil loss, plant materials should be effectively utilized as mulch either after weeding or harvesting during high-risk periods, and the farming calendar should be re-arranging to bring forward cassava planting or postpone harvesting.

Chapter 4

Water erosion mitigation practices in the agricultural highlands of Thua Thien Hue province

4.1. General

Water erosion caused by heavy rainstorms and surface runoff is a serious issue in agricultural highlands globally (Coppin and Richards, 1990), but especially in developing countries in tropical and subtropical regions (Lal, 2001). The loss of topsoil, which contains the highest levels of nutrients and organic matter, during the erosion process (Polyakov and Lai, 2008) decreases on-site soil productivity and increases the amount of sediment and other pollutants in the off-site receiving water (Segarra et al., 1991; Lal, 2001; Zhu et al., 2013). Consequently, there is an economic cost associated with enhancing soil productivity and an environmental cost in managing the sediment contamination and pollution of surface waters (Pennock, 2019).

Many practical techniques, such as minimizing changes in land use, eliminating or reducing tillage, and maintaining a sufficient coverage area, have been applied to mitigate water erosion (Pennock, 2019). One of the most efficient techniques is residue mulching (Mostaghini et al., 1994). Many studies have reported that applying residue mulch maintains and protects the soil and increases soil health (Armbrust and Jackson, 1977). Organic mulch protects the soil surface against the detachment force of rain, stops the spreading out of runoff, and decreases the runoff rate (Wishmeir, 1973; Cerdà et al., 2016).

To manage water erosion in Vietnam, scientists have suggested many practical techniques, such as planting trees along contour lines, planting trees in ditches (e.g., tea, sugarcane, pineapple); planting trees in holes (e.g., coffee, rubber, citrus, avocado), covering the soil with green manure plants, rice straw, sugarcane leaves, grass residue, polyethylene, or rootstock; plowing and weeding along contour lines; crop rotation, intercropping, and overlapping crops; arranging appropriate planting and harvesting times; using a sloping land-farming model; and minimal farming (Nguyen and Thai, 1999). The most feasible practice should be, however, based on specific rainfall, topographical, and soil conditions in the targeted area.

Thua Thien Hue Province is located in the central part of Vietnam and is characterized by a unique climatic condition with quite high rainfall due to frequent typhoon attacks during September to December. Mountainous ethnic minorities inhabit the highland area of the province with minimal application of modern agriculture. For stabilizing and developing their livelihood, finding appropriate agricultural land management that could mitigate soil erosion risk is an urgent issue.

To clarify the site-specific conditions in rainfall and soil characteristics that contribute to the processes generating surface runoff and soil erosion and apply the results obtained to make recommendations that will decrease soil erosion risks at local farmers' practices, we carried out a series of field measurements. The results of our previous study indicate that there is insufficient coverage area in the initial stage after planting cassava and after harvesting, which causes soil loss and runoff after heavy rainfall events. Intercropping with cassava and *Acacia* did not significantly affect water erosion in the first year (Le et al., 2022). The present study was conducted to provide better recommendations for local farmers and the government regarding water erosion mitigation by the intercropping and surface mulching in sloping croplands.

4.2. Material and Methods

4.2.1. Description of the research area

This study was conducted in the Nham Commune, which is located at 16°1343″N, 107°1059″E, in the A Luoi District, Thua Thien Hue Province, Vietnam. Four ethnic minority groups make up more than 90% of the total population of this district. The agricultural land is located mainly on steep slopes (mostly with an incline greater than 20°), with an elevation of 600-800 m above sea level. The study location is in a tropical monsoon climate zone, with an average annual rainfall of 3,808 mm and an average air temperature of 21.7 °C over the previous 30 years. The major wet season occurs from August to December, with the majority of the rainfall occurring in October and November. The minor wet season occurs from March to July.

The soil in the study site is derived mainly from sedimentary rock and/or felsic igneous rock (i.e., granite and rhyolite); hence, it was strongly acidic and classified as Ferralic Acrisols (almost) or Dystric Cambisols, according to the FAO-UNESCO soil classification system (Thua Thien Hue People's Committee, 2005). The average land area per capita used for agricultural production is 1,240 m^2 in the A Luoi District and 2,714 m^2 in the Nham Commune.

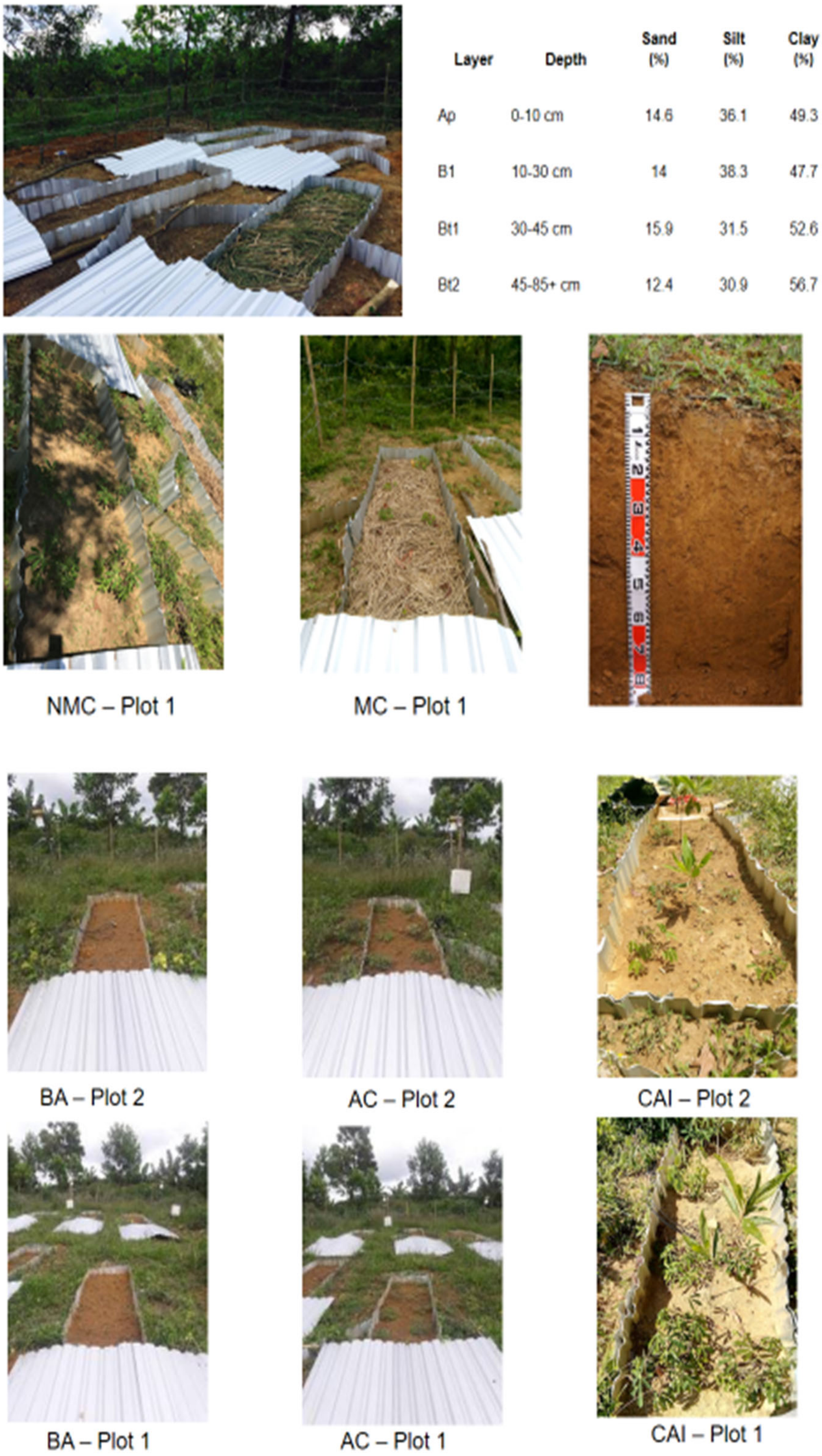
The livelihood of the ethnic groups in the A Luoi District involves traditional economic activities, such as cultivation, animal husbandry, natural exploitation, handicrafts, and exchanging and/or selling products at local markets. For these groups, the cultivation of food crops (mainly paddy rice, upland rice, cassava, and maize) is the main livelihood. They follow traditional slash-and-burn cultivation techniques, which usually involve nomadic farming. However, from the 1980s to the present day, the people of this region cultivate two paddy rice crops. The first crop, which is grown from February to May, is known as one-fifth-month (winter-spring) rice, and the second crop, which is grown from June to September, is known as tenth-month (summer-autumn) rice. One upland rice crop is also grown from May to November. Maize is planted as a mono-crop or intercropped with upland rice. Cassava is grown as a mono-crop from February to October and from April to November, or intercropped with *Acacia*. The farming tools used in this region consist of large knives, diggers, rakes, and prick-hole sticks.

To obtain new fields, people residing in the highlands destroy (slash and burn) both primary and secondary forests. These fields are then used for 1–3 crops, followed by 3–7 years of lying fallow depending on their fertility status. The success of the crops mostly depends on the natural conditions of the land as the local people do not usually apply fertilizers or maintain their crops (Ha and Hoang, 2012). Animals, such as buffalo, cattle, and goats, are grazed in the forest, whereas pigs and poultry are kept inside gardens. Animals are raised to worship their gods , supply meat for personal consumption, and sell at the market. The animals are not used to working on the farms or providing manure.

4.2.2. Experimental design

In the previous study (Le et al., 2022), to clarify which environmental factors affect runoff generation and soil loss under the specific climatic and soil conditions in the study area, we analyzed the short-term water budget for almost two consecutive years (2017 to 2018) after preparing new cropping fields in February 2017, using small-scale runoff plots with the following three treatments: a bare land (BA) plot, an April cassava (AC) plot, and April cassava + September *Acacia* intercropping (CAI) plot, the last of which was installed to understand the effect of cassava and *Acacia* intercropping on water erosion mitigation. Runoff and soil loss, the runoff coefficient, and sediment concentration were monitored in these plots. In the present study, to investigate the impact of mulching on soil erosion, in addition to tracing the effects of the intercropping after two years, two new treatments, mulching (MC) and non-mulching (NMC), were set up on April 30, 2018, in addition to the AC plot, which was opened at 14 months ago. Each treatment had two replicates. The plot size was 0.8 m wide × 2.4 m long, which was large enough to exclude microtopography that may affect runoff dynamics (Funakawa et al., 2007). The experimental monitoring period lasted from May 1, 2018, to November 30, 2019, and included two cassava crops and one fallow period. In the AC, CAI, MC, and NMC plots, cassava was planted on May 1 and harvested on November 30 in 2018 and 2019. *Acacia* was planted on September 5, 2017, in the CAI plots. The fallow period lasted from December 1, 2018, to April 30, 2019. At the beginning of the new crop, after seeding the cassava, 10 Mg ha^{-1} of air-dried *Imperata cylindrica* leaves that were 25 cm long and 1 cm wide was applied to each MC plot (Figure 4.1). The soil surface within all plots was kept free of weeds throughout the experimental period. Weeding was performed once every 2 weeks to ensure that the percentage of weed coverage was less than 5%. The proportion of soil covered by grass mulching was 100% when the new crops were first planted, and this was continuously reduced to approximately zero after the cassava was harvested. The maximum soil coverage by the 2018 and 2019 cassava crops was 65% and 60%, respectively. *Acacia* plants were 1 m high when they were 8 months old at the beginning of the experiment and 3.5 m high, with a closed canopy, when they were 27 months old at the end of the experiment.

The plots were enclosed with non-erodible aluminum sheets after clearing natural vegetation. The BA, AC, and CAI plots were on a slope ranging from 11.7° to 17°. The MC and NMC plots were on a slope ranging from 9° to 11°. Each plot had one large bucket (60 L) that was used to collect runoff water and sediment. A tipping bucket rain gauge (TE525MM; Texas Electronics, Dallas, TX, USA) was used to record rainfall. A CS215 sensor was used to record the atmospheric temperature. All sensors were connected to a CR1000 data logger (Campbell Scientific, Inc., Logan, UT, USA). Rainfall data were recorded every 10 min, while atmospheric temperature data were recorded every 30 min.



Layer	Depth	Sand (%)	Silt (%)	Clay (%)
Ap	0-10 cm	14.6	36.1	49.3
B1	10-30 cm	14	38.3	47.7
Bt1	30-45 cm	15.9	31.5	52.6
Bt2	45-85+ cm	12.4	30.9	56.7

NMC – Plot 1

MC – Plot 1

BA – Plot 2

AC – Plot 2

CAI – Plot 2

BA – Plot 1

AC – Plot 1

CAI – Plot 1

Figure 4.1. Soil properties and experimental setting.

4.2.3. Rainfall and runoff analyses

An event was recorded when it was flanked by a rainless period of longer duration. If the adjacent no-rain period was shorter than the rain period, it was incorporated into the rain event. Dry periods with a duration < 1 h were always included within a major event, whereas dry periods > 6 h were always separated into two events (Veneziano and Lepore, 2012).

The wet season consisted of two parts: the minor wet season, from the end of February to the end of July, and the major wet season, from August to the end of December. The average intensity of the rainfall events was calculated as I_{1hrs}, which was defined as the ratio of the total amount of rainfall to the duration of the rain event. The maximum rainfall intensity was denoted as I_{10}, which was calculated based on the amount of rainfall measured at 10 min intervals. Rain showers were classified as “light,” “moderate,” or “heavy” when the rates were approximately 0 to 0.25 cm h^{-1}, 0.26 to 0.76 cm h^{-1}, or greater than 0.76 cm h^{-1}, respectively (Linsley, 1977). Runoff water trapped in the 60 L buckets was collected every 2 weeks, or when the volume of runoff water was approximately 2/3 of the bucket volume, and was weighed and then converted to depth units.

4.2.4. Soil properties and sediment collection

The soil texture in the study area was characterized as clay type, based on the United States Department of Agriculture guidelines. The soil particle content in the surface layer consisted of 14.6% sand, 36.1% silt, and 49.3% clay. The bulk density ranged from 1.03 Mg m^{-3} at the surface layer to 1.24 Mg m^{-3} at a soil depth greater than 40 cm. The initial saturated hydraulic conductivity varied from 0.2 mm h^{-1} at the 40–45 cm depth layer to 7.3×10^2 mm h^{-1} at the top layer. Soil sediment particles trapped in the 60 L buckets were collected every 2 weeks, or when the volume of runoff water was approximately 2/3 of the bucket volume, and were air-dried and then weighed.

4.2.5. Data analysis

The sediment concentration in the surface runoff water was calculated based on the total amount of sediment and the total amount of runoff collected in the 60 L buckets over the same period. A two-factor ANOVA with replication and Tukey’s honestly significant difference test (HSD, $\alpha = 0.05$) were used to evaluate the impact of mulching and intercropping on water erosion mitigation. All statistical analyses were performed using Microsoft Excel software.

4.3. Results

4.3.1. Rainfall characteristics

Because of these errors that happened to the tipping bucket rain gauge and air temperature sensors, rainfall and air temperature monitoring ended on August 31, 2019. Significant differences in the amount of monthly rainfall and the average air temperature were observed. In comparison, the amount of rainfall during the first 8 months in 2019 was less than half of the amount of rainfall during the first 8 months of 2018. The monthly average air temperature was 2.3 to 5.1 ºC higher in 2019 than in 2018 (Figure 4.2). El Niño was the reason for the significant differences in rainfall and air temperature regime in the study site between the two consecutive years. According to Thua Thien Hue Provincial People's Committee (2021), El Niño phenomenon occurs frequently and has caused severe droughts in Thua Thien Hue province. Severe droughts caused by El Niño occurred in 1977, 1993-1994, 1997-1998, 2012, 2014 - 2016, and 2019. In 2019, El Nino caused a prolonged drought and appeared even during the major rainy season in Thua Thien Hue province.

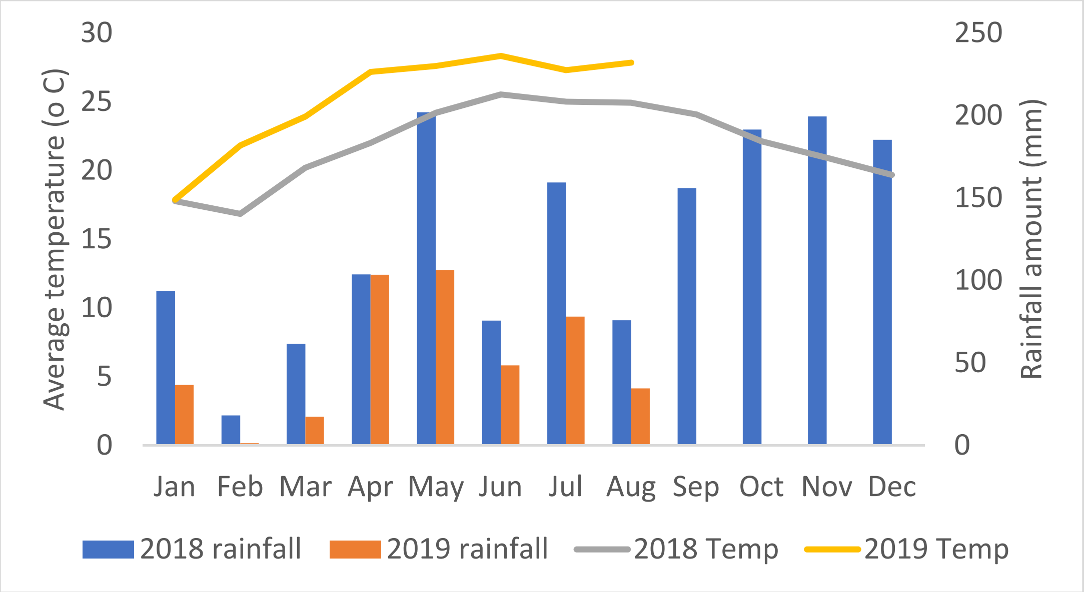


Figure 4.2. Monthly rainfall and temperature from January 2018 to August 2019.

However, it should be noted that quite high precipitation was occasionally recorded from September to December due to typhoon attacks. A considerable amount of rainfall is brought even during the dry season from January to March. The rainy season in Thua Thien Hue varies significantly from year to year, in terms of the start time, peak month and the ending time. The rainy season can range from 4 to 6 months. Precipitation is one of the most variable climatic factors in space and time. The total annual rainfall may differ from the average one by 600-800 mm depending on the region, equivalent to a coefficient of variation of 23-25%. Between a year with a lot of rain and a year with little rain, the total annual rainfall can vary from 2 to 3 times (Thua Thien Hue Provincial People's Committee, 2021).

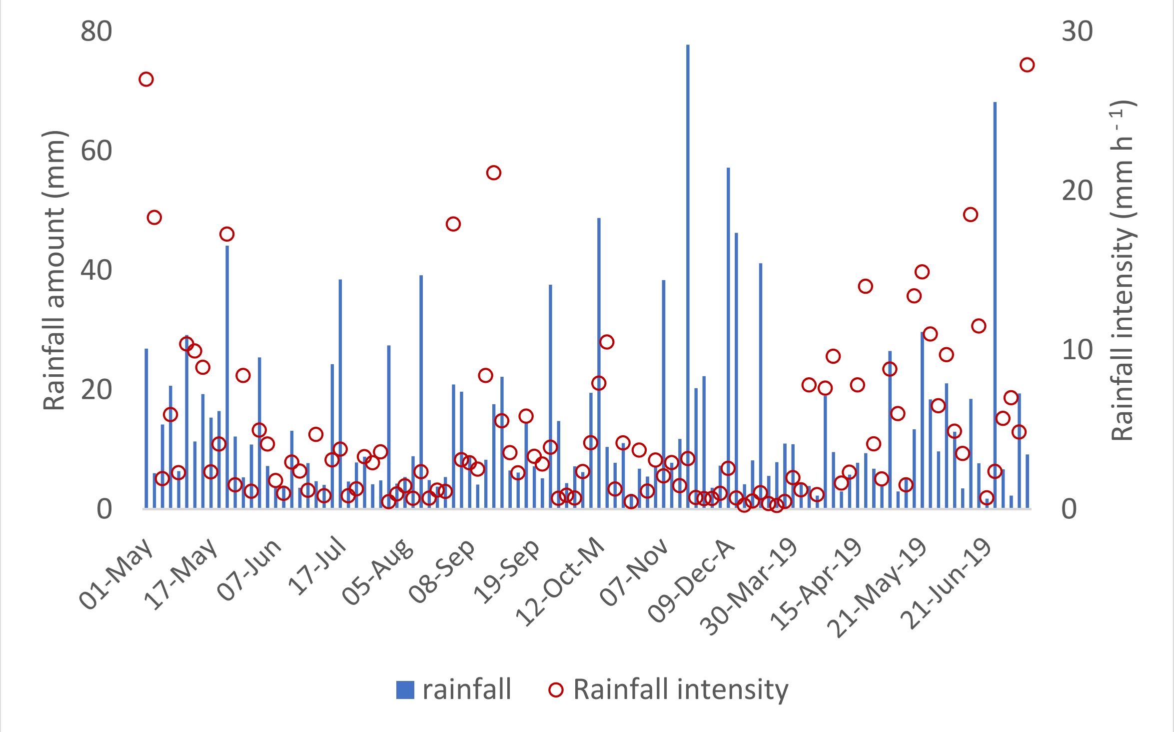


Figure 4.3. Rainfall events with different average rainfall intensities during the experimental period.

During the monitoring period, 110 rain events, including 24, 36, and 50 events that were classified as heavy, moderate, and light rain, respectively, accounted for 94% of the rainfall volume observed (the remaining events were drizzle events). In the 2018 crop season, 70 rainfall events occurred, with a total rainfall of 1,014 mm. There were 23 rainfall events, with a total of 306 mm of rainfall, observed in the fallow period from December 1, 2018, to April 30, 2019. In the 2019 crop seasons, only 17 events, with a total rainfall amount of 251 mm, were recorded. The results of the I_{1hrs} classification indicated that heavy rain events were distributed mainly at the beginning of the crop season (May 2018 and 2019) and the end of the fallow period, whereas light rain events occurred mostly in the fallow period and the late part of the 2018 crop season. Moderate rain events were evenly distributed throughout the 2018 and 2019 crop seasons (Figure 4.3).

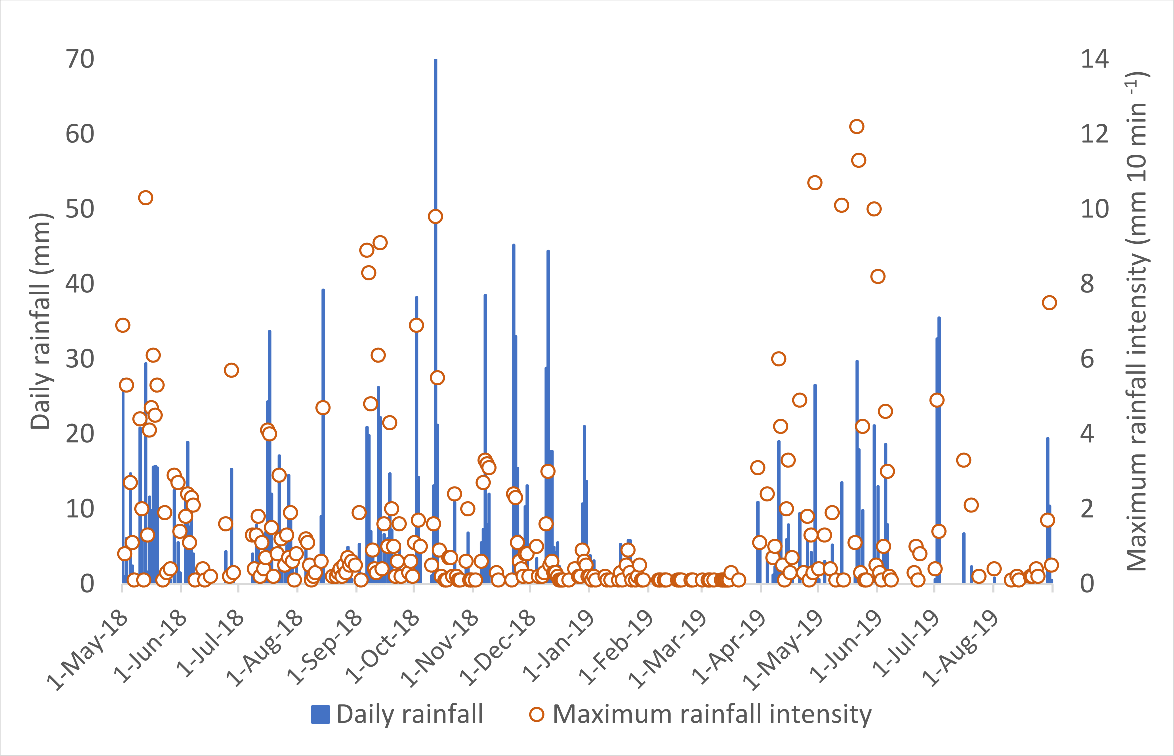


Figure 4.4. Daily rainfall and maximum 10-min intervals of rainfall intensity during the experimental period.

The largest events observed in the fallow periods of the 2018 and 2019 crop seasons were 57.2 mm over 23 h on December 9–10, 2018; 77.8 mm over 24 h on November 22–23, 2018; and 68.2 mm over 28 h on July 2–3, 2019 (Figure 4.3). The I_{10max} values recorded in the fallow periods of the 2018 and 2019 crop seasons were 10.7 mm on April 29, 2019; 10.3 mm on May 13, 2018; and 12.2 mm on May 21, 2019 (Figure 4.4).

4.3.2. Runoff, soil loss amount, and sediment concentration in runoff water

The rainfall properties, runoff amount, soil losses, runoff coefficients, and sediment concentrations in runoff water during the experimental period are shown in Table 4.1. The differences in the runoff amount, soil loss amount, and sediment concentration were significant among the plots. The crop cover in the AC (second year) and NMC (first year) plots similarly reduced the runoff volume by 17% despite the difference in the period after opening these fields; the quantity of mulch in the MC plot reduced the runoff volume by 26.7%; and the extensive coverage area generated from the outstanding growth of the *Acacia* from the second year reduced the runoff volume by 41%, compared with the data from the BA plots. The increased coverage area of the crops and grass mulching in the AC, NMC and CAI, and MC plots reduced the soil loss by 24.1%, 41.2%, and 78.7%, respectively, compared with the soil loss in the BA plots. There were no differences in sediment concentrations among the AC, CAI, and NMC plots. Grass mulching reduced the sediment concentration in the runoff water by 69% in the MC plot compared to the BA plots.

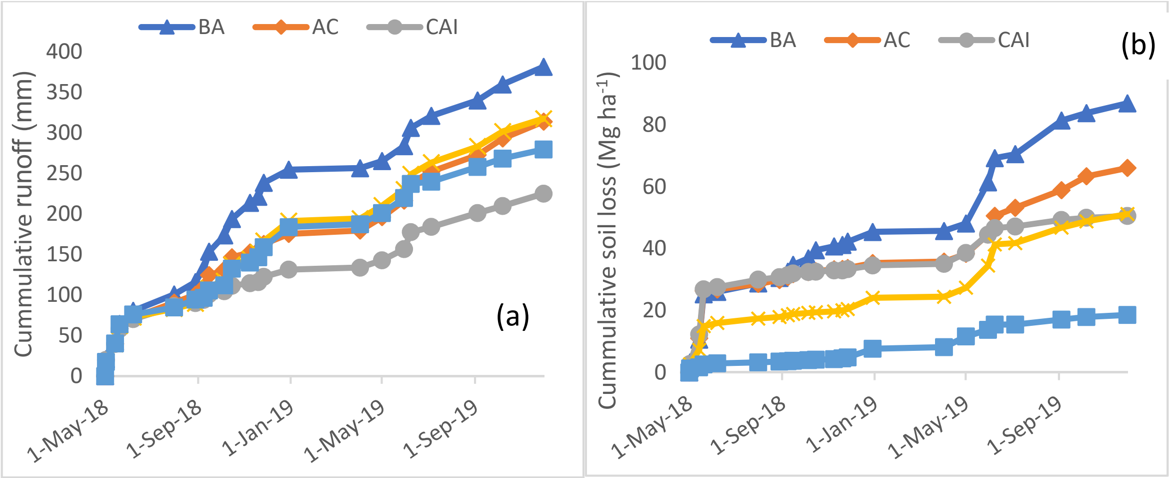


Figure 4.5. Cumulative soil loss and runoff for the five treatments.

Figure 4.5 shows the cumulative runoff (a) and soil loss (b) during the experimental period. In all treatments, substantial runoff and soil loss occurred when a series of heavy rains came during the beginning of the 2018 crop season (May 2018), the final part of the fallow period, and the beginning of the 2019 crop season (May 1 to June 8, 2019). In the BA, AC, CAI, and NMC plots, the maximum soil losses recorded in the period from May 14 to 20, 2018, were 14.6, 15.3, 14.6, and 7.7 Mg ha $^{-1}$, respectively. In contrast, the greatest soil loss of 3.5 Mg ha^{-1} in the MC plot was recorded in the final part of the fallow period (from April 2 to May 1, 2019) when heavy rains came and the grass mulching had completely decayed. In the BA, AC, and CAI plots, the highest accumulated runoff occurred during the period from May 30 to June 8, 2019, when a series of three heavy and two moderate rain events occurred. The NMC and MC plots achieved their highest accumulated runoff in the period from May 14-20, 2018, when a series of three heavy rain events produced 74.8 mm of rain, when the soil surface on the plots was disturbed for setting and seeding.

Before June 7, 2018, there were no differences in cumulative runoff among the treatments. The runoff accumulated much faster in the BA plot than in the other plots. Since September 8, 2018, when the *Acacia* was in its second year, the cumulative runoff rate in the CAI plot began slowing down significantly. During the fallow period, especially between December 29, 2018, and April 2, 2019, the cumulative runoff rate did not differ among treatments due to negligible rainfall. One month later (June 8, 2019), the cumulative runoff rate in the MC plot decreased below the cumulative runoff rate of the AC and NMC plots (Figure 4.5a).

In the 2018 crop season, because the crops were arranged at lower slope locations, the cumulative soil loss rates in the NMC plot, and especially in the MC plot (combination effect of mulching and lower slope location), were much lower than those in the BA, AC, and CAI plots. Differences in soil loss accumulation rates among the BA, AC, and CAI plots were not observed until September 9, 2018. Then, the accumulation rate in the BA plot became greater than the accumulation rate in the AC and CAI plots. During the fallow period, there was no difference in the soil loss accumulation rate among the treatments due to negligible rainfall. When the 2019 crop season began, the cumulative soil loss rate was stable in the BA, AC, and MC plots, but became faster in the NMC plot, and markedly slower in the CAI plot. In the CAI plot, the soil loss accumulated slowly from the beginning of the 2019 crop season because of the more extensive coverage area produced by the 21-month-old *Acacia* (Figure 4.5b).

A two-way ANOVA with replication showed that the differences in soil losses, runoff volumes, runoff coefficients, and sediment concentrations among treatments and periods were statistically significant. Tukey's HSD test ($\alpha = 0.05$) indicated that the amount of runoff and soil loss and the sediment concentration were significantly lower in the cropping treatments than in the bare land. The amount of runoff generated during the experimental period and the runoff coefficient in the CAI plot were significantly lower than those in the other treatment plots. Moreover, the amount of soil loss and the sediment concentration in runoff water in the MC plot were significantly lower than those in the other treatment plots. There were no differences in the amount of runoff or the runoff coefficients among the AC, NMC, and MC plots. There were no differences in the runoff coefficients among the BA, AC, and NMC plots. A significantly greater amount of soil loss and a higher sediment concentration were observed during the fallow period compared with the crop season, only in the MC plot. The runoff coefficient was significantly higher in the early crop season than in the fallow period (Table 4.1).

Table 4.1. Rainfall characteristics and differences among treatments in the amount of runoff and soil loss, runoff coefficients, and sediment concentration in surface runoff water.

Treatment	Period	Total rainfall (mm)	Rainfall events	Total runoff (mm)	Total soil loss (Mg ha^{-1})	Runoff Coefficient (%)	Sediment concentration (g L^{-1})
		A		**B**	**C**	**100 × B/A**	**100 × C/B**
1st Bare land – BA	2018 early crops season	437.1	32	100.9a	28.8a	23.1a	28.5b
	2018 late crops season	622.8	38	137.7a	13.5d	22.1a	9.8d
	Fallow period	344.2	23	26.9c	5.9e	7.8b	21.8c
	2019 early crops season	232.9	15	55.7b	22.4b	23.9a	40.2a
	2019 late crops season	34.6*	2	60.5b	16.4c	-	27.1bc
	Total	**1671.6**	**110**	**381.7A**	**86.9A**		
	Average					**19.2A**	**25.5A**
2nd April cassava – AC	2018 early crops season			90.8a	28.6a	20.8b	31.5a
	2018 late crops season			72.2a	5.1c	11.6c	7.1d
	Fallow period			33.2c	4.6c	9.6c	13.8c
	2019 early crops season			56.3b	14.9b	24.2a	26.4ab
	2019 late crops season			61.6b	12.8b	-	20.8b
	Total			**314.2B**	**66.0B**		
	Average					**16.5AB**	**19.9B**
3rd April cassava – September acacia – CAI	2018 early crops season			86.4a	30.0a	19.8a	34.7a
	2018 late crops season			36.2b	3.4c	5.8b	9.3c
	Fallow period			20.4c	5.3c	5.9b	25.8b
	2019 early crops season			41.2b	8.5b	17.7a	20.7b
	2019 late crops season			41.0b	3.4c	-	8.3c
	Total			**225.2C**	**50.6C**		
	Average					**12.3C**	**19.8B**
4th Non mulching – April cassava – NMC	2018 early crops season			83.4a	17.4a	19.1b	20.9b
	2018 late crops season			83.5a	3.1d	13.4c	3.7c
	Fallow period			43.6c	6.8c	12.7c	15.7b
	2019 early crops season			53.0bc	14.4b	22.8a	27.2a
	2019 late crops season			54.2b	9.4c	-	17.3b
	Total			**317.8B**	**51.1C**		
	Average					**17.0AB**	**17.0B**
5th Grass mulching – April cassava – MC	2018 early crops season			84.8a	3.3b	19.4a	3.9c
	2018 late crops season			74.3a	1.6b	11.9c	2.2c
	Fallow period			42.2b	6.7a	12.3c	16.0a
	2019 early crops season			38.8b	3.8b	16.6b	9.9b
	2019 late crops season			39.7b	3.1b	-	7.8bc
	Total			**279.8B**	**18.5D**		
	Average					**15.1B**	**7.9C**
		HSD$_{0.05\text{-}Treatment}$		**9.7**	**2.74**	**2.84**	**5.92**
		HSD$_{0.05\text{-}Period}$		**9.7**	**2.74**	**2.66**	**5.92**

Different letters indicate significant differences ($P < 0.05$) by Tukey's honestly significant difference test for two factors with two replicates (different capital letters indicate significant differences among treatments, whereas different lowercase letters indicate significant differences among periods). * Due to an error in the rain gauge sensor, the rainfall data during the 2019 crop season did not accurately reflect the amount of rainfall in September, October, and November, 2019.

4.4. Discussion

4.4.1. Impact of grass mulching on runoff and soil loss mitigation

Water erosion requires the following three processes: soil detachment by energy from raindrops, transport by surface runoff, and sediment deposition downhill (Kinnell, 2006; Matsumoto et al., 2016, Pennock, 2019). Mulching, an old technique, was used to mitigate water erosion and manage soil moisture and temperature. This technique is one of the practical techniques to develop sustainable agriculture and climate change adaptation (Bhanooduth Lalljee, 2013). Many studies have shown that residue mulching protects the soil surface against the forced invasion of rain drops, stops the spreading of surface runoff, and promotes the infiltration of rainwater into deeper soil layers, thus reducing runoff generation (Welle et al., 2006; Babalola et al., 2007; Montenegro et al., 2013; Donjadee and Tingsanchali, 2016; Nishigaki et al., 2017). Mostaghini et al. (1994) reported that various types of mulch decrease soil loss by up to 90% compared with soil loss in bare land. Donjadee and Tingsanchali (2016) reported that applying a rice straw at 5 Mg ha^{-1} reduces runoff and soil loss by 52.5% and 62.9%, respectively, compared to bare land. Nishigaki et al. (2017) reported that there was no difference in the amount of runoff, but more than half of the soil loss was mitigated by grass mulching in comparison with bare land.

In this study, statistically significant differences in the amount of runoff and soil loss, the runoff coefficient, and the sediment concentration in runoff water indicated that grass mulching might be effective at mitigating runoff and soil loss. However, mulch application had a greater impact on soil loss than on runoff generation. Indeed, applying air-dried *Imperata cylindrica* grass residue at 10 Mg ha^{-1} per crop season to a cassava plantation area reduced the runoff and soil loss by 26.7% and 78.7%, respectively, compared to bare land. Moreover, mulching reduced the sediment concentration in runoff water by 69% compared to bare land, indicating the superior ability of mulch to protect the soil surface against the detachment force generated by rain drops.

Although the erosion-mitigating effect of mulching was thus significant, it should be noted that such effect noticeably decreased due to the complete decay of grass mulching during the later fallow period, in which there still is a considerable amount of rainfall.

4.4.2. Practical effects of Acacia and cassava intercropping on water erosion mitigation

In Vietnam, intercropping is a useful practical technique to mitigate water erosion on sloping crop land. Crops that are usually intercropped with the main crop are peanuts, maize, upland rice, coffee, tea, and *Acacia* (Nguyen and Thai, 1998; Howeler and Aye, 2014; Huynh et al., 2020). In this study, *Acacia* was intercropped with cassava.

In a previous study, we reported that, in the first year, the cassava + *Acacia* intercropping system was not effective at mitigating water erosion (Le et al., 2022). In this study, water erosion monitoring began 8 months after the *Acacia* was planted and ended when the plants were 27 months old. The growth of the *Acacia* plants in the second and third years had a significant effect on runoff and soil loss mitigation. Compared to bare land, the intercropping system reduced the amount of runoff, the amount of soil loss, the runoff coefficient, and the sediment concentration in runoff water by 41%, 41.2%, 36%, and 22.3%, respectively. The greatest reduction in the amount of runoff and the runoff coefficient (73.7%) were recorded in the late part of the 2018 crop season. At the beginning of the 2019 crop season, when the *Acacia* canopy was closed, the combined impact of cassava and *Acacia* growth reduced the amount of soil loss by 69.3% and the sediment concentration in runoff water by 56.5%, compared to bare land. These findings indicated that, from the second year, intercropping of cassava + *Acacia* mitigated runoff and soil loss. However, these practical techniques only showed a significant impact on water erosion mitigation if the *Acacia* canopy was closed. It would be recommended to additionally incorporate the mulching treatment in the early stage of *Acacia* growth when applying this intercropping management.

4.5. Conclusions

We found that grass mulching and intercropping had a significant impact on water erosion mitigation under the specific climatic and soil conditions of this area. Applying air-dried grass mulch at the time of cassava seeding in early May at a rate of 10 Mg ha^{-1} per year to sloping cropland under 11° mitigated more than a quarter of the runoff and three-quarters of the soil loss compared to bare land. The intercropping of cassava and *Acacia* reduced the amount of runoff and soil loss by more than two-fifths compared to bare land after canopy closing in the second year. However, we must keep in mind that when the mulch had completely decayed, a high risk of water erosion occurred in the mulching plots during the fallow period after harvest. To increase the efficiency of these practical techniques for water erosion mitigation, grass residue should be applied at the same rate twice, once after seeding and again after harvesting. Grass mulching should also be applied to the intercropping system once or twice until the *Acacia* canopy is closed.

Chapter 5
General discussion

5.1. Water erosion generation on sloping cropland in A Luoi district, Thua Thien Hue province, Central Vietnam

Applying a short-term water budget approach has well investigated the mechanism of water erosion on mountainous sloping cropland in A Luoi district, Thua Thien Hue province, Central Vietnam. I found that tropical storms strongly affected the rainfall regime; the rainfall is unevenly distributed in major and minor rainy seasons; hence, the soil moisture content intensely fluctuated in the minor rainy seasons but was usually wet in the major seasons.

Similar to the general theoretical perspective of the water erosion mechanism stated in previous studies (Kinnel, 2006; Matsumoto et al., 2016), the process happened on the research site not only requires the detachment of soil fractions via high-energy raindrops but a high volume of surface runoff for transporting the loose components. In my study, the water erosion occurred intensely after heavy rain events came or/and runoff generated powerfully. In addition, the unbalance in seasonal rainfall distribution, the seasonal fluctuation of soil moisture content, and the spatio-temporal difference in vegetation coverage cause significant changes in the water erosion mechanisms. In the minor rainy seasons (which lasted from March to July), when the crop cover area was unremarkable, the portion of heavy rain was vigorous, and the fluctuation in soil moisture was significant, the integrated impact of maximum rainfall intensity (at 10 min intervals) and/or rainfall volume and initial volumetric water content activated surface runoff. Soil loss occurred only if the runoff was powerfully generated. In the major rainy seasons (which occurred from August to December), the soil was mostly in wet conditions, with high clay content that caused the soil surface to be very sticky and plastic, and the percolation rate of water was limited. Hence, most of the rainfall could runoff. Furthermore, the maximum rainfall intensity (at 10 min intervals) of most rainfall events was low. Soil aggregates were only slightly disrupted, and only a small volume of sediment was detached from the soil surface. Thus, soil loss was generated only if the maximum rainfall intensity (at 10 min intervals) was high (Chapter 3).

On the other hand, the soil physical characteristics test indicated the importance of the saturated hydraulic conductivity of soil layers in the relationship with water erosion generation that is continuous water erosion causes the loss of topsoil and organic matter, the decline in the size of soil aggregate, and infiltration capacity of the soil layers. Consequently, the runoff and soil loss generation occurred increasingly seriously (Chapter 3).

5.2. Water erosion mitigation practices in the agricultural highland, Thua Thien Hue province, Central Vietnam

In the first study that investigated the mechanisms of water erosion and its seasonal changes in the research site, I found a high risk of water erosion observed during two periods of the year. The first lasted from the middle of April to the end of May when a series of heavy rains came while crop coverage was trivial or the soil surface was disturbed for beginning the new cassava crops. The second was the typhoon season which lasted from the end of October to the end of November. During that time, the soil surface was vulnerable to water erosion after cassava harvesting. Contrarily, the lowest risk of water erosion occurred between the middle of December and the end of February, when precipitations were from light rain and drizzle events. In terms of cropping management, the February – October cassava crop had the advantage of decreasing the risk of surface runoff and soil loss compared to the April – November cassava crop. The cassava-acacia intercropping showed less effect on water erosion mitigation in the initial year of cropping (Chapter 3).

To make specific practical recommendations to local land managers and farmers, I tested grass mulching, an old practical technique, and monitored the practical effect of the 2nd and 3rd year cassava-acacia intercropping on water erosion mitigation. Similar to other previous studies (Welle et al., 2006; Babalola et al., 2007; Montenegro et al., 2013; Donjadee and Tingsanchali, 2016; Nishigaki et al., 2017), we observed the superior ability of mulch to mitigate water erosion. This ability could be mulching protects the soil surface against the forced invasion of raindrops, stops the spreading of surface runoff, and promotes rainwater infiltration into deeper soil layers, thus reducing runoff and soil loss generation. However, when the mulch had completely decayed, a high risk of water erosion occurred. Besides, the cassava-acacia intercropping showed its significant effect on water erosion mitigation only the acacia canopy was closed. (Chapter 4).

The research provided useful information on the mechanism of water erosion in the mountainous sloping cropland, Thua Thien Hue province, Central Vietnam. Furthermore, the research has successfully tested the usefully and applicably practical techniques that can efficiently mitigate the water erosion process in the agricultural highlands of Central Vietnam. From there, the study suggests optional recommendations as follows:

1) Grass residue should be applied at the same rate of 10 Mg ha^{-1} twice, once after beginning new crops and again after harvesting;

2) Grass mulching should also be applied to the intercropping system once or twice until the acacia canopy is closed;

3) Re-arranging the cropping calendar to bring cassava planting forward or delay harvesting.

Chapter 6

Conclusion

Central Vietnam is one of three geographical regions of Vietnam where hills and mountains make up more than 75% of the natural land area of the region, frequently affected by extreme climates that cause water erosion such as typhoons and tropical depressions. To clarify which environmental factors affect water erosion generation, and the seasonal variations in water erosion risks in Central Vietnam, the study analyzed the short-term water budget of small-scale runoff plots that developed on a slope of the highland region. Besides, by testing the two classical practical techniques that could mitigate water erosion, including grass mulching and intercropping, I suggest feasible and specific practical solutions to the local land managers and farmers to control water erosion risks.

Tropical storms strongly affect the rainfall regime of sloping croplands in Thua Thien Hue province, Central Vietnam. The factors that trigger runoff generation are the maximum rainfall intensity at 10 mins intervals, the rainfall amount, and the initial soil moisture content of the surface layer. The driving forces that cause soil loss are the maximum rainfall intensity at 10 min intervals and the runoff amount generated during rainfall events. The crop coverage and the saturated hydraulic conductivity of soil layers strongly impacted surface runoff and soil loss generation. Besides, the seasonal variations in water erosion risks have been clearly observed. All findings have been thoroughly discussed in chapter 3. On the other hand, the findings through testing the effectiveness of practical techniques such as grass mulching and intercropping could be beneficial for water erosion control strategy of local government (chapter 4).

References

Abu Hammad, A. H., Borresen, T. and Haugen, L.E. (2006). Effects of rain characteristics and terracing on runoff and erosion under the Mediterranean. Soil and Tillage Research 87, 39–47.

Aksoy, H. and Kavvas, M.L. (2005). A review of hillslope and watershed scale erosion and sediment transport models, Catena 64, 247–271, https://doi.org/10.1016/j.catena.2005.08.008.

Armbrust, D.V., and Jackson, J.D. (1977). Temporary wind erosion control: Cost and effectiveness of 34 commercial materials. Journal of Soil and Water Conservation 26, 154–157.

Babalola, O., Oshunsanya, S.O., and Are, K. (2007). Effects of vetiver grass (Vetiveria nigritana) strips, vetiver grass mulch, and an organomineral fertilizer on soil, water and nutrient losses and maize (Zea mays, L) yields. Soil and Tillage Research 96, 6–18 .

Babatunde, A., Truong, T., Pradeep, K., Robert, M., Marie, C. and Robert, D. (2016). Economics of climate change adaptation: Agriculture sector analysis for Vietnam. UNDP. doi:10.13140/RG.2.2.36707.66083

Carlos, S. (2005). Estimating spatial patterns of soil erosion and deposition in the Andean region using geo-information techniques – A case study in Cochabamba, Bolivia. Ph.D. thesis. Wageningen University, Netherlands.

Cerdà, A. (1998). The influence of aspect and vegetation on seasonal changes in erosion under rainfall simulation on a clay soil in Spain. Canadian Journal of Soil Science 78, 321–330 .

Cerdà, A., González-Pelayo, Ó, Giménez-Morera, A., Jordán, A., Pereira, P., Novara, A., Brevik, E.C., Prosdocimi, M., Mahmoodabadi, M., Keesstra, S., Orenes, F.G., and Ritsema, C.J. (2016). Use of barley straw residues to avoid high erosion and runoff rates on persimmon plantations in Eastern Spain under low frequency – High magnitude simulated rainfall events. Soil Research 54, 154–165. DOI:10.1071/SR15092.

Coppin, N.J., and Richards, I.J. (1990). Use of vegetation in civil engineering. CIRIA, Butterworths, London.

Dabney, S.M., Yoder, D.C., and Vieira, D.A.N. (2012). The application of the Revised Universal Soil Loss Equation, Version 2, to evaluate the impacts of alternative climate change scenarios on runoff and sediment yield, Journal of Soil and Water Conservation 67, 343–353. https://doi.org/10.2489/jswc.67.5.343.

Dane, J.H., and Hopmans, J.W. (2002). Pressure plate extractor. In: Methods of soil analysis: part 4 physical methods. Dane, J.H., and Topp, G.C. (eds). American Society of Agronomy. Inc. Madison, Wisconsin, USA; 688–690 .

Donjadee, S., and Tingsanchali, T. (2016). Soil and water conservation on steep slopes by mulching using rice straw and vetiver grass clippings. Agriculture and Natural Resources 50, 75–79. doi.org/10.1016/j.anres.2015.03.001.

Douglas, I. (2006). The local drivers of land degradation in South-East Asia. Geographical Research 44, 123–134.

Dunin, F.X. (1976). Infiltration: its simulation for field conditions. Pages 199–227 in J. C. Rodda, ed. Facets of hydrology. John Wiley and Sons, Bristol, UK.

Environmental Database Division (2002). State of the environment in Vietnam 2001. Ministry of Science, Technology and Environment of Vietnam (Vietnamese).

Evans, R. and Boardman, J. (2016). A reply to Panagos et al., 2016 (Environmental Science & Policy 59 (2016) 53–57. Environmental Science & Policy 60, 63–68.

FAO (2015). Revised world soil charter. Food and Agriculture Organization of the United Nations, Rome. 10 pp. (also available at http://www.fao.org/documents/card/en/c/e60df30b-0269-4247-a15f-db564161fee0/).

FAO, and ITPS (2015). Status of the world's soil resources - main report. Food and Agriculture Organization of the United Nations and intergovernmental technical panel on soils. Rome. 649 pp. (also available at http://www.fao. org/3/a-i5199e.pdf).

Funakawa, S., Minami, T., Hayashi, Y., Naruebal, S., Noichana, C., Panitkasate, T., Katawatin, R., Kosaki, T., and Nawata, E. (2007). Process of runoff generation at different cultivated sloping sites in north and northeast Thailand. Japanese Journal of Tropical Agriculture 51, 12–21 .

Gaubi, I., Chaabani, A., Ben Mammou, A., and Hamza, M.H. (2017). A GIS-based soil erosion prediction using the Re- vised Universal Soil Loss Equation (RUSLE) (Lebna watershed, Cap Bon, Tunisia), Natural Hazzards 86, 219–239, https://doi.org/10.1007/s11069-016-2684-3.

General Statistics Office (2017). Statistical Yearbook of Vietnam 2015. Statistical Publishing House, Hanoi, Vietnam.

Grossman, R.B., and Reinsch, T.G. (2002). Bulk density and linear extensibility. In: Method of soil analysis part 4. Dane, J. H., & Topp, G. C. (eds). American Society of Agronomy. Inc.: Madison, Winconsin, USA; 201–228 .

Gyssels, G., Poesen, J., Bochet, E. and Li, Y. (2005). Impact of plant roots on the resistance of soils to erosion by water: A review. Progress in Physical Geography 29 (2), 189–217.

Ha, P., and Hoàng, H.Đ.T. (2012). Ảnh hưởng của văn hoá truyền thống đến canh tác nương rẫy và biến động diện tích rừng ở xã Hồng Bắc, huyện A Lưới, tỉnh Thừa Thiên Huế. Hue University Journal of Science: Agriculture and Rural Development 75, 29–41. doi: 10.26459/jard.v75i6.3131 (Vietnamese).

Hamanaka, A., Inoue, N., Shimada, H., Sasaoka, T., and Matsui, K. (2014). An experimental study for assessment of soil erosion at rehabilitation area in Indonesian coal mine. Proceedings of the International Symposium on Land Reclamation and Ecological Restoration 14, 171–175.

Hao, H., Wang, J., Guo, Z., and Hua, L. (2019). Water erosion processes and dynamic changes of sediment size distribution under the combined effects of rainfall and overland flow. Catena 173, 494–504. https://doi.org/10.1016/j.catena.2018.10.029

Hino, M., Odaka, Y., Nadaoka, K., and Sato, A. (1988). Effect of initial soil moisture content on the vertical infiltration process – A guide to the problem of runoff-ratio and loss. Journal of Hydrology 102, 267–284.

Hoang, T.T.H., Phan, T.C., Hoang, M.T., Wen, C. and Richard, B. (2010). Sandy soils in South Central Coastal Vietnam: Their origin, constraints, and management. 19th World Congress of Soil Science, Soil Solutions for a Changing World. 1 – 6 August 2010, Brisbane, Australia. Published on DVD.

Horton, R. E. (1945). Erosional development of streams and their drainage basins: Hydrophysical approach to quantitive morphology. Geological Society of American Bulletin 56, 275–370.

Howeler, R., and Aye, T.M. (2014). Sustainable management of cassava in Asia. From research to practice. CIAT, the Nippon Foundation, Cali, Colombia. 148 p.

Hung, L. and Tien, P.C. (1986). Upper Paleozoic Stratigraphy in Indochina. In: Geology of Campuchia, Laos and Vietnam. Science Publisher, Hanoi, Vietnam, 53–64 (Vietnamese).

Huynh, C.V., Pham, T.G., Nguyen, T.Q., Nguyen, L.H.K., Tran, P.T., Le, Q.N.P., and Nguyen, M.T.H. (2020). Understanding Indigenous Farming Systems in response to Climate Change: An Investigation into Soil Erosion in the Mountainous Regions of Central Vietnam. Applied Sciences 10, 50–91. doi:10.3390/app10155091.

Kinnell, P.I.A. (2006). Simulations demonstrating interaction between coarse and fine sediment loads in rain-impacted flow. Earth Surface Processes and Landforms 31, 355–367. doi: 10.1002/esp.1249.

Kinnell, P.I.A. (2016). A review of the design and operation of runoff and soil loss plots. Catena 145, 257–265.

Kirkby, M.J., and Chorley, R.J. (1967). Throughflow, overland flow and erosion. Hydrological Sciences Journal 12 (3), 5–21. doi: 10.1080/02626666709493533.

Klute, A. (1965). Laboratory measurement of hydraulic conductivity of saturated soil. In:. Agronomy Monographs. Black, C. A., Evans, D. D., White, J. L., Ensminger, L. E., & Clark, F. E. (eds), 210-221. American Society of Agronomy. Inc.: Madison, Winconsin, USA, 210–221.

Klute, A. (1986). Water retention: Laboratory methods. In: Methods of soil analysis. part 1. Physical and mineralogical methods (2nd ed.); 9. Klute, A. (ed). Madison: SSSA Book Series. http://redbiblio.unne.edu.ar/pdf/0603-003891_I.pdf. ASA, Inc. and SSSA, Inc., Madison, Wisconsin, USA, 635–662.

Kulikov, M., Schickhoff, U., and Borchardt, P. (2016). Spatial and seasonal dynamics of soil loss ratio in mountain rangelands of south-western Kyrgyzstan. Journal of Mountain Science 13, 316–329, https://doi.org/10.1007/S11629-014-3393-6.

Lal, R. (1998). Soil erosion impact on agronomic productivity and environment quality. Critical Reviews in Plant Sciences 17, 319–464. doi.org/10.1080/07352689891304249.

Lal, R. (2001). Soil degradation by erosion. Land Degradation & Development 12, 519–539.

Lalljee, B. (2013). Mulching as a mitigation agricultural technology against land degradation in the wake of climate change. International Soil and Water Conservation Research 1, 68–74.

Le, B.T. (1998). Vietnam – Territories and Geographical Areas. The Gioi Publishing House, Hanoi, Vietnam. (Vietnamese)

Le, B.T. (2009). Vietnam – Nature. Viet Nam Education Publishing House, Hanoi, Vietnam (Vietnamese).

Le, D. H., Shibata, M., Kohmoto, Y., Nguyen, H. L., and Funakawa, S. (2022). Analysis of the processes that generate surface runoff and soil erosion using a short-term water budget on a mountainous sloping cropland in central Vietnam. CATENA 211, 1–14. https://doi.org/10.1016/j.catena.2022.106032

Lee, H.S., Hoang, T.T.H, Pham, D.P., Mihye, L., Delia, G., Phung, D.C., Vu, M.T., and Nguyen, V.H. (2017). Seasonal and geographical distribution of bacillary dysentery (shigellosis) and associated climate risk factors in Kon Tum Province in Vietnam from 1999 to 2013. Infectious Diseases of Poverty, 6 (1), 113. DOI 10.1186/s40249-017-0325-z

Linsley, R. (1977). Hydrology for engineers (2nd ed.). McGraw-Hill.

Mai, V., T. (2007). Soil erosion and nitrogen leaching in northern Vietnam: Experimentation and modeling. PhD thesis. Wageningen University, Netherlands.

Mathys, N., Klotz, S., Esteves, M., Descroix, L. and Lapetite, J.M. (2005). Runoff and erosion in the Black Marls of the French Alps: Observations and measurements at the plot scale. Catena 63, 261–281.

Matsumoto, S., Ogata, S., Shimada, H., Sasaoka, T., Kusuma, G. J., and Gautama, R.S. (2016). Application of Coal Ash to Postmine Land for Prevention of Soil Erosion in Coal Mine in Indonesia: Utilization of Fly Ash and Bottom Ash. Hindawi

Publishing Corporation, Advances in Materials Science and Engineering, 1–9. doi.org/10.1155/2016/8386598.

Mekonnen, M., Keesstra, S.D., Stroosnijder, L., Baartman, J.E.M., and Maroulis, J. (2015). Soil conservation through sediment trapping: A review. Land Degradation and Development 26, 544–556.

Merz, R. and Blöschl, G. (2009). A regional analysis of event runoff coefficients with respect to climate and catchment characteristics in Austria. Water Resources Research 45, 1. doi:10.1029/2008WR007163.

Meyles, E., Williams, A., Ternan, L.D.J., and Dowd, J. (2003). Runoff generation in relation to soil moisture patterns in a small Dartmoor catchment, Southwest England. Hydrological Processes 17, 251–264. doi: 10.1002/hyp.1122.

Mizugaki, S., Onda, Y., Fukuyama, T., Koga, S., Asai, H., and Hiramatsu, S. (2008). Estimation of suspended sediment sources using 137Cs and 210Pbex in unmanaged Japanese cypress plantation watersheds in southern Japan. Hydrological Processes 22(23), 4519–4531.

Montenegro, A.A.A., Abrantes, J.R.C.B., De Lima, J.L.M.P., Singh, V.P., and Santos, T.E.M. (2013). Impact of mulching on soil and water dynamics under inter- mittent simulated rainfall. CATENA 109, 139–149. DOI:10.1016/j.catena.2013.03.018.

Mostaghimi, S., Gidley, T.M., Dillaha, T.A., and Cooke, R.A. (1994). Effectiveness of different approaches for controlling sediment and nutrient losses from eroded land. Journal of Soil and Water Conservation 49, 615–620.

Naipal, V., Reick, C., Pongratz, J., and Van Oost, K. (2015). Improving the global applicability of the RUSLE model – adjustment of the topographical and rainfall erosivity factors, Geosci. Model Dev., 8, 2893–2913, https://doi.org/10.5194/gmd-8-2893-2015.

National Institute for Soils and Fertilizers (NISF) and Department of Science, Technology and Product Quality (DSTPQ), Ministry of Agriculture and Rural Development (MARD). (2002). The Basic Information of Main Soil Units of Vietnam. The gioi Publishing House, Hanoi, Vietnam (Vietnamese).

Ngan, P.K., Huoc, L.H. and Long, P.D. (1986). Lower Paleozoic stratigraphy in Indochina. In: Geology of Campuchia, Laos and Vietnam. Science Publisher, Hanoi, Vietnam. 30–46 (Vietnamese).

Nguyen, N. B., and Nguyen, H. K. L. (2014). Basin resources management: Simulating soil erosion risk by soil and water assessment tool (SWAT) in Ta Trach river watershed, central Vietnam. Journal of Vietnamese Environment 6(2), 165–170.

Nguyen, T.S., and Thai, P. (1999). Upland soils in Vietnam: Degradation and rehabilitation. Agricultural Publishing House, Hanoi, Vietnam (Vietnamese).

Nguyen, V.D., D., I., Morrow, J. M., Lindley, S., Dao, K., Nguyen, T. B., Tran, T.V., Le, H.T., and Nguyen, T. (2008). Erosion and nutrient loss on sloping land under intensive cultivation in Southern Vietnam. Geographical Research 46, 4–16. doi: 10.1111/j.1745-5871.2007.00487.x.

Nguyen, X.H. and Pham, A.H. (2018). Assessing Soil Erosion by Agricultural and Forestry Production and Proposing Solutions to Mitigate: A Case Study in Son La Province, Vietnam. Applied and Environmental Soil Science Volume 2018. https://doi.org/10.1155/2018/2397265

Nishigaki, T., Sugihara, S., Kilasara, M., and Funakawa, S. (2017a). Surface runoff generation and soil loss under different soil and rainfall properties in the Uluguru Mountains, Tanzania. Land Degradation and Development 28, 283–293. doi: 10.1002/ldr.2499.

Nishigaki, T., Shibata, M., Sugihara, S., Mvondo-Ze, A. D., Araki, S., and Funakawa, S. (2017b). Effect of mulching with vegetative residues on soil water erosion and water balance in an oxisol cropped by cassava in East Cameroon. Land Degradation and Development 28, 682–690. doi: 10.1002/ldr.2568.

Panagos, P., Borrelli, P., Poesen, J., Meusburger, K., Ballabio, C., Lugato, E., Montanarella, L. and Alewell, C. (2016). Reply to “The new assessment of soil loss by water erosion in Europe. Panagos P. et al., 2015 Environmental Science and Policy 54, 438–447—A response” by Evans and Boardman [Environmental Science & Policy 58, 11–15]. Environmental Science & Policy 59, 53–57.

Penna, D., Tromp-van Meerveld, H.J., Gobbi, A., Borga, M., and Dalla Fontana, G.D. (2011). The influence of soil moisture on threshold runoff generation processes in an alpine headwater catchment. Hydrology and Earth System Sciences 15, 689–702. doi: 10.5194/hess-15-689-2011.

Pennock, D. (2019). Soil erosion: the greatest challenge for sustainable soil management. Food and Agriculture Organization of the United Nations (FAO), Rome. 92 pp.

Pham, T. G., Degener, J., and Kappas, M. (2018). Integrated universal soil loss equation (USLE) and Geographical Information System (GIS) for soil erosion estimation in A Sap basin: Central Vietnam. International Soil and Water Conservation Research 6, 99–110. https://doi.org/10.1016/j.iswcr.2018.01.001.

Pham H.T. (2008). Soil erosion risk modeling within upland landscapes using re- motely sensed data and the RUSLE model (A case study in Huong Tra district, Thua Thien Hue province, Vietnam). International Symposium on Geoinformatics for Spatial Infrastructure Development in Earth and Allied Sciences. Hanoi, Vietnam, 4–6 December 2008.

Pham, T.Q.A. (2015). Evaluating the interactions between soil erosion and nutrient accumulation with various vegetation ground cover conditions. PhD Dissertation. Tokyo University of Agriculture and Technology, Japan.

Pham, X.P. (2000). People participation in forest management in Vietnam. In: Decentralization and devolution of forest management in Asia and pacific; 2000/1. Enters, T., Durst, P. B., & Victor, M. (eds). Regional Community Forestry Training Centre Report No.18 and FAO Regional Office for Asia and Pacific (RAP) Publication. Bangkok, Thailand; 87–93.

Pimentel, D. (2006). Soil erosion: A food and environmental threat. Environment, Development and Sustainability 8, 119–137.

Polyakov, V.O., and Lal, R. (2008). Soil organic matter and CO_2 emission as affected by water erosion on field runoff plots. Geoderma 143, 216–222.

Prats, S.A., MacDonald, L.H., Monteiro, M., Ferreira, A.J.D., Coelho, C.O.A., and Keizer, J.J. (2012). Effectiveness of forest residue mulching in reducing post-fire runoff and erosion in a pine and a eucalypt plantation in north-central Portugal. Geoderma 191, 115–124. doi: 10.1016/j.geoderma.2012.02.009.

Rawlings, J.O., Pantula, S.G., and Dickey, D.A. (1998). Applied regression analysis: A research Tool (2nd ed.). Inc: Springer. New York, USA.

Römkens, M.J.M., Helming, K., and Prasad, S.N. (2002). Soil erosion under different rainfall intensities, surface roughness, and soil water regimes. CATENA 46, 103–123.

Rubianca, B., Bethanna, J., Deborah, M. and Kevin, N. (2018). A review of the (Revised) Universal Soil Loss Equation ((R)USLE): with a view to increasing its global applicability and improving soil loss estimates. Hydrology and Earth System Sciences 22, 6059–6086. https://doi.org/10.5194/hess-22-6059-2018.

Sadeghi, S.H.R., Gholami, L., Khaledi Darvishan, A., and Saeidi, P. (2014). A review of the application of the MUSLE model worldwide, Hydrological Sciences Journal 59, 365–375, https://doi.org/10.1080/02626667.2013.866239.

Segarra, E.R., Ervin, R.T., Dicks, M.R., and Taylor, D.B. (1991). On-site and off-site impacts of soil erosion: Their implications for soil conservation policy. Resources, Conservation and Recycling 5, 1–19.

Sidle, R.C., Ziegler, A.D., Negishi, J.N., Nik, A.R., Siew, R., and Turkelboom, F. (2006). Erosion processes in steep terrain – Truths, myths, and uncertainties related to forest management in Southeast Asia. Forest Ecology and Management 224, 199–225.

Socialist Republic of Viet Nam (2004). National report on disaster reduction in Vietnam – for the World Conference on Disaster Reduction, Kobe-Hyogo, Japan, 18–22 January 2005, Hanoi, Vietnam.

Socialist Republic of Viet Nam (2018). Final Country Report of the Land Degradation Neutrality Target Setting Programme. Hanoi, Vietnam.

Tarboton, D.G. (2003). Rainfall – Runoff process. Civil and Environmental Engineering Faculty Publications, paper 2570.

Thai, P. and Nguyen, T.S. (1994). Land degradation and its data collection and analysis in Vietnam. In: The collection and analysis of land degradation data (FAO Regional Office for Asia and the Pacific) RAPA Publication (Bangkok) 251–261.

Thai, P. and Nguyen, T.S. (1998). Effect of anti-erosive practices to soil conservation on sloping land of Vietnam. Vietnam soil science. (Khai, T. ed.) Agricultural Publishing House (Hanoi) 22–26.

Thanh, T.Dz., Hoe, N.D. and Hong, N.D. (1986). A generalying on Devonian system in Indochina. In: Geology of Campuchia, Laos and Vietnam. Science Publisher, Hanoi, Vietnam. 46–53 (Vietnamese).

Thi, P.T. (1985). Metamorphic complexes of the Socialist Republic of Vietnam. In:Sang Man Lee ed. Explanatory text of the metamorphic map of South and East Asia (1:10,000,000)，90–97.

Thorne, C.R., Zevenbergen, L.W., Grissinger, E.H., and Murphey, J.B. (1985). Calculator programe and nomograph for on-site predictions of ephemeral gully erosion, United States Department of Agriculture Soil Conservation Service, United States.

Thua Thien Hue People’s Committee (2005). Geographical and Tradition Hue, part 1 – Nature. Socical Sciences Publishing House, Hanoi, Vietnam. (Vietnamese).

Thua Thien Hue People’s Committee (2021). Synthesis report - Climatic Assessment of Thua Thien Hue province. Attached to Decision No. 1789 /QD-UBND issued on July 22, 2021, by the People's Committee of Thua Thien Hue province. (Vietnamese)

To, X.P, Chan, L. H. and Cao, T.C. (2021). Supply of raw acacia wood in Vietnam - Status and trends (Vietnamese).

Torri, D. and Poesen, J. (2014). A review of topographic threshold conditions for gully head development in different environments. Earth-Science Reviews 130, 73–85.

Tran, A.P. (1995). Open and bare lands in Vietnam. Vietnam Soil Science 5, 67–69. (Vietnamese)

Tran, N.H. (2001). Soil erosion by rain; its effect on soil fertility and crop yield. Agriculture and Rural Development Monthly Journal 5, 334–335. (Vietnamese)

Tran, N.N. (1995). The geology of Vietnam: A brief summary and problems. Geoscience Reports of Shizuoka University, 22 (July, 1995), 1–10.

Tran, T.P., Nguyen, B.N., Chau, V.T.T., and Huynh, V.C. (2014). Modeling soil erosion within small Moutainous watershed in central Vietnam using GIS and SWAT. Resources and Environment 4, 139–147. doi: 10.5923/j.re.20140403.02.

Truong, D.T., Nguyen, Q.V. and Do, T.V.H. (2012). Assessment of potential soil erosion by REVISED MORGAN – MORGAN – FINNEY model in Dakrong district, Quang Tri province. Hue University Journal of Science 74A (5), 173–184 (Vietnamese).

Truong, V.T., Hoang, T.T., Cao, D.P., Hayashi, M., Tadono, T., and Nasahara, K.N. (2019). JAXA Annual Forest Cover Maps for Vietnam during 2015–2018 Using ALOS-2/PALSAR-2 and Auxiliary Data. Remote Sensing, 11(20), 2412. https://doi.org/10.3390/rs11202412

Vezina, K., Bonn, F., and Pham, V.C. (2006). Agricultural land-use patterns and soil erosion vulnerability of watershed units in Vietnam's northern highlands. Landscape Ecology 21, 1311–1325. doi: 10.1007/s10980-006-0023-x.

Veneziano, D., and Lepore, C. (2012). The scaling of temporal rainfall. Water Resources Research 48, 8516. doi: 10.1029/2012WR012105.

Vietnam Ministry of Agriculture and Rural Development (2021a). Ministry of Agriculture and Rural Development, 2021. Decision 1558/QD-BNN-TCLN on announcing the national forest status in 2020 (Vietnamese).

Vietnam Ministry of Agriculture and Rural Development (2021b). Status of special-use and protection forests in Vietnam 2019 (Vietnamese).

Vietnam Ministry of Natural Resources and Environment (2021). Report on the state of the national environment for the period 2016–2020. Dan tri Publishing House, Hanoi, Vietnam. (Vietnamese)

Vietnam Soil Science Association (2000). Vietnam soil, Agricultural Publishing House, Hanoi, Vietnam. (Vietnamese)

Vu, D.T. (2015). Soil conservation methods and their impact on nitrogen cycling and competition in maize cropping systems on steep slopes in Northwest Vietnam. PhD Dissertation. University of Hohenheim, Germany.

Vu, V.L. (1999). First assessment about sea pollution in the southern coastal zone of Vietnam. In: Ministry of Environmental and Resource Management (Ed.), Country workshop on environment. Science and Technology Publishing House, Hanoi, Vietnam, 274–281 (Vietnamese).

Welle, S., Chantawarangul, K., Nontananandh, S., and Jantawat, S. (2006). Effectiveness of grass strips as barrier against runoff and soil loss in Jijiga area, northern part of Somali region, Ethiopia. Kasetsart Journal of Natural Science 40, 549–558.

Whipkey, R. Z. (1965). Subsurface stormflow from forested slopes. International Association of Scientific Hydrology. Bulletin 10 (3), 74–85.

Wischmeier, W.H. (1973). Conservation tillage to control water erosion. Soil Science Conservation Society of America. In Conservation Tillage, 133–141.

Wischmeier, W.H. and Smith, D.D. (1978). Predicting rainfall erosion losses, Agriculture Handbook 537, 285–291, https://doi.org/10.1029/TR039i002p00285.

Xue, J., and Gavin, K. (2008). Effect of rainfall intensity on infiltration into partly saturated slopes. Geotechnical and Geological Engineering 26, 199–209. doi: 10.1007/s10706-007-9157-0.

Yang, W., Li, D., Sun, T., and Ni, G. (2015). Saturation-excess and infiltration-excess runoff on green roofs. Ecological Engineering 74, 327–336. doi: 10.1016/j.ecoleng.2014.10.023.

Zhu, T.X. (2013). Spatial variation and interaction of runoff generation and erosion within a semi-arid, complex terrain catchment: A hierarchical approach. Journal of Soils and Sediments 13, 1770 – 1783.

Zimmerer, K.S. (1993). Soil erosion and labour shortages in the Andes with special reference to Bolivia, 1953- 91: implications for "Conservation with Development". World Development 21(10): 1659–1675.

Publications

Chapter 3

Le, D. H., Shibata, M., Kohmoto, Y., Nguyen, H. L., and Funakawa, S. (2022). Analysis of the processes that generate surface runoff and soil erosion using a short-term water budget on a mountainous sloping cropland in central Vietnam. CATENA 211, 1–14. https://doi.org/10.1016/j.catena.2022.106032