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Spatial-temporal relationships between crops production and soil erosion: Case of Western Province of Rwanda

A thesis submitted in partial fulfilment for the degree of Master of Geo-Information Science for Environment and Sustainable Development in University of Rwanda

By

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DECLARATION:

This thesis is my original work and has not been presented for a degree in any other university. It was defended in August 2018, corrected and re-submitted in March 2021.

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LIST OF ACRONYMES AND ABREVIATIONS

RCMRD: Regional Center of Mapping of Resources for Development

USGS: United States Geological Survey

UNEP: United Nations Environment Programme

MA: Millennium Ecosystem Assessment

ISRIC: International Soil Reference and Information Centre

EEA: European Environment Agency

FAO: Food and Agriculture Organization

PASTA: Strategic Plan for the Transformation of Agriculture in Rwanda

NDVI: Normalized Difference Vegetation Index

GLASOD: Global Assessment of Human-Induced Soil Degradation

DEM: Digital Elevation Model

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ABSTRACT

The Western Province of Rwanda is vulnerable to soil erosion due to its steep topography, high rainfall and deforestation. Consequently, the agriculture on steep slopes exceeding more than 5 % without adequate soil erosion control measures, has intensified the soil erosion and the decline in agriculture productivity. The objectives of this thesis are to study the spatial-temporal relationship between the soil erosion and crop production in Western Province of Rwanda and to recommend strategic interventions for decision and policy-makers on how to allocate agricultural investments and watershed management efforts. The ratio of Normalized Difference Vegetation Index (NDVI) between the year 2000 and the year 2015 was overlaid to the ratio of soil erosion rates between the same period. The results revealed that between 2000 and 2015, 18% of the area under cultivation was enduring increasing crop production and increasing soil erosion or *tradeoff* between the two ecosystem services while 19% of the area under cultivation was suffering a decrease in crop production and an increase in soil erosion which is also called a trap or a loss between the two ecosystem services. Amongst others, we recommend that in *tradeoffs* areas, farmers should invest a part of their returns in soil conservation in order to make their harvest sustainable while Government efforts in areas of *traps* or *loss* are urgent to help farmers who are blocked under critical thresholds in production–asset investment relationships.

CHAPTER 1: INTRODUCTION

1.1 Background

Ecosystem services are the benefits that people obtain from ecosystems. Ecosystem services include **provisioning services** as the products that humans derive from nature such as food, water, timber, fiber and other materials; **regulating services** as the benefits that people obtain from the regulation of ecosystem processes such flood mitigation, climate regulation, erosion control and water purification; **cultural services** which provide recreational, aesthetic, and spiritual benefits; and as well as the **supporting services** that are necessary for the production of all other ecosystem services such as production of biomass and oxygen, soil formation and retention, nutrient cycling, water cycling, photosynthesis and the provision of habitats for plants and animals (CCICED 2010). Thus, ecosystem services are a powerful lens through which to understand human relationships with the environment and to design environmental policy (Brauman *et al.* 2007).

Different ecosystem services are closely interrelated and determining how to manage multiple ecosystem services across the landscapes is challenging (Raudsepp-Hearne *et al.* 2010; Nguyen 2015). According to (Dasgupta (2008); Swallow *et al.* (2009)), the patterns of demographic and socio-economic changes generate tradeoffs between provisioning, regulating, supporting and cultural ecosystem services. Jessop (2014) summarizes these patterns by arguing that natural resource management decisions frequently involve the choices that reflect the tradeoffs among ecosystem services. Decisions related to a single ecosystem service does not often consider the implications for linked ecosystem services (Chen *et al.* 2014). Particularly, there is a tension between provisioning ecosystem services whose proxy can be the quantities of agriculture production and regulating ecosystem services whose proxy can be the quantities of sediment yields (Swallow *et al.* 2009). This view is also shared by Zhang *et al.* (2007) who argued that ecosystem services from agriculture as provisioning services depend upon a web of supporting and regulating services as inputs to production (e.g., soil fertility and pollination). Consequently, focusing on single provisioning ecosystem services in isolation from regulating services has frequently resulted in policy failures (Elmqvist *et al.* 2011). The relation between soil erosion and crop production has been explored by many studies (Babоulé *et al.* 1994; Ighodaro *et al.* 2013; Pimentel & Burgess 2013). The magnitude of effect of soil erosion on crop production depends very much on the types of changes happened to the land cover. If vegetation/forest cover increases and agricultural activities decrease, then sedimentation caused by soil loss will also decrease (Boix-Fayos *et al.* 2008; Syahli 2015).

In Rwanda, most of the cultivated land has steeper slopes that are not protected (GoR 2004b). Consequently, the agriculture on steep slopes exceeding more than 5 % without adequate soil erosion control measures, has intensified the soil erosion and the decline in agriculture productivity United Nations Environment Programme (UNEP 2011). Thus, the absence of a standard soil erosion monitoring programme in Rwanda is one of the major environmental data and research gaps and is seriously hampering environmental management (UNEP 2011).

1.2 Problem Statement

Soil erosion in Rwanda is a major long-standing environmental problem. The country's fragile soils, steep topography, low natural vegetation cover and high rainfall signify that it naturally experiences very high erosion rates (UNEP 2011; Rushemuka *et al.* 2014). Little scientific outputs of spatially explicit quantitative information on the effect of erosion on agricultural productivity exist. The PSTA III report states that there is a general lack of information on erosion rates. In this context, a major sub target of Strategic Plan for the Transformation of Agriculture in Rwanda III (PSTA III) is the recalibration of erosion (GoR 2013) and the best ways of efficiently protecting soil against erosion are yet to be researched and spread throughout the country (GoR,2017).

Most of the cultivated land has steeper slopes that are not protected according to the recommended erosion control measures (GoR 2004b). Consequently, the agriculture on steep slopes exceeding more than 5 % without adequate soil erosion control measures has intensified the soil erosion and the decline in agriculture productivity. Clay *et al.* (1996) found a decline in productivity on 48.7 percent of the cropland, 37.5 percent showed no change, and improvement was reported for only 13.8 percent and this was determined by soil conservation investments such as terraces and hedgerows at 84%. Byiringiro and Reardon (1996) found that farms with greater investment in soil conservation had much better land productivity than the average while those with very eroded soils did much worse than the average.

Although soil erosion control is a national priority, the adoption of soil conservation measures by farmers remains greatly limited. The non-adoption of soil erosion control measures has been tied to lack technical knowledge, lack of resources, land tenure insecurity and lack of perceived benefits where erosion control measures may take up extra land and reduce their already limited area for crop cultivation (UNEP 2011).

According to UNEP (2011), GIS modeling estimates have shown the extreme gravity of the soil erosion problem facing Rwanda, with 47 percent and 34 percent of the country experiencing soil erosion rates of between 50 and 100 tons per hectare per annum, respectively as illustrated in the table 1 below.

Erosion rate (tons /ha /year)	**Surface Area in Square km**	**Proportion of total surface area (%)**
0-30	113	0.45
30-50	2967	11.77
50-100	11,953	47.41
100-150	8,524	33.81
150-300	142	0.56
Water bodies	1,511	6.0
Total	25,210	100

Table 1: Preliminary soil erosion rates estimates in Rwanda
Source: UNEP (2011)

Overall, the country is estimated to be losing 1.4 million tons of soil per year which is equivalent to a decline in the country's capacity to feed 40,000 people per year (Karamage *et al.* 2016b). The amount of plant nutrients lost annually is estimated at about 945,000 tons of Organic Matter, 41,210 tons of Nitrogen, 3,055 tons of Potassium and 280 tons of Phosphorous (GoR 2007). The results of the research conducted by the national agricultural research institute (ISAR) and by other scientists indicate that on five of the seven research stations where erosion was measured, erosion would remove the fertile topsoil within 30 years if no anti-erosion techniques were used (Karamage *et al.* 2016c).

The Western province is one of the most vulnerable areas to soil erosion in Rwanda. According to Karamage *et al.* (2016c), 3 out of the 10 most eroded districts in Rwanda are in the Western Province and the Western Province alone contribute to 22.4% of the national soil erosion while according to UNEP (2011), Karongi, Nyamasheke and Rusizi districts of the Western Province are among the most eroded districts with 1%, 1% and 4% respectively of their areas affected by highest soil erosion rates of 150-300 tons/hectare/year.

Although soil losses are generally acknowledged to be quite high, the magnitude and the spatial pattern of the impact of soil erosion on agriculture are still unclear at different spatial scale - national, regional and local scale (Karamage *et al.* 2016c). There are few long-term studies in Rwanda with reliable data on soil erosion rates and the scarcity of information in the country makes it difficult to develop objective assessments of soil erosion and design anti-erosion strategies (REMA 2015b; Karamage *et al.* 2016a; Karamage *et al.* 2016b; Karamage *et al.* 2016c). Moreover, the linkage between soil erosion and land productivity in Rwanda is under-researched (GoR, 2017).

In spite of the above-mentioned lacking data, methodological challenges and gaps of knowledge for understanding the impact of soil erosion on agricultural production, it is important to tackle these methodological challenges by conducting integrated assessments in real-world contexts at scales relevant for managers and policy-makers (Carpenter *et al.* 2006; Chan *et al.* 2006; Smajgl *et al.* 2011). An urgent action is needed to effectively address the effect of soil erosion on agricultural production in the Western Province of Rwanda. This requires to know hotspots of soil erosion and crop production, to quantify the changes of erosion and crop production over time, thus the need of developing maps which deal with the linkage between agriculture production and erosion. By producing ecosystem services maps to estimate where ecosystem services are produced, areas where ecosystems are stressed emerge and clarify difficult trade-offs being made at the local level (UNEP 2005).

The general objective of this study is to study the spatial-temporal relationship between the soil erosion and crop production by using i) Normalized Difference Vegetation Index (NDVI) as a proxy indicator for crop production which provide reliable spatially and temporally continuous data with global coverage and decent resolution(LV 2013) compared to estimates from farmers interviews which are used in Rwanda (NISR 2016b) and which are subjective and not representative (Lopresti *et al.* 2015) and ii) the Revised Universal Soil Loss Equation (RUSLE) as soil erosion model in the Western Province of Rwanda. It is hypothesized that there may be tradeoffs, synergies or traps between crop production and soil erosion in Western Province of Rwanda.

1.3 Research objectives and research questions

The general objective of this research is to study the spatial-temporal relationship between the soil erosion and crop production by using NDVI as a proxy indicator for crop production and soil erosion in the Western Province of Rwanda. The specific objectives and their related research questions are presented in table 2 below.

Research objectives	Research Questions
1. To assess the spatial-temporal distribution of soil erosion as a regulating ecosystem service in Western Province of Rwanda.	1. How erosion rates are spatially distributed in Western Province of Rwanda in the years 2000, 2015? 2. What was the temporal trend of spatial distribution of erosion rates in Western Province of Rwanda?
2. To analyze the spatial-temporal distribution of crop production as provisioning ecosystem services in Western Province of Rwanda.	3. How was agriculture production distributed in Western Province of Rwanda in the years 2000, 2015? 4. What are the general trends of agriculture production between 2000 and 2015 in Western Province?
3. To study the spatial relationships between crop production and erosion in the study area.	5. Are there some relationships between crop production and soil erosion in the study area?
4. To make recommendation for policy-making, agricultural investments and watershed management	6. What can policy-makers, agricultural investments and watershed management do?

Table 2: Research objectives and research questions

1.4 Research Justification

Trade-off analysis is an important feature in assessing ecosystem services in natural resource management (Carpenter et al. 2008). Identification of ecosystem services to inform trade-offs in natural resource management is an evolving field of research (Butler et al. 2011; University of Edinburgh2016) which plays a central role in the design of sustainable agro-ecosystems (Rounsevell et al. 2012). It is also increasingly being a common approach for environmental policy-making and management in government agencies and businesses (University of Edinburgh2016). Results from our study will have multiple uses in rural planning, agricultural investment, and watershed management (Swallow et al. 2009). In Rwanda, there are households and areas which are in vicious cycles of low income, low investment in soil management, declines in soil fertility, and soil loss and households which are able to achieve higher incomes and investments, maintain soil fertility, and conserve soil on their farms (Byiringiro & Reardon 1996; Clay et al. 1996). The identification of these areas would assist Rwandan policy-makers in general and agricultural practitioners of the Western Province in particular in working towards sustainable agro-ecosystems.

1.5 Thesis Structure

This thesis is divided into five chapters. Chapter 1 introduces the thesis by providing its background, its problem statement, its research objectives and questions as well as the justification of the research. Chapter 2 conceptualizes the thesis by explaining the different key concepts underlying soil erosion and crop production. Chapter 3 describes the study area and provides the methodology followed by the thesis. Chapter 4 presents the results and discusses them while chapter 5 is the conclusion of the thesis.

1.6 Scope of the Thesis

This thesis studies the spatial-temporal relationship between soil erosion and crop production in the Western Province of Rwanda in the period lying between the year 2000 and the year 2015.

CHAPTER 2: CONCEPTUAL FRAMEWORK

In this chapter, the concept of soil erosion will be detailed along with the different method used to spatially model soil erosion. Factors and causes of soil erosion and interactions between them will also be briefly described. The effects of soil erosion on crop production will be shown and a concept from Millennium Ecosystem Assessment (MA) which uses a matrix to determine the interrelation between multiple ecosystem services at the zero-point of the diagram will be introduced and discussed.

2.1Definition of the key concepts

2.1.1 Understanding the soil erosion

2.1.1.1 Definition of soil erosion

Soil erosion is defined as the wearing away of topsoil. Topsoil is the top layer of soil and is the most fertile because it contains the most organic, nutrient-rich materials. One of the main causes of soil erosion is water erosion, which is the loss of topsoil due to water (Morgan 2005). When rain drops reach the soil, they detach soil particles. The degree to which this happens depends on the size and speed of the falling raindrops. The detached soil particles are subsequently transported by overland water flow. Erosion occurs when the precipitation rate exceeds the infiltration rate of the soil (European Commission2009).

There are two main groups of erosion: the *natural erosion process* and the *anthropogenic erosion* or man induced erosion. In natural conditions, the soil productivity remains constant and the erosion is in equilibrium. If anthropogenic activities interfere with practice of agriculture but it is done by applying conservation techniques, the effect on soil erosion can still be zero (Zachar 1982). Anthropogenic erosion is the intensification and acceleration by human activities, such as inappropriate cultivation techniques and cropping practices, changes in hydrological conditions, deforestation and land marginalization or abandonment (European Commission2009).

The most influential factors of soil erosion are soil erodibility, climatic erosivity, terrain and ground cover. Susceptibility of soil to agents of erosion or soil erodibility is determined by soil properties like texture, structure, soil organic matter content, clay minerals, exchangeable cations and water retention and transmission properties. Erosivity is influenced by environmental factors primarily climate including drop size distribution and intensity of rain, amount and frequency of rain, runoff amount and velocity, and wind velocity. Terrain characteristics have a significant impact on rate of soil erosion by water and gravity agents. Importantly terrain characteristics include slope gradient, length, aspect, and shape. Ground cover exerts a strong moderating impact on dissipating the energy supplied by agents of soil erosion (Lal 2001). The factors of soil erosion, the causes of soil erosion and interaction between them are presented schematically in Figure 1 bellow.

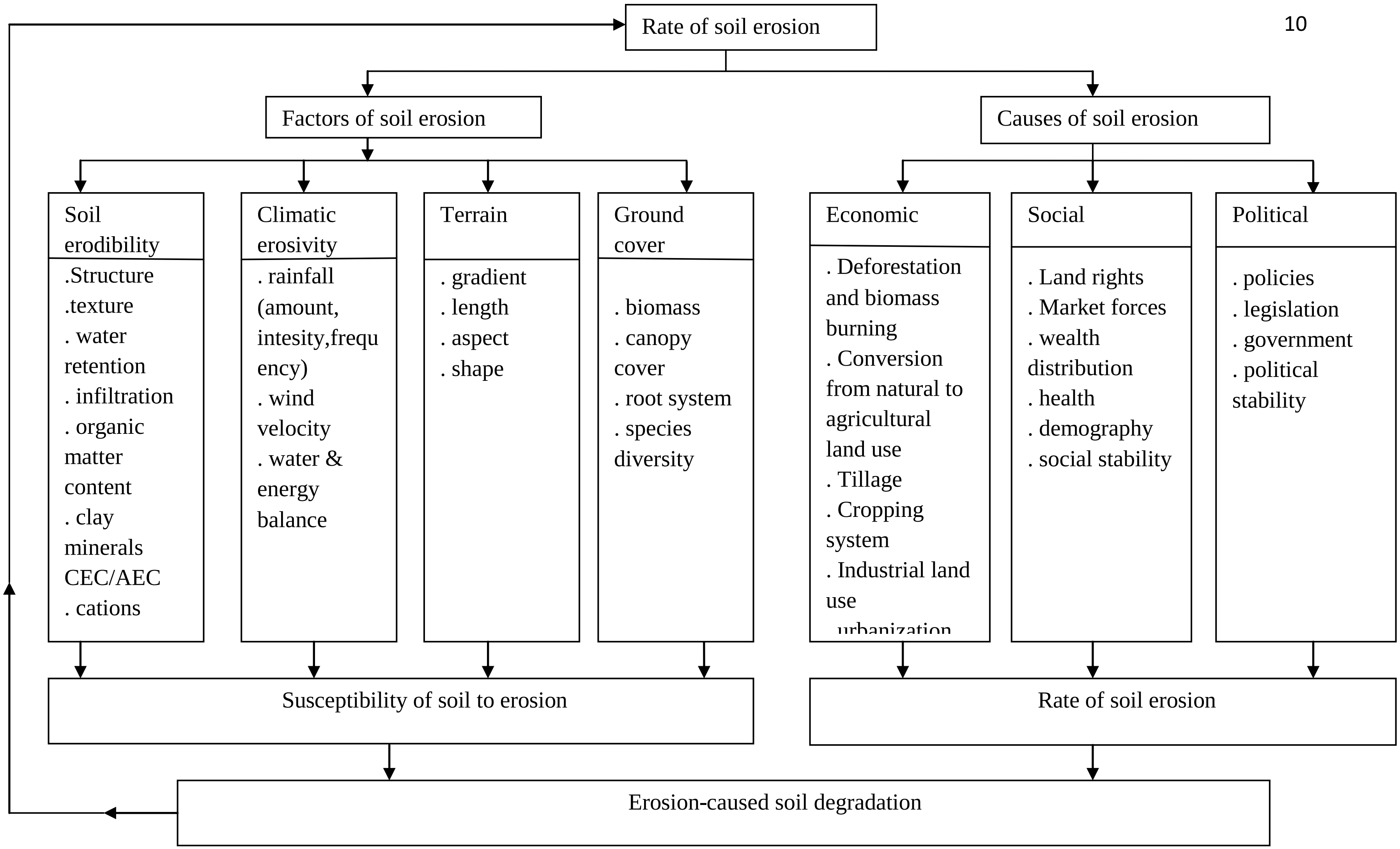


Figure 1: Factors of soil erosion, causes of soil erosion and interaction between them

Source: (Lal 2001)

The effects of soil erosion processes is modified by biophysical environment comprising soil, climate, terrain, and ground cover, and interaction between them (Figure 1). Susceptibility of soil to agents of soil erosion, soil erodibility, is determined by inherent soil properties, e.g., texture, structure, soil organic matter content, clay minerals, exchangeable cations, and water retention and transmission properties. Erosivity is influenced by environmental factors primarily climate including drop size distribution and intensity of rain, amount and frequency of rain, runoff amount and velocity, and wind velocity. Terrain characteristics have a significant on rate of soil erosion by water and gravity agents. Important terrain characteristics include slope gradient, length, aspect, and shape. Ground cover exerts a strong moderating impact on dissipating the energy supplied by the agents of soil erosion.

The effect of biophysical processes governing soil erosion is influenced by economic, social and political causes (Figure1). Social causes that can accentuate the rate of erosion-induced soil degradation include subsistence or resource-based agriculture, poverty and literacy, poor health and malnutrition, political instability, and high demographic pressure (Figure 1). Social, economic, and policy causes influence mainly the type of land use and management. These causes then influence the rate of soil erosion which determines the severity of soil degradation (Figure 1).

By integrating the soil erodibility map, the rainfall erosivity map, the slope length and steepness map and the land cover map, and by documenting that these factors of soil erosion were accelerated by different causes of soil erosion such as rapid increase of population, deforestation and biomass burning, the present research has integrated all these factors and causes of soil erosion.

2.1.1.2 Erosion process

Soil erosion is a three-phase process consisting of the ***detachment*** of individual soil particles from the soil mass and their ***transport*** by erosive agents such as running water and wind. When sufficient energy is no longer available to transport the particles, a third phase, ***deposition***, occurs (Morgan 2005). Combinations of these detachment and transport processes give rise to the three main processes, rain splash, rain-wash and rill wash. For rain splash, grains are detached by drop impact and jump through the air. The net rate of downhill transportation increases with the slope gradient and decreases with the grain size that is transported. The rates of material transport by rain splash are generally low. For rain flow, grains are detached by raindrop impact, and carried farther than for rain splash within a thin layer of flowing water. Both rain splash and rain flow are commonly grouped together as inter-rill erosion processes. Where flow is sufficiently intense to entrain soil particles directly, small channels or rills are formed on the surface, and material is eroded by rill flow, which is concentrated along these drainage lines (Grimm *et al.* 2001). The process of soil erosion is presented in Figure 2 below.

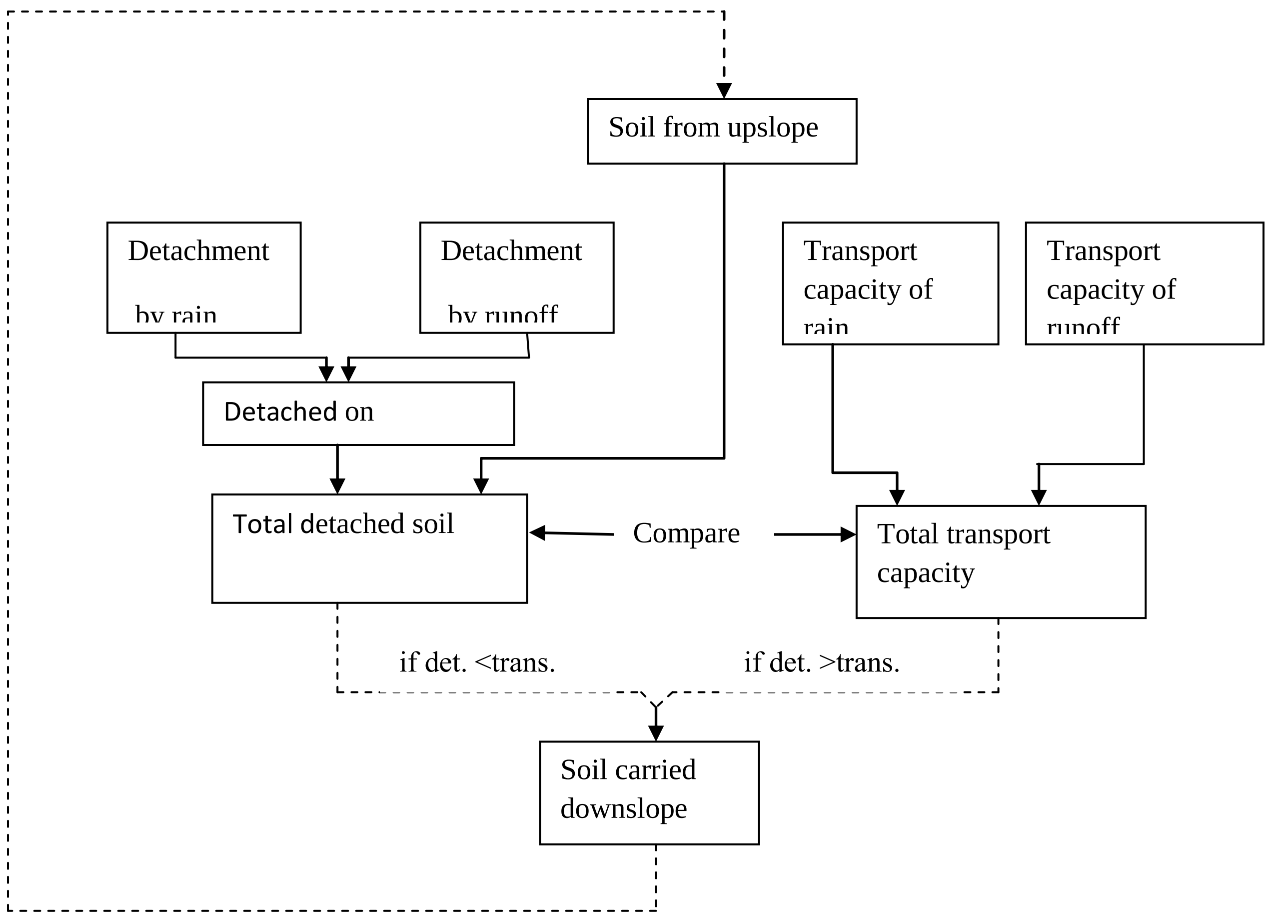


Figure 2: Flowchart of soil erosion by water
Source: Morgan (2005)

This erosion process consisting of soil detachment and soil transport downslope also referred as rill and sheet erosion is applicable to the study area of the present research since both rill and sheet erosion are present in Rwanda(Lewis *et al.* 1988; Roose & Ndayizigiye 1997; UNEP 2011).

2.1.1.3 Effects of soil erosion on crop production

Basically, soil erosion is a natural process which becomes intolerable when it is accelerated by human and the amount of soil loss affects soil quality and reduces the crop productivity (DeLong *et al.* 2015; Sonneveld *et al.* 2016). Further, soil erosion is intolerable when it starts to reduce significantly the soil fertility, soil thickness, water storage capacity of the soil and thus the crop productivity (Li *et al.* 2009). Soil erosion has many effects ranging from loss of nutrients (Gulati & Rai 2014), loss of soil organic matter (Karlen & Rice 2015), reduction of soil depth (Pimentel & Burgess 2013), effects on yields and plant density as some seeds are taken away by splash and runoff during heavy storms on unstable soils and plants uprooted by rill erosion and others are buried under sediments (Halim & Osman 2015).

In Rwanda, erosion has long been assumed to be severe and a major reason for the poverty and food insecurity in general (Karamage *et al.* 2016c) and it remains a serious limiting factor to the agricultural production (Rutebuka *et al.* 2017).

2.1.2 Crop yield as function of vegetation health

The health of crops at different growth stages influences crop yields (Schepers & Holland 2012) and crop growth analysis has been using the Normalized Difference Vegetation Index (NDVI) (Lewis *et al.* 2010; Sultana *et al.* 2014). In this way for example, while estimating wheat yield, Sultana *et al.* (2014) found that the correlation among NDVI at booting, grain filling, and maturity stages with grain yields was positive with R^2=0.90, R^2=0.90 and R^2=0.95 respectively. While trying to understand the spatial temporal vegetation dynamics in Rwanda, Ndayisaba *et al.* (2016) also used NDVI.

According to Rouse et al. (1974), NDVI can generally be calculated from vegetation canopy reflectance in the red (670 – 680 nm) and near-infrared (750 – 850 nm) wavelengths using broad-band remotely sensed data. The presence of chlorophyll pigment in green vegetation and leaf scattering mechanisms cause low spectral reflectance in the red and high reflectance in the near infrared, respectively. Reflectance values change in the opposite direction if vegetation is under stress (Kogan, 1994). Hence, the NDVI measures vegetation vigour and greenness (Tarpley et al., 1984) and is calculated as follows: NDV= $\frac{NIR-R}{NIR+R}$, where NIR and R represent the reflectance of the near infrared and the red, respectively.

The NDVI is unitless, with values ranging from -1 to +1. Healthy green vegetation normally has the highest positive values while surfaces without vegetation, such as bare soil, water, snow, ice or clouds usually have low NDVI values that are near zero or slightly negative.

If soil erosion affects loss of nutrients (Gulati & Rai 2014), loss of soil organic matter (Karlen & Rice 2015), reduction of soil depth (Pimentel & Burgess 2013), yields and plant density (Halim & Osman 2015), then one deducts that soil erosion is linked to yields estimated using NDVI.

2.1.3. Ecosystem services; soil erosion and Crop yield

The concept of ecosystems services has become an important model for linking the functioning of ecosystems to human welfare. Understanding this link is critical in decision-making contexts. While there have been several attempts to come up with a classification scheme for ecosystem services, there has not been an agreed upon, meaningful and consistent definition for ecosystem services. Ecosystem services are the aspects of ecosystems utilized (actively or passively) to produce human well-being. The key points are that 1) services must be ecological phenomena and 2) that they do not have to be directly utilized. Defined this way, ecosystem services include ecosystem organization or structure as well as process and/or functions if they are consumed or utilized by humanity either directly or indirectly. The functions or processes become services if there are humans that benefit from them. Without human beneficiaries they are not services (Fisher *et al.* 2009).

Ecosystem services approach has emerged as a conservation framework that links human economies and natural systems through the benefits that people receive from nature (Posner 2015). Different ecosystem services are closely interrelated and determining how to manage multiple ecosystem services across landscapes is challenging (Raudsepp-Hearne *et al.* 2010; Nguyen 2015). While demands for ecosystem services such as food and clean water are growing, human actions are at the same time diminishing the capability of many ecosystems to meet these demands (MilleniumEcosystemAssessement 2003). Resource management decisions frequently involve choices that reflect tradeoffs among ecosystem services. As a consequence, they may make decisions that diminish the value of some services while enhancing the value of others (Jessop 2014). Particularly, there is a tension between provisioning ecosystem services whose proxy can be the quantities of agriculture production amongst others and regulating ecosystem services say amongst others erosion control whose proxy can be the quantities of sediment yields (Swallow et al. 2009).

Tradeoffs between ecosystem services emerge as situations in which one service increases at the cost of another one (Swallow *et al.* 2009; Raudsepp-Hearne *et al.* 2010; Jessop 2014). The reverse of trade-offs are ***synergies***, which can be defined as situations in which both services increase. Situations where both ecosystem services decrease are called ***traps or loss*** (Bennett et al. 2009; Swallow et al. 2009; Haase et al. 2012). In order to better understand the interrelation between ecosystem services, these interactions can be integrated on a single diagram which comprises X and Y axes and whose starting point is zero as shown in Figure 3 bellow.

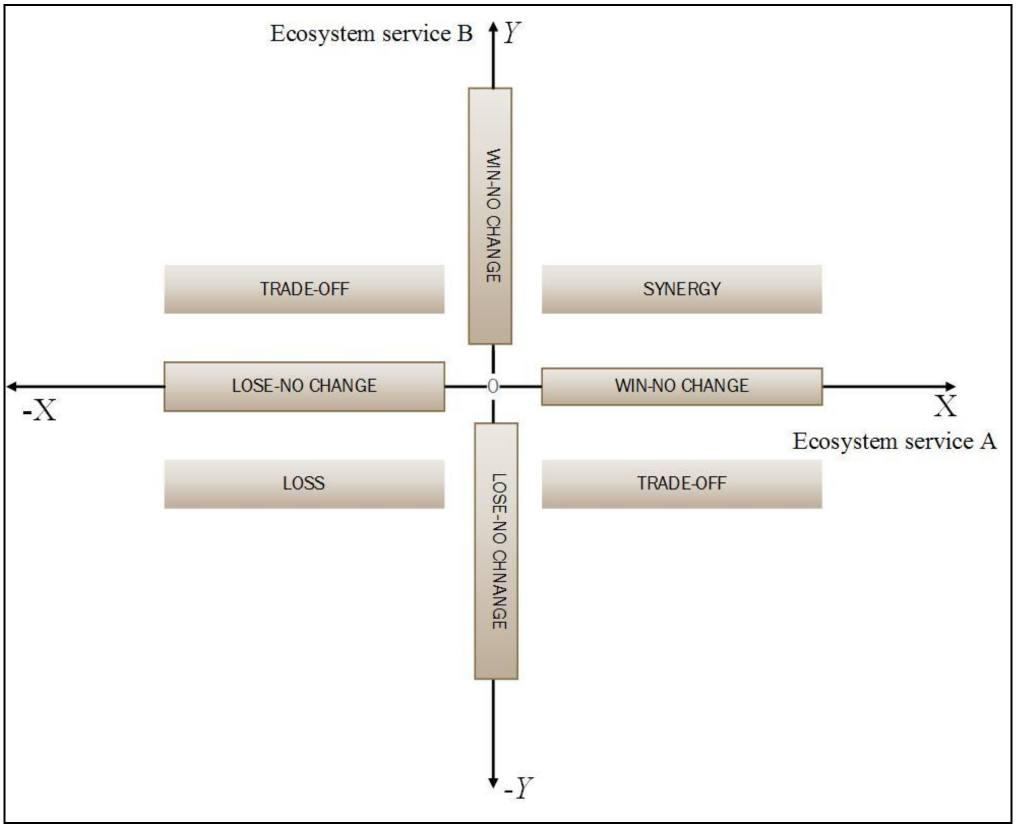


Figure 3: Interrelation between Ecosystem Services
Source: Haase et al. (2012)

In the present research, agriculture production or provisioning ecosystem service is referred to Ecosystem A while erosion control or regulating ecosystem service is Ecosystem B. At their intersection is point zero. [0, 0] point means that there is neither a change in agriculture production, nor a change in soil erosion. [0, X] axis means that agriculture production is the case where agriculture production increases and there is no change in soil erosion, a scenario also called ***win-no change***. [0, Y] axis stands for a scenario in which there is no change in agriculture production and an increase in soil erosion control, a scenario also called ***win- no change***. [0, -X] axis means that agriculture production is decreasing while there is no change in soil erosion, a situation also called ***lose-no change***. [0, -Y]. A situation between X and Y axes is the situation in which agriculture production and soil erosion control increase simultaneously, a scenario also called ***synergy*** between the two ecosystem services. When agriculture production increases and soil erosion control decreases simultaneously [X, -Y], the situation is called a tradeoff between the two ecosystem services. When agriculture production and soil erosion control decrease at the same time, this scenario is called a ***loss or a trap*** between the two ecosystem services.

These tradeoffs are not always explicit, and can exist without our knowledge. Therefore, decisions related to a single ecosystem service should consider the implications for linked ecosystem services (ChinaCouncilforInternationalCooperationonEnvironmentandDevelopment 2010). Trade-offs in ecosystem services can be classified along three axes: spatial scale, temporal scale, and reversibility (Rodríguez *et al.* 2006; Power 2010). Spatial scale refers to whether the effects of the trade-off are felt locally or at a distant location. Temporal scale refers to whether the effects take place relatively rapidly or slowly. Reversibility expresses the likelihood that the perturbed ecosystem services may return to its original state if the perturbation ceases (Rodríguez *et al.* 2006).

Concepts and approaches from the Millennium Ecosystem Assessment (MA) have been applied in a study of ecosystem service tradeoffs, synergies and traps with predictions of soil erosion yields serving as the main measure of regulating services and agricultural production serving as the measure of provisioning service (Swallow *et al.* 2009). Under the MA, the crop production as provisioning ecosystem services and soil erosion as regulating ecosystem service can be integrated since within the MA assessments can be interlinked and undertaken at local, watershed, national, regional, and global scales (MA 2005).

Similarly, these approaches of (Swallow *et al.* (2009); Haase *et al.* (2012)) will be applied in the present research in order to identify in the Western Province of Rwanda areas of *Synergy*: a win-win situation that involves an increase in NDVI and decrease in soil erosion, *Win-no change*: An improvement in NDVI and no obvious changes in the soil erosion, *Lose-no change*: A decline in NDVI and no obvious changes in the soil erosion, *Trade-off*: A win-lose or lose-win situation that involves increasing NDVI and decreasing erosion control (or increasing soil erosion), *Loss (or trap)*: A decrease of NDVI and increasing soil erosion and *No change*: No changes in NDVI and soil erosion. The present research has decided to use these approaches because they provide a better understanding of the spatial patterns of ES, their trade-offs and their relationship to land cover change which is absolutely necessary (Egoh *et al.* 2009; Lautenbach *et al.* 2011).

2.2. Spatial modeling of soil erosion and crop yield

2.2.1. Soil erosion modeling

In soil erosion modeling, it is not possible to take measurements of soil erosion at every point in the landscape. It also takes time to build up a sufficient database to ensure that the measurements are not biased by an extreme event or a few years of abnormally high rainfall. Long-period measurements are required to study how erosion rates respond to changes in land use and climate or the use of erosion-control measures. In order to overcome these deficiencies, models can be used to predict erosion under a wide range of conditions. The results of the predictions can then be compared with the measurements to ensure their validity. If the predictions are sufficiently accurate, the developed model may be used to estimate erosion in other areas of similar conditions (Morgan 2005).

The use of Geographic Information Systems (GIS) and remote sensing in soil erosion modeling is very important. GIS makes it possible to apply spatial techniques to create and integrate maps of the different factors affecting the soil erosion (Kim 2006; Kumar *et al.* 2014; Pacheco *et al.* 2014). Approaches used to assess soil erosion fall under two main groups: expert-based and model-based methods.

2.2.1.1 Expert-based methods

Expert-based methods are based on scores that are assigned to factors related to soil erodibility, erosivity, slope angle and land cover. These include for example the Coordination Information Environment (CORINE) method; Global Assessment of Human-Induced Soil Degradation (GLASOD); and the hot spots approach.

2.2.1.1.1 The Coordination Information Environment (CORINE)

The CORINE Programme was established in 1985 to : guide and implement community environment policy, and incorporate an environmental dimension into other policies, by providing information on priority topics; ensure optimum use of financial and human resources by organizing, influencing and encouraging initiatives by international organizations, national governments or regions to obtain environmental information; develop the methodological base needed to obtain environmental data which are comparable at a community level.

The soil erosion analysis using CORINE is based on factorial scores for soil erodibility (4 classes), erosivity (3 classes) and slope angle (4 classes). The scores are multiplied, giving a combined score that represents potential erosion risk. To assess actual soil erosion risk, the potential erosion risk map is combined with a land cover factor (2 classes). Erodibility is estimated from soil texture, depth and stoniness. Erosivity is estimated from the Fournier and Bagnouls-Gaussen climatic indices. Slope gradient is included, but without a slope length correction, and vegetation and crop management are collapsed into two categories of protected, and not fully protected, using data from the associated CORINE land cover database. These factors are combined to estimate three categories of potential and actual soil erosion risk. Potential risk excludes vegetation factors, and so identifies land at risk, while Actual risk includes the vegetation factor to indicate whether the potential is being realized (Gobin *et al.* 2002).

The advantage of the CORINE soil erosion assessment is its simplicity in that it provides a clear forecast, on an objective basis, for the whole of the area studied. Its limitation is that on a qualitative basis, comparison of the Erosion maps to show a too great dependence on the climatic factors in determining erosion risk, with relatively less weight given to important factors of erodibility and land cover(Gobin *et al.* 2002). This is the reason why CORINE approach is not applicable for the case of the present research.

2.2.1.1.2 Global Assessment of Human-Induced Soil Degradation (GLASOD)

The main objective of the GLASOD project was to strengthen the awareness of decision makers on the risks resulting from inappropriate land and soil management to the global well-being. It was produced by the International Soil Reference and Information Centre (ISRIC) in 1988 in partnership with a large number of soil scientists. It is based on responses to a questionnaire, which has been sent to recognized experts in all countries (Oldeman *et al.* 1991). As a result, regional soil degradation status maps were produced and these regional maps were correlated to provide the Global Assessment of Human-Induced Soil Degradation world map of soil degradation.

It was the first comprehensive global overview on soil degradation, which created awareness and highlighted the need for a more objective approach and for validation. The impossibility of making truly objective comparisons between, and often within areas in interpreting GLASOD results is its major limitation. No expert knows all the erosion sites within his or her own area with equal confidence, and scales within each area tend to be from best to worst, without absolute scales for objective comparison (Gobin *et al.* 2002). These limitations make GALSOD not applicable in our study area.

2.2.1.1.3 The ‘Hot Spots’ approach

An analysis and mapping of soil problem areas (Hot spots) in Europe was published in the European Environment Agency (EEA)-UNEP joint message on soil (EEA 2000). The advantage of the method is that it is good at localizing significant erosion. Its limitation is that, in its present form, the most important information contained in these maps lies in the considerable experience of its compilers, which it is hard to document or quantify. It is also clear that sites of high erosion identified on this map are definitely areas of high impact, but that there is no reliable way to extrapolate these local results, even to their surrounding area (Gobin *et al.* 2002). Therefore, the hotspot approach is not applicable to the study area of the present research.

A problem with most methods based on scoring is that the results are affected by the way the scores are defined. In addition to this, classifying the source data in e.g. slope classes results in information loss, and the results of the analyses may depend strongly on the class limits and the number of classes used. Moreover, unless some kind of weighting is used each factor is given equal weight, which is not realistic. If one decides to use some weighting, choosing realistic values for the weights may be difficult (Grimm *et al.* 2001). The way in which the various factors are combined into classes that are functional with respect to erosion risk (addition, multiplication) may pose problems (Morgan 1995). Finally, as factorial scoring produces qualitative erosion classes, the interpretation of these classes can be difficult(Grimm *et al.* 2001).

As far as the present study is concerned, in order to avoid any bias in the definition of classes, weight assignment, and given that we have no expertise required to assign credible values to produce quantitative erosion classes, we have decided to not use any of the expert-based models to produce the spatial distribution of soil erosion in the Western Province of Rwanda. Moreover, methods based on questionnaire surveys (GLASOD) or erosion measurement sites (Hot Spots) are likely to be inadequate on their own (Gobin *et al.* 2002).

2.2.1.2 Model-based methods

These erosion models can be classified in a number of ways. One may make a subdivision based on the time scale for which a model can be used: some models are designed to predict long-term annual soil losses, while others predict single storm losses (event-based). Alternatively, a distinction can be made between lumped models that predict erosion at a single point, and spatially distributed models (Grimm *et al.* 2001). Another useful division is the one between *empirical models* based on identifying statistically significant relationships between assumed important variables where a reasonable database exists and *physically-based models* based on mathematical equations to describe the processes involved in the model, taking account of the laws of conservation of mass and energy (Morgan 2005).

Within the model-based methods, input variables are derived from standard meteorological data (total rainfall in the wettest month in mm and annual precipitation in mm), soil maps (soil type), multi-temporal satellite imagery (land cover), digital elevation models (slope) and a limited amount of field data for field calibration. This way, erosion risk can be assessed over large, spatially diverse areas without the need for extensive field surveys. The model based methods for soil erosion modeling include for example the Revised Universal Soil Loss Equation and The Soil Loss Estimator for Southern Africa.

2.2.1.2.1 Revised Universal Soil Loss Equation

In 1978, Universal Soil Loss Equation (USLE) was firstly introduced (Wishmeir & Smith 1978). USLE is an empirical model to predict soil loss on cultivated land in order to be able to determine erosion control (FAO no date). The Revised Universal Soil Loss Equation (RUSLE) was then introduced as a revision and update of the widely used Universal Soil Loss Equation (USLE) by including improved computation of soil erosion factors such as monthly factors, incorporation of the influence of profile convexity/concavity and improved empirical equations for the L and S factors(Renard *et al.* 1991; Breiby 2006). According to McCool *et al.* (1995), the Universal Soil Loss Equation has been revised to more accurately estimate soil loss from both crop and rangeland areas. The revision includes data not available at the time USLE was initiated in 1978. RUSLE uses four independent variables, rainfall erosivity, soil erodibility, topography and vegetation cover to estimate long-term soil loss more accurately than USLE(Renard *et al.* 1997; Yang *et al.* 2003; Karamage *et al.* 2016c).

The RUSLE Equation of soil erosion model within a catchment is expressed by A=R.K.L.S.C.P; Where: A= Average annual soil loss; R= Rainfall/ Erosivity as the power of rainfall to erode the soil resulting from the energy of falling raindrops; LS= topographic factors of slope length L and the Steepness S; K= Soil erodibility is a measure of the vulnerability of soil to erosion which is influenced of the physical characteristics of the soil; C= crop management is the ratio of soil loss under a given crop to that of bare soil; and P= support practice factor which compares the soil loss from cultivated land without conservation practice to that with conservation practice (Onyando *et al.* 2005).

RUSLE approach is applicable and has been applied by the present study for soil erosion modeling in our study area because not only Norén and Spörndly (2009) suggested that more excessive erosion studies using the Universal Soil Loss Equation might be necessary to further understand erosion in Rwanda, but also it is the most appropriate method to estimate annual soil erosion rates (tones/ha/year) over a large area caused by rainfall (sheet or rill erosion) when there are constraints of availability of time and long-term soil erosion monitoring data like in Rwanda (UNEP 2011). Rainfall erosivity map was derived from UNEP (2011) given that annual average rainfall amount is not very dynamic in Rwanda (McSweeney 2011). R Factor map was also derived from the database created by UNEP (2011) because physical properties of soil are also not dynamic(Kim 2006). Slope length and steepness (LS) factor map was created using the following formula LS = $\left(\frac{\text{Fac}\times\text{Cell value}}{22.13}\right)^{m}\left(0.065+0.045(S)+0.0065(S^2)\right)$ that Bizuwerk *et al.* (2008) have developed based on Wishmeir and Smith (1978). C Factor map of the year 2000 and for the year 2015 were obtained by assigning C values proposed by Wishmeir and Smith (1978) and Morgan (2005) to the different land cover types of the RCMRD land cover map of 2000 and 2015 respectively. P factor values were assigned according to percentages slope of the study area as described by (Shin 1999) cited in (Kim 2006). The raster maps of R, K, LS, C and P were multiplied using raster calculator tool of ArcGIS software since the RUSLE formula is A=R.K.L.S.C.P

2.2.1.2.2 The Soil Loss Estimator for Southern Africa (SLEMSA)

The Soil Loss Estimator for Southern Africa (SLEMSA) was developed largely from the Zimbabwe Highveld to evaluate the erosion resulting from different farming systems so that appropriate conservation measures could be recommended. The technique has since been adopted throughout the countries of Southern Africa. According to Elwell (1978) , the equation of SLEMSA is : $Z = K \times \quad X \times \quad C$ where Z is mean annual soil loss (in tons per hectare), K is mean annual soil loss (in tons per hectare) from a standard field plot, 30m long, 10m wide, at 2.5°slope for a soil of known erodibility (F) under a weed-free bare fallow, X is a dimensionless combined slope length and steepness factor and C is a dimensionless crop management factor. Norén and Spörndly (2009) suggested that more excessive erosion studies using the Soil Loss Estimations in Southern Africa (SLEMSA) might be necessary to further understand erosion in Rwanda. However, given that comparison between SLEMSA and RUSLE methods do not always favor SLEMSA in the tropics (Igwe *et al.* 1997), the present research has found SLEMSA not appropriate for our study area.

2.2.2 Crop yield estimation

In developing countries, official crop production estimates are either inaccurate or nonexistent (LV 2013). This was also the case in Rwanda in the years of 2000, the starting of our study period, since the National Institute of Statistics in Rwanda whose attributions include to provide coherence in national agricultural data systems was not yet established (Donovan 2008). Rwanda official estimates of yield are currently made mainly through interviews with farmers (NISR 2016b). Taking into account the subjectivity and low representativeness of this technique, agricultural estimates through remote sensors especially through Normalized Difference Vegetation Index (NDVI) are increasingly being considered worldwide (Son *et al.* 2014; Lopresti *et al.* 2015; Shao *et al.* 2015). In fact, satellite systems provide spatially and temporally continuous data with global coverage and decent resolution and timely acquisition of such data is available and mostly inexpensive through several online portals and archives (LV 2013). In the present study, eMODIS NDVI maps of a spatial resolution of 250 meters in GeoTIFF format downloaded from FEWSNET portal have been used as a proxy indicator of crop production in western province of Rwanda since NDVI highly correlate with crop growth and crop production according to various researches like Mkhabela *et al.* (2005), Lewis *et al.* (2010) and Sultana *et al.* (2014). For visualization purposes, Simonetti *et al.* (2014) has been followed and NDVI values will be reclassified into 3 main classes namely 0-0.1(rocks/sands), 0.2-0.5(unhealthy crops) and 0.6-0.9 (healthy crops).

CHAPTER 3: METHODOLOGICAL APPROACH

3.1 Study Area

3.1.1 Location of Western Province in Rwanda

The Western Province is one of the four Provinces of Rwanda and Kigali City. It shares its boundary with the Northern Province and Democratic Republic of Congo in north; Southern Province in East; Burundi and DRC in west. The location of the Western Province of Rwanda is shown in Figure 4 below.

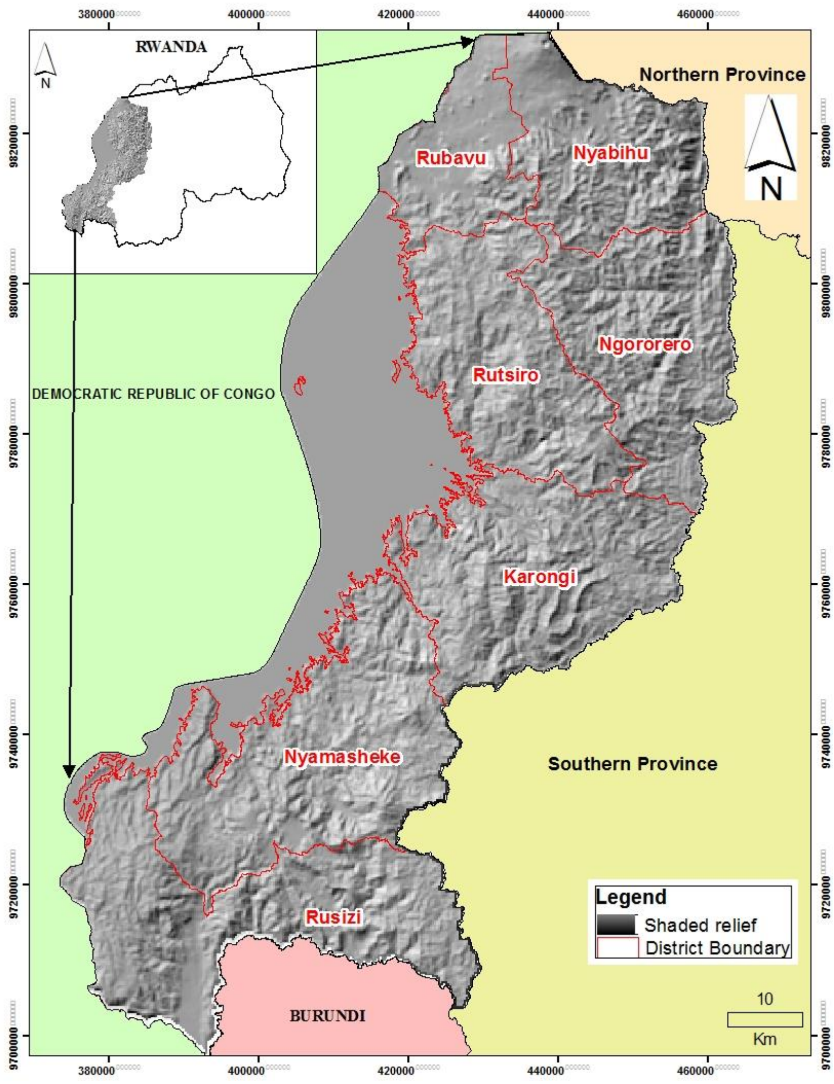


Figure 4: Location of Western Province

It has an area of over 5,882 Square kilometers. The Western Province is divided into 7 districts (Rubavu, Nyabihu, Ngororero, Rutsiro, Karongi, Nyamasheke and Rusizi), 96 sectors, 538 cells and 3612 villages (GoR 2017).

3.1.2 Physical Characteristics

The Western Province is hilly and mountainous and the lowest topography elevation value is 923 meters in the south of the western province in Rusizi District, Bugarama Sector, Ryankana Cell, Gombaniro Village while the highest elevation value is 4321 meters located in the North of the Western Province in Nyabihu District, Kabatwa Sector, Rugarama Cell, Masasa Village. The study area receives an annual average rainfall of more than 1500 mm and an average annual temperature between 15-17^{0}C (Netherlands Commission of Environment Assessment2015). Due to its location at the intersection of Congo and Nile Basins, the hydrography of this region is rich with various watersheds and very dense drainage network as illustrated in Figure 5 below.

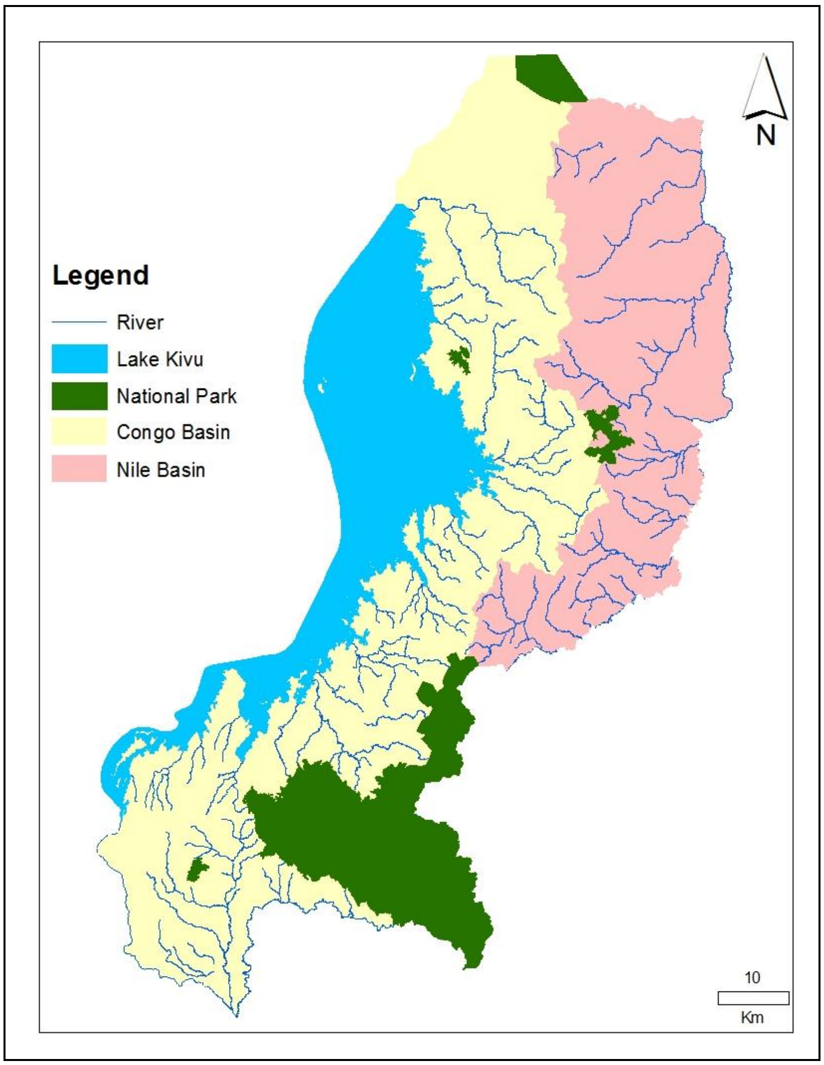


Figure 5: Hydrography of the Western Province

Land use is mainly agriculture and a wide range of crops are grown in the Province due to its location in various agro ecological zones. The priority crops include: maize, beans, wheat, rice, Irish potato, banana and cassava (GoR 2017).

3.1.3 Socio-economic characteristics

According to the Fourth Population and Housing Census, the Western Province was the 3rd most populated province in Rwanda with 2,471,239 inhabitants of whom 1,168,445 are male and 1,302,794 are female. The population density is 420 inhabitants per square kilometer (NISR 2012b). 22% of the Population is working age. Among the working age population, 88% are employed while 0.9% are unemployed. Among the working age population, 13.5% are wage farm, 16.2% are wage non-farm, 56.2 % are independent farmer, while 12.7 % are independent non farmer (NISR 2016a).

3.2 Methodology

3.2.1 Diagram of the methodological workflow

Before data processing, we have started by removing lake Kivu, Nyungwe National Park, Gishwati - Mukura National Park, and Cyamudongo Forest from our study area using clipping tool of ArcGIS software because they are not part of arable land in the western province Rwanda. We have not removed wetlands from our study area because most arable land including wetlands is under cultivation in Rwanda (GoR 2011c, 2012b).

R Factor map of 2015, K Factor map of 2015, the digital elevation model (DEM), and land cover map of 2015 were resampled to 250 meters in order to be analyzed with the NDVI maps. The flow direction, flow accumulation and slope were calculated from the resampled DEM and then the formula of

$$LS = \left(\frac{\text{Fac}\times\text{Cell value}}{22.13}\right)^m \left(0.065 + 0.045(S) + 0.0065(S^2)\right)$$

was applied to them in order to obtain the Slope length and steepness Factor map. From the slope map, P values were assigned to different slope values in order to obtain the P Factor map. R, K, LS, C and P were multiplied using raster calculator tool of ArcGIS software and the soil erosion map of 2015 was obtained.

For the year 2000, only C Factor map changed and the one of 2000 was used instead of 2015. R Factor map and K Factor map, LS Factor map and P Factor map were not changed since annual average rainfall amount is not very dynamic in Rwanda (McSweeney 2011), physical properties of soil are constant(Kim 2006) and slope does not change over years. The multiplication of R, K, LS, C and P gave us the soil erosion map of 2000.

On another hand, NDVI of 2001 and NDVI of 2015 were used to evaluate crop production for the year 2000 and 2015 respectively.

In order to evaluate the trend of soil erosion between the years of 2000 and 2015, the soil erosion map of 2015 was divided with the soil erosion map of 2000 using the raster calculator tool of ArcGIS Software. Using the reclassify tool of ArcGIS software, the values of trend of soil erosion were grouped in negative values which mean a decrease in soil erosion, values equal to one which mean areas where soil erosion did not change and values greater than one which mean the areas where soil erosion has increased. Similarly, the NDVI map of 2015 was divided with the NDVI map of 2000 in order to obtain the trend of NDVI in the period between 2000 and 2015. Once again using the reclassify tool of ArcGIS software, the values of trend of NDVI were grouped 3 categories. First in negative values which mean a decrease in crop production, secondly in values equal to one which mean areas where crop production did not change and thirdly in values greater than one which mean the areas where crop production has increased.

By overlaying the NDVI/crop growth/production map composed of areas of decreasing, constant and increasing values and the soil erosion map composed of areas of decreasing, constant and increasing erosion values using "*intersect" tool* of ArcGIS software. Following the classification of interactions between ecosystem services within a region provided by(Haase *et al.* 2012) , and using the *select* tool of ArcGIS Software, the following areas were selected: **Synergy** (a win-win situation that involves an increase in NDVI and decrease in soil erosion); **Win-no change (**an improvement in NDVI and no obvious changes in the soil erosion) ; **Lose-no change (**A decline in NDVI and no obvious changes in the soil erosion); **Trade-off: (**a win-lose or lose-win situation that involves increasing NDVI and decreasing erosion control (or increasing soil erosion); **Loss or trap (**a decrease of NDVI and increasing soil erosion) ; and **No change** (no changes in NDVI and soil erosion) and the map of spatial-temporal relationship between crop production and soil erosion in the western province of Rwanda in the period between the year 2000 and the year 2015 was obtained. Figure 6 below draws the methodological workflow followed by the present research.

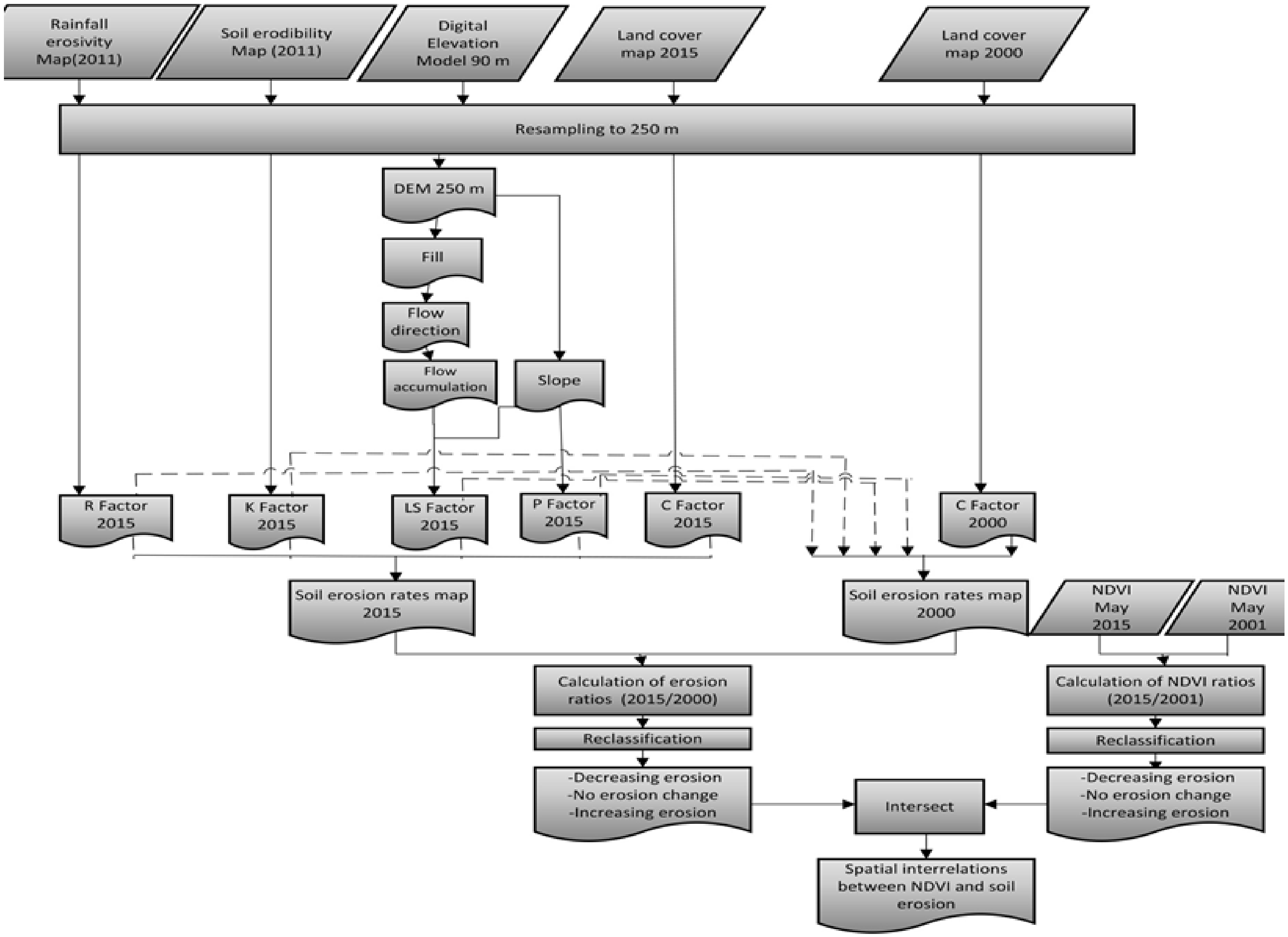


Figure 6: Diagram of the methodological workflow

3.2.2 Land cover changes mapping

Land cover can be used as a proxy for ecosystem distribution. The conversion from natural ecosystems to semi-natural, agricultural or artificial systems is a major cause of loss of biodiversity and associated ecosystem services. Therefore, a particular requirement for mapping is that the flow of ecosystem services can be coupled to land cover or land use data in order to quantify how changes in land cover have affected changes in ecosystem service supply (Maes *et al.* 2011).

In order to analyze land cover and land cover change over the study area, the present study has used land cover maps (or classified images) of the years 1990, 2000, 2010 and 2015. These maps were downloaded from the online portal of the Regional Center for Mapping of Resources for Development (RCMRD). Their metadata show that they were obtained through supervised image classification of Landsat images (30 m of spatial resolution) and the accuracy of the images classification is described in table 3 bellow.

Year	Overall classification accuracy (%)	Overall Kappa Statistics
1990	82.20	0.7534
2000	82.73	0.7662
2010	81.30	0.7407
2015	78.35	0.7137

Table 3: Accuracy Assessment of used land cover data
Source: RCMRD online data portal. Link: http://geoportal.rcmrd.org/maps/631

According to Laba *et al.* (2002), the level of accuracy of several regional-scale land cover mapping projects does not exceed 70% independent of level of taxonomic details or methodological approaches and improvements are not likely except for sensors with high spectral, spatial and temporal resolutions which can achieve an accuracy of 80%. Therefore, the level of accuracy of the RCMRD classified images is enough to study the spatial tradeoffs, synergies and traps between agriculture production and soil erosion in western province of Rwanda.

For the purposes of analysis and further processing, they were converted from raster format to vector format. The area covered by the arable land in the Western Province by excluding Lake Kivu, Nyungwe National Park, Gishwati-Mukura National Park, and Cyamudongo Forest was estimated to be 4201 square kilometers. In the same way, the areas covered by different land cover classes from the land cover maps of the years 1990, 2000, 2010 and 2015 was calculated and the percentages of their coverage were calculated compared to the total area of the arable land in order to quantify land cover change.

3.2.3 Soil erosion modeling in Western Province

The choice for a particular model largely depends on the purpose for which it is intended and the available data, time and money. One should also be aware of which processes are actually being modeled. For example, the well-known Universal Soil Loss Equation was developed to predict rill- and inter-rill erosion only (Morgan 2005). Therefore, one cannot expect this model to perform well in areas where gully erosion is the dominant erosion type (Morgan 2005). However, compared to other soil erosion risk methods such as Coordinated Information on the Environment (CORINE), Global Assessment of Soil Degradation (GLASOD) and Hot Spots approaches, RUSLE probably gave the most detailed information about the Europe-wide distribution of soil erosion risk (Gobin *et al.* 2002).

Norén and Spörndly (2009) suggested that more excessive erosion studies using the Universal Soil Loss Equation or the Soil Loss Estimations in Southern Africa (SLEMSA) might be necessary to further understand erosion in Rwanda. However, given that comparison between the two methods do not always favor SLEMSA in the tropics (Igwe *et al.* 1997), the present research has decided to use RUSLE (an update of USLE) (Renard *et al.* 1997), a widely used method in erosion modeling (Kim 2006; Teh 2011; Molla & Sisheber 2017), to assess the spatial-temporal distribution of soil erosion in the Western Province of Rwanda. On an other hand, in order to estimate annual soil erosion rates (tones/ha/year) over a large area caused by rainfall (sheet or rill erosion), GIS modeling is an appropriate tool to use when there are constraints of availability of time and long-term soil erosion monitoring data (UNEP 2011).

The equation for RUSLE is the following: **A(tons/Ha/Year)= RK(LS)CP;** Where: **A** where A is the average annual soil loss in ton/ha/year; **R** is the rainfall erosivity factor(MJ mm/ ha/ h/ year); **K** is the soil erodibility factor(t h/ MJ/mm); **LS** is the slope length and steepness or topographic factor, a unitless terrain factor; **C** is a unitless vegetation cover factor; and **P** is a dimensionless soil conservation practices factor.

3.2.3.1 Soil erosion assessment for the year 2000

- **R Factor Map**: In a study based in Kenya,Rowntree (1982) suggested the Fournier Index is a more effective method of estimating local erosivity in tropical catchments than conventional methods based on maximum rainfall intensity. This Index is calculated as:

  $$F = \frac{p^2}{P}$$

  Where:

  F = the Fournier Index value

  p = total rainfall in the wettest month in mm

  P = annual precipitation in mm

By using as input data (i) monthly and annual rainfall data from as many meteorological stations across the country as possible; (ii) monthly/annual rainfall data from a remotely sensed source,UNEP (2011) built a database of rainfall erosivity (R) across Rwanda.

Given that annual average rainfall amount is not very dynamic in Rwanda (McSweeney 2011), the present study has used R Factor Map from data derived from the above-mentioned database of UNEP (2011).

- **K Factor Map**: Due to lack of data on the average long-term rate of soil loss in response to specific rainfall erosivity (soil erodibility), UNEP (2011) estimated K factor values based on soil type from a first approximation in the standard nomograph (Morgan 1995) which determine K factor for a soil based on its texture; % silt plus very fine sand, % sand, % organic matter, soil structure, and permeability. Given that physical properties of soil are constant(Kim 2006) and the information on chemical property (fertility) was not available, the present study used K Factor values from the above-mentioned data created by UNEP (2011). However, the implicit assumptions on which the soil erodibility concept is built, i.e. firstly that the K-factor is valid for all erosion processes and secondly that it can be estimated by a few, usually physical soil properties, are questionable according to Bryan *et al.* (1989).
- **LS Factor Map**: There are different equations to calculate LS factor. Bizuwerk *et al.* (2008)proposed that slope length and slope steepness can be used in a single index, which expresses the ratio of soil loss as defined by (Wishmeir & Smith 1978), as shown in equation:

$$LS = \left(\frac{\text{Fac} \times \text{Cell value}}{22.13}\right)^m \left(0.065 + 0.045(S) + 0.0065(S^2)\right)$$

Where: **Fac** = Flow Accumulation; **Cell value** = Spatial resolution of DEM

S = Slope in %; **m** varies from 0.2-0.5 depending on the slope percent. m= 0.5 if the percentage slope is 5 or more, 0.4 on slopes of 3.5 to 4.5 percent, 0.3 on slopes of 1 to 3 percent and 0.2 on uniform gradients of less than 1 percent. From 90 meters Digital Elevation Model (DEM), the present thesis has calculated LS factor Map using the above-mentioned formula.

- **C Factor Map**

As in (Wishmeir and Smith (1978); Morgan (2005)), land cover map of 2000 was used to assign C values of Forestland = 0.001, Grassland= 0.01, Cropland= 0.20 and Settlements= 1.

- **P-Factor Map**

According to (Nachtergaele *et al.* (; GoR (2004a); Karamage *et al.* (2016c)) the agriculture system in Rwanda is rudimentary with minimum soil conservation measures. Therefore, the present study has used slope to assign P values on a contouring landscape as recommended by Kim (2006) in table 4 below because in our study area there is no management but just contouring. Table 4 below represents the value of support practice factor according to the cultivation method and slope (Kim 2006).

Slope (%)	Contouring	Strip Cropping	Terracing
0.0 - 7.0	0.55	0.27	0.10
7.0 - 11.3	0.60	0.30	0.12
11.3 - 17.6	0.80	0.40	0.16
17.6 - 26.8	0.90	0.45	0.18
26.8 >	1.00	0.50	0.20

Table 4: P factor value according to the cultivation method and slope
Source: Kim (2006)

To do so, the slope was calculated from the Digital Elevation Model (DEM) using the *slope calculator tool* of ArcGIS software. From the slope obtained, and using the *reclassify tool* of ArcGIS software, the slope values were transformed into 5 classes: Firstly 0.0 - 7.0, secondly 7.0 - 11.3, thirdly 11.3 - 17.6, fourthly 17.6 - 26.8 and fifthly 26.8 >. The reclassified map was converted from raster to vector and the first class was assigned a P value of 0.55. Similarly, the second class was a P value of 0.60, the third class was assigned a P value of 0.80, the fourth class was assigned a P value of 0.90 and the fifth class was assigned a P value of 1.

3.2.3.2 Soil erosion assessment for the year 2015

- **R Factor Map:** The same R Factor map of 2000 was used based on the same factor that rainfall is not very dynamic in Rwanda(McSweeney 2011).
- **K Factor Map:** The same K Factor Map as the one in 2000 was used given that physical properties of soil are constant (Kim 2006) and the information on chemical property (fertility) was not available.
- **LS Factor Map:** The LS factor map used for 2000 was considered for the year 2015 as slope is almost constant.
- **C Factor Map:** Land cover map of 2015 was used instead of land cover map of 2000 and C values were assigned as previously done for the year 2000.
- **P Factor Map:** The same P factor map of 2000 was used because slope does not change over years.

3.2.3.3 Trend of soil erosion between 2000 and 2015

In order to measure the change in erosion rates between 2000 and 2015, the ratio between the two maps was calculated by dividing the 2015 values with values of 2000 ($\frac{2015\ Erosion\ Map}{2000\ Erosion\ Map}$) following (Swallow *et al.* 2009) using the "***raster calculator***" tool of ArcGIS software. In the ratio result, and similarly to (Swallow *et al.* (2009); Haase *et al.* (2012)) values which are between 0 and 1 would indicate reduction of erosion rates, values which are equal to 1 would mean a no change of erosion rates between 2000 and 2015 while values which are greater than 1 would mean an increase of erosion rates. With the ***"reclassify"*** tool of ArcGIS software, the ratio values were reclassified into three classes, 0-1= decreasing erosion, 1 no erosion change and >1= increasing erosion.

3.2.4 NDVI distribution and changes, as a proxy of crop growth

3.2.4.1 NDVI distribution assessment for the year 2000

The long-term Landsat data have successfully been used for land cover studies, ecological characterizations, and other Earth science applications (Goward *et al.* 2000; Homer *et al.* 2004; Wulder *et al.* 2008).

However, despite the advantage of the historical high spatial resolution Landsat images, using Landsat data for ecosystems monitoring compared to MODIS land surface products has some limitations. These limitations include the following : Thirsty, the 16-day Landsat revisit time (or possible 8-day revisit capabilities through two Landsat satellites (USGS) decreases the availability of cloud-free surface observation data (Irish *et al.* 2006; Ju & Roy 2008) relative to the 1~2 day revisit time of MODIS. Secondly, the wide wavelength ranges in the Landsat NIR and shortwave infrared bands may decrease the spectral sensitivity to vegetation canopy and may induce more atmospheric contamination in the raw data (Gao *et al.* 2006; Roy *et al.* 2008). Thirdly, the weak cloud and aerosol detection compared to the MODIS sensors may cause more uncertainty in the Landsat land surface products (Ackerman *et al.* 1998; Irish *et al.* 2006; Helmer & Ruefenacht 2005). Finally, the sparse Landsat temporal observations limit the use of temporal smoothing techniques to correct the NDVI values for cloudy pixels (Gu & Wylie 2015).

Due to the above-mentioned reasons, the present research has used the Moderate Resolution Imaging Spectro-radiometer (MODIS) NDVI data also known as eMODIS NDVI of 250 meters resolution from Food Early Warning Systems (FEWS). Since the FEWS eMODIS NDVI database starts from 2001 up to nowadays (USGS-USAID-FEWS NET2013), the 2001 NDVI map was used on behalf of the 2000 map assuming that there has not been a big change between the 2001 NDVI values and the 2000 NDVI values. The April 2001 NDVI map should have been used because it is the wettest month in Rwanda making soil erosion most active and thus making it the most suitable month for soil erosion study, but the present research has used the May map because the April map had a lot of holes or no data.

The MODIS NDVI map had no projection and could not be overlaid to other spatial data of the research. As preprocessing, this was corrected using the "*define projection tool*" of ArcGIS Software and ITRF_2005 Coordinate System was assigned to it to match the projection of the remaining data used in the present research.

The MODIS NDVI is mapped linearly and its values range from 0 to 200. As preprocessing, the formula of NDVI = $\frac{Value-100}{100}$ provided by metadata was applied using the ArcGIS "*raster calculator*" tool in order to get the normal range of NDVI which is from 0 to 1.

3.2.4.2 NDVI distribution assessment of the year 2015

For consistency, the May 2015 eMODIS NDVI map which was also obtained from the same source as for the year 2001 was used in the present research. The 2015 eMODIS NDVI was also preprocessed by the same formula of NDVI = $\frac{Value-100}{100}$ provided by metadata.

3.2.4.3 Trend of NDVI between 2000 and 2015

In order to measure the change in crop production between 2000 and 2015, the ratio between the two raster maps was calculated by $\frac{2015\ NDVI\ Map}{2000\ NDVI\ Map}$ using the "*raster calculator"* tool of ArcGIS software. As in section 4.2, values which are between 0 and 1 would mean a decrease in NDVI and therefore a period of declining crop growth or crop production; values equal to 1 would mean a no change in NDVI, and consequently a period of an unchanged crop growth/production; while values greater than 1 would mean an increasing NDVI resulting in an increase of crop growth/production. The generation of these three classes of NDVI maps was done using the *"Reclassify"* tool which is available in ArcGIS 10.6 software.

3.2.5 Relationship between crop growth and erosion

3.2.5.1 Maps standardization

There were R factor map (vector format), K factor map(vector format), Digital Elevation Model (90 meters), C factor map (30 meters) of 2000 and C factor map (30 meters) of 2015, eMODIS NDVI of 2001(of 250 meters) and eMODIS NDVI of 2015 (of 250 meters). When you are processing between multiple datasets, the cell resolution, like the registration, needs to be the same. When multiple raster datasets are input into any ArcGIS Spatial Analyst function and their resolutions are different, one or more of the input datasets will be automatically resampled using the nearest neighbor assignment to the coarsest resolution from input datasets. This process is called resampling(McCoy & Johnston 2001).

Therefore, we have resampled R factor map (vector format), K factor map (vector format), Digital Elevation Model (90 meters), C factor map (30 meters) of 2000 and C factor map (30 meters) of 2015, eMODIS NDVI of 2001(of 250 meters) to 250 meters using the "*resample"* tool of ArcGIS Software. The NDVI data were not resampled because they already had a resolution of 250 meters.

3.2.5.2 Map overlay for interrelation assessment

Using the "*intersect" tool* of ArcGIS software, the NDVI/crop growth/production map composed of areas of decreasing, constant and increasing values and the soil erosion map composed of areas of decreasing, constant and increasing erosion values were overlaid. Following the classification of interactions between ecosystem services within a region provided by(Haase *et al.* 2012) , and using the *select* tool of ArcGIS Software, the following areas were selected: **Synergy** (a win-win situation that involves an increase in NDVI and decrease in soil erosion); **Win-no change (**an improvement in NDVI and no obvious changes in the soil erosion) ; **Lose-no change (**A decline in NDVI and no obvious changes in the soil erosion); **Trade-off: (**a win-lose or lose-win situation that involves increasing NDVI and decreasing erosion control (or increasing soil erosion); **Loss or trap (**a decrease of NDVI and increasing soil erosion) ; and **No change** (no changes in NDVI and soil erosion).

CHAPTER 4: RESULTS AND DISCUSSION

4.1. Land Cover and Land Cover Change

Calculation made by the present research has found that the area of the arable land in the western province is 4208 square kilometers. Table 5 bellow presents the changes in different land covers in the Western Province in the year 2000, the year 2010 as well as the year 2015 compared to the total arable land.

Land Cover and Land Cover change in Western Province						
Land Cover Category	**2000**		**2010**		**2015**	
	Km^2	**%**	**Km^2**	**%**	**Km^2**	**%**
Forestland	2094	49.76	1852.78	44.03	1046.95	24.88
Grassland	167.48	3.98	286.14	6.80	295.40	7.02
Cropland	1908.75	45.36	2013.95	47.86	2798.74	66.51
Settlements	10.52	0.25	188.52	4.48	55.54	1.32
Otherland			1.26	0.03	0.84	0.02

Table 5: Land Cover and Land Cover Change

The analysis of land cover change shows a decrease of forestland of 5.73% from 2000 to 2010 and a large decrease of 19.15% from 2010 to 2015. Overall, the area of forestland decreased from 49.76 % to 24.88 % that is a decrease of 24.88 % over a period of 15 years only. At the same time, the area covered by cropland in the Western Province of Rwanda increased slightly of 2.5% from 2000 to 2010 and increased drastically of 18.65% from 2010 to 2015. Overall, the area of cropland increased from 45.36 % to 66.51 % that is an increase of 21.15 % in a period of 15 years only. GoR (2012b) also argues that there has been a significant physical expansion (13%) of total cultivated area in the country between 2004 and 2011. Analysis also shows that the overall increase of grassland from 2000 to 2015 is of 3.04 % while the increase of settlements is of 1.07%.

Briefly, the land use across the western province of Rwanda between 2000 and 2015 indicates a tradeoff between cropland which has increased of 21.15% and forest which has decreased of 24.88%. In particular, this tradeoff is obvious in the South, the Center and North-West parts as also indicated by figure 5 and figure 7. This expansion of agriculture at the expense of forests is due to : Firstly increasing population growth in the western province which is of 1.9(NISR 2012a) and this implies a growing demand for food and fuel woods(GoR 2011b) for a population whose more than 80% depend on farming(GoR 2012b), secondly to the declining productivity of previously established farms(Brown & Hugues 2017), thirdly the resettlements which followed the civil war(Basnet & Vodacek 2015). The consequences of these intensified cropland expansion, deforestation and urbanization in this region are soil erosion and landslides (Muvundja *et al.* 2009; Pasche *et al.* 2010; Karamage *et al.* 2016a). Yet, agricultural intensification without soil conservation practices in Rwanda has significant detrimental effects on soil, such as lower fertility(Nahayo *et al.* 2016)

4.2 Spatial-temporal distribution of soil erosion

4.2.1 R Factor Map

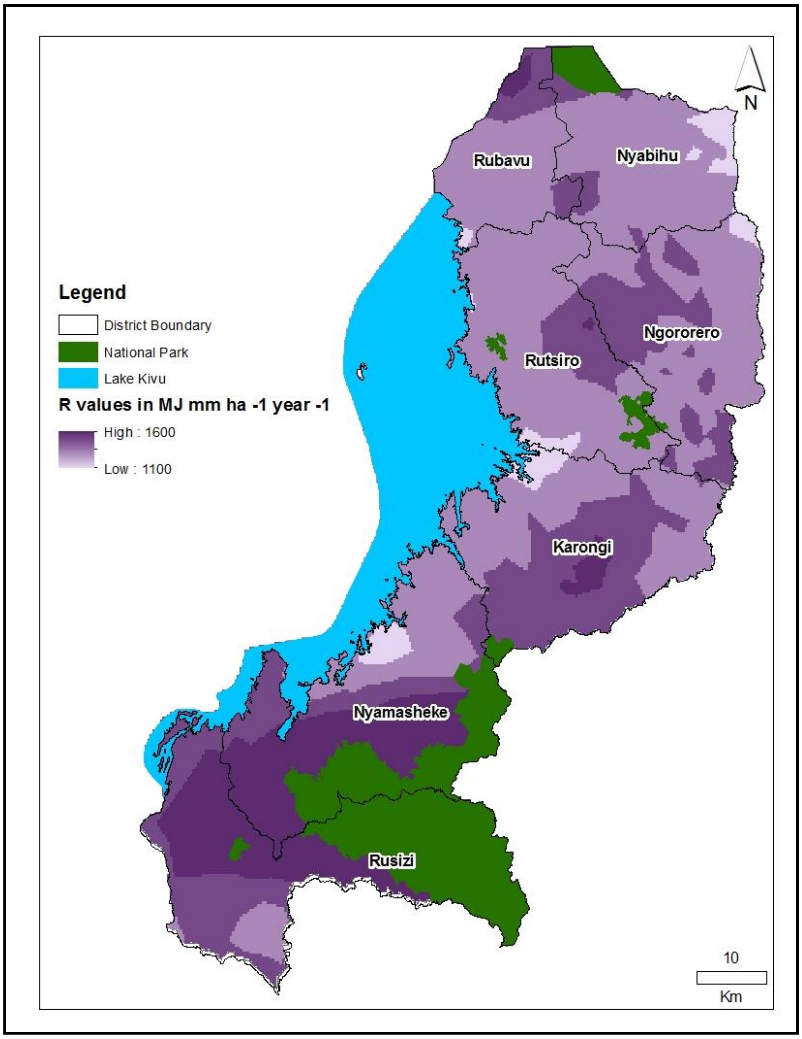


Figure 7: Rainfall erosivity Map

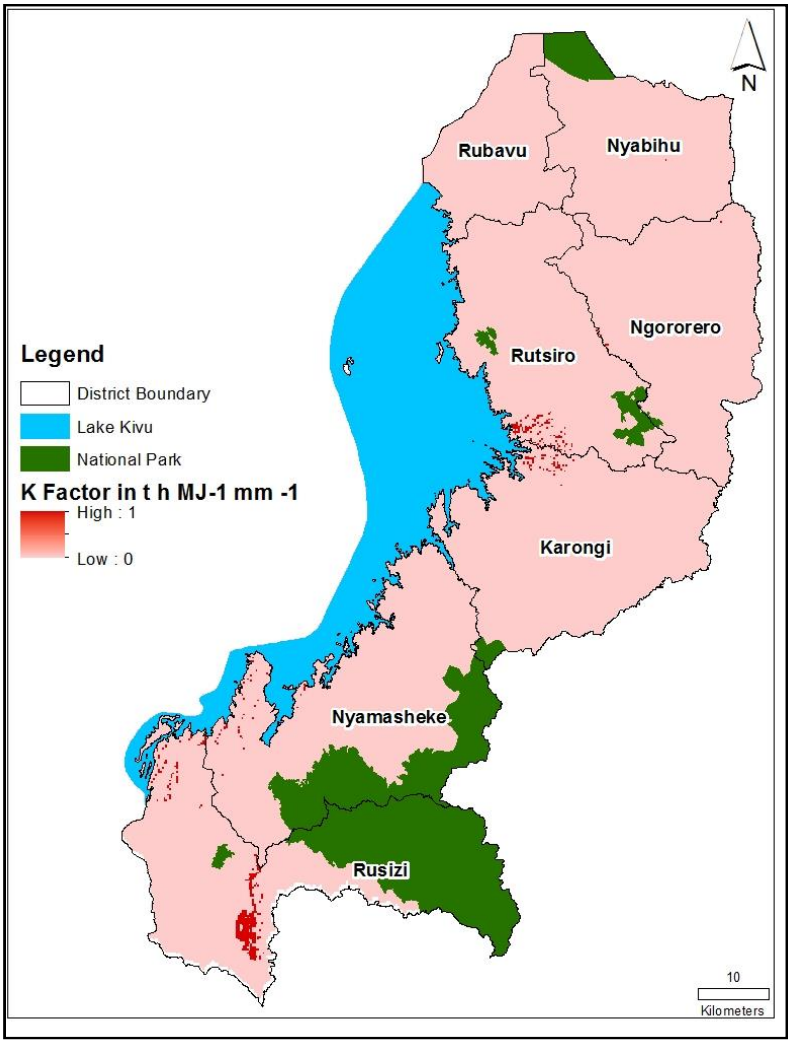
Fournier Index is a more effective method of estimating local erosivity in tropical catchments than conventional methods based on maximum rainfall intensity. This Index is calculated as follow: $\boldsymbol{F} = \frac{\mathbf{p2}}{\mathbf{P}}$; where: **F** = the Fournier Index value; **p=** total rainfall in the wettest month in mm, and **P**=annual precipitation in mm (Rowntree 1982).

R Factor map (Figure 7) indicates that rainfall erosivity values decrease from 1600 and above in the proximity of Nyungwe National Park in the South to 1100 in the North and Center of the Province. The results of the present research are in harmony with (Sun *et al.* 1996) who argues that annual rainfall in Nyungwe National Park averages 1744 mm and(Netherlands Commission of Environmental Assessment2015) who argues that the long-term mean annual rainfall in the Western Province of Rwanda is more than 1500 mm. Moreover, R values in the present research are close to R values suggested by Roose and Ndayizigiye (1997) who says that rainfall erosivity in Rwanda ranges between 250-700. However, R values of the present research disagree with the R values of 3202-6068 developed by Karamage *et al.* (2016a) who assumed that long-term rainfall records are inexistent in Rwanda due to the destruction of meteorological stations by the 1994 genocide against Tutsi and consequently has used the formula of $R = 38.46 + 3.48 \times P(Lo\ et\ al. 1985)$ where P is the mean annual precipitation in mm instead of using the Fournier's Index which has the merits of being based on readily available monthly rainfall data (Claessens *et al.* 2008).

Finally, rainfall erosivity values found by the present research increase with the proximity with Nyungwe National Park. This is because the closer to a forest the higher is the rainfall (Sheil & Murdiyarso 2009).

4.2.2 K Factor Map

Soil erodibility reflects the susceptibility of soil particles to detachment and transport by rainfall. It is the rate of erosion per unit erosion index from a standard plot and its value ranges from 0 to 1, with 0 indicating soils with the least susceptibility to erosion whilst 1 indicates soils which are highly susceptible to soil erosion by water(Kumar *et al.* 2014).



The above Figure 8 indicates that K values which range between 0.13-017 and between 0.10-0.15 are predominant in Western Province. The K values found by the present research are in line with the recently published K-value estimations for East Africa (Taeye 2016). However, the only reliable way to establish local values for K is to use runoff plots under the standard conditions of bare fallow (Morgan 1995).

Figure 8: Soil erodibility Map

4.2.3 Slope length and Steepness Factor (LS) Map

Among the six input layers to RUSLE is the combined slope length and slope angle or steepness (LS-factor). The combined LS-factor describes the effect of topography on soil erosion.

The L-factor gives the impact of slope length while the S-factor accounts for the effect of slope steepness. The LS factor is dimensionless, having values equal to and greater than 0 (Panagos *et al.* 2015). The slope length and slope steepness can be used in a single index, which expresses the ratio of soil loss as defined by (Wishmeir & Smith 1978).

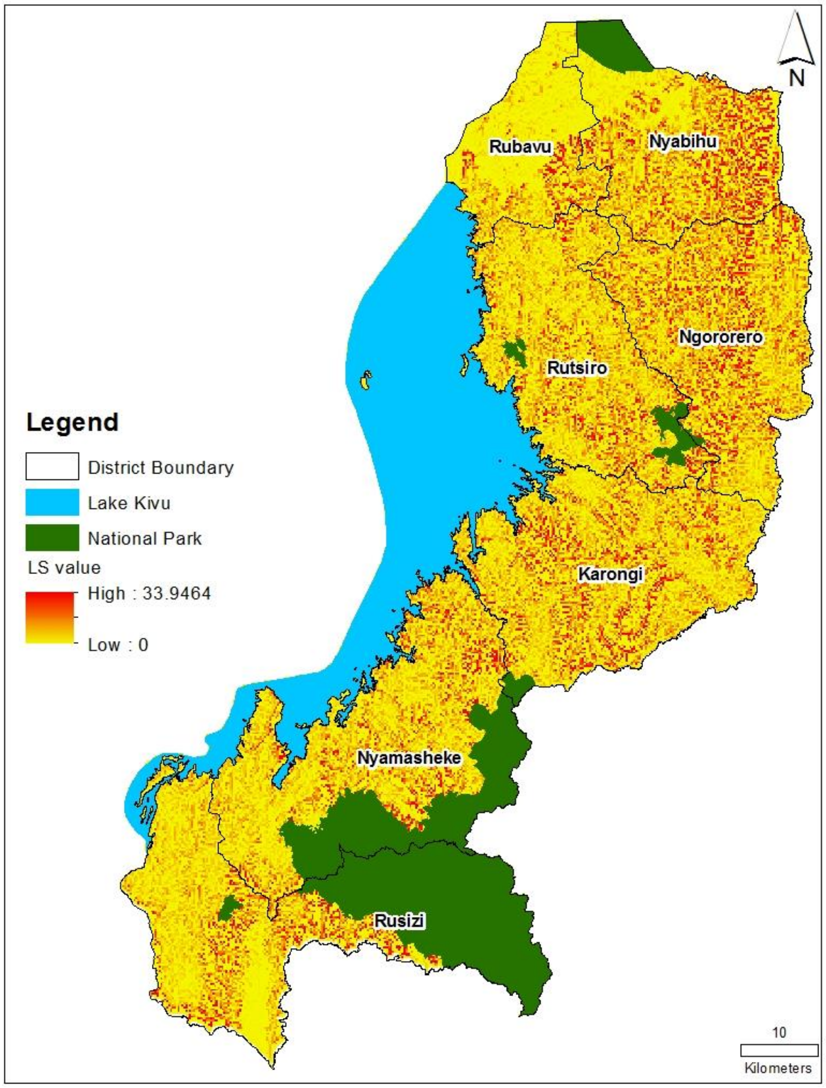


Figure 9: Slope length and steepness Map

Figure 9 above tells that LS values range from 0 to 33.9. According to the same figure, high values of LS are distributed all across the study area but are more found in the East of the Western Province probably because of the proximity to the Congo-Nile ridge which is characterized by much more steep slopes. The Congo-Nile Divide is the area where the sources of the Congo and Nile Rivers both are found within the Nyungwe and Kibira National Parks in Rwanda and Burundi. Streams and rivers flowing west end up in the Congo river while those flowing east end up in the Nile. Similar LS values ranging between 0 and 30 in the Western Province were also found by Karamage *et al.* (2016c). Considering that LS values not exceeding 10 are relatively low (Molla & Sisheber 2017), most of the province is covered by low LS values at 99% of the total area under cultivation while high LS values of 11-33 are mostly found in the North-West of the province.

4.2.4 C Factor Map of the year 2000 and C Factor Map of the year 2015

The C factor reflects the effects of cropping and management practices on soil erosion rates in agricultural lands and the effects of vegetation canopy and ground covers on reducing the soil erosion in forested regions(Renard *et al.* 1997). C factor ranges from 1 to approximately 0. C value is equal to 1 when the land has continuous bare fallow and have no coverage. C value is lower when there is more coverage of a crop for the soil surface resulting in less soil erosion(Kumar *et al.* 2014).

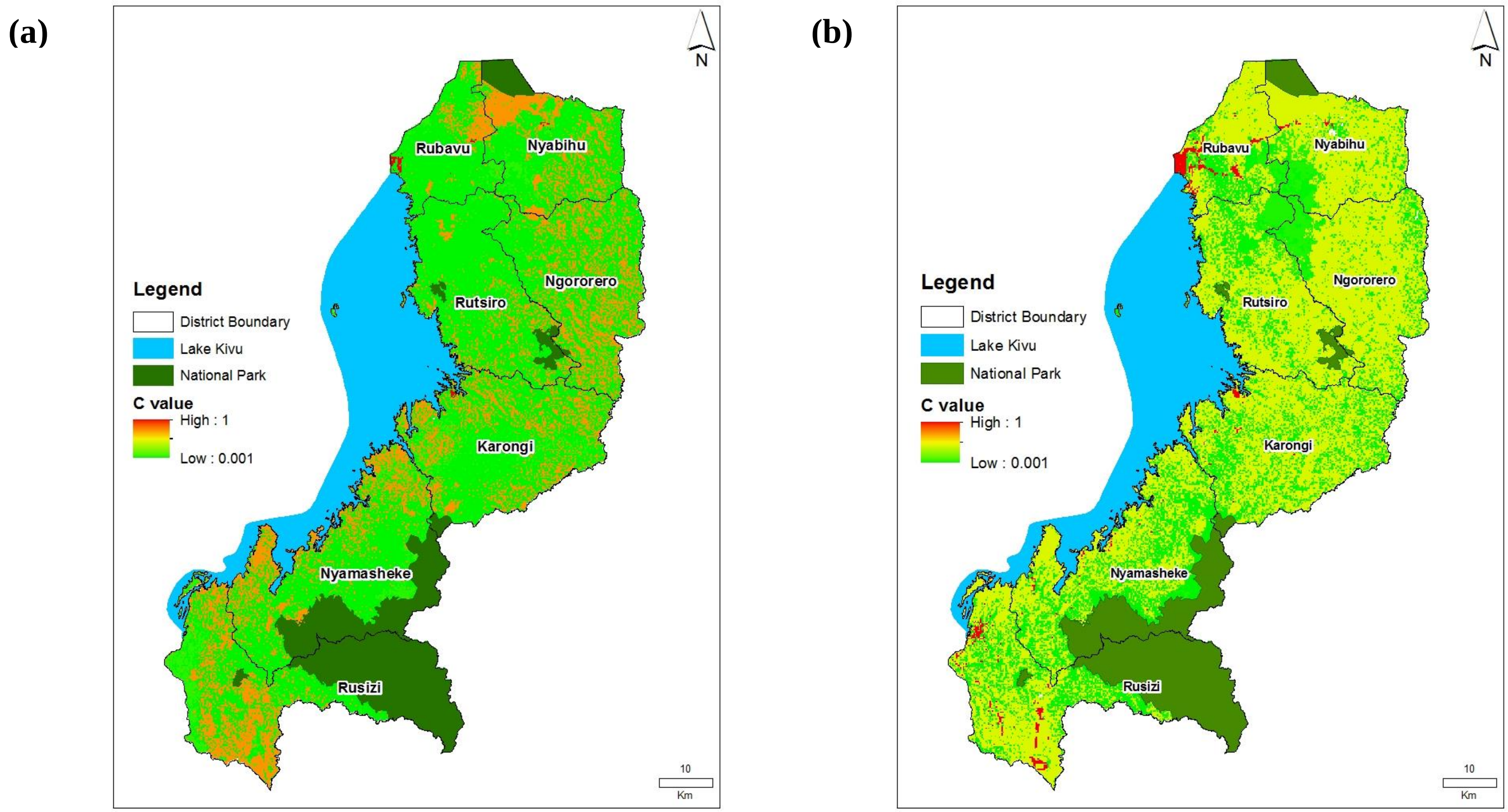


Figure 10: Cover management Map for Year 2000 and for Year 2015

From the land cover map of 2000, the present study established the C factor map of 2000 (Figure 10a) by attributing representative C factor values recommended by (Wishmeir and Smith (1978); Morgan (2005)) to land cover classes as follow: Forestland = 0.001, Grassland= 0.01, Cropland= 0.20 and Settlements= 1. In Figure 10a, lower C values (forests) are located especially in the South-East and North-West of the study area covering 49.76% of the study area (see Table 5) while higher C values (cropland) are found across the study area and analysis shows that they cover 45% of the study area (see Table 5).

From the land cover map of 2015, the present study has established the C factor map of 2015 (Figure 10b above) by attributing representative C factor values recommended by (Wishmeir and Smith (1978); Morgan (2005)) to land cover classes as follow: Forestland = 0.001, Grassland= 0.01, Cropland= 0.20 and Settlements= 1.

Covering only 24.88 % of the study area (see Table 5), Figure 10b shows that lower C values (forests) are few and scattered across the study area while higher C values (cropland) are predominant cover 66.51 % of the study area (see Table 5). A very similar land cover in the west of Rwanda was also found by Karamage *et al.* (2016c). Fig 10b indicates a big increase in cropland across all the Western Province between 2000 and 2015 which is of 21.15 % according to table 5 with biggest increases occurring in the North of the study area in Rubavu, Rutsiro, Ngororero, and Nyabihu Districts. According to GoR (2012a), these are the District which have seen the biggest increase in population and in population density between the 2002 and the 2012 population census as summarized in table 6 below.

District	Percentage increase of Population between 2002 and 2012	Population density in 2012
Rubavu	38.1%	1041
Rutsiro	22.2%	556
Ngororero	18.5%	493
Nyabihu	10.1%	279

Table 6: Percentage increase of Population and Population density between 2002 and 2012 Source: GoR (2012a)

In their research on spatial-temporal dynamics of critical ecosystems services in Rwanda, Rukundo *et al.* (2018) also attributed agricultural expansion to high demographic pressure.

4.2.5 P Factor Map

Erosion control practices (P) factor expresses the effects of conservation practices that reduce the amount and rate of water runoff, which reduce erosion due to agricultural management practices such as contour tillage and planting, strip-cropping, terracing, and subsurface drainage(Wishmeir & Smith 1978; Kim 2006). P values range between 0 and 1 and the lower the P-factor value is, the better the practice is for controlling soil erosion(Angima *et al.* 2003).

According to (Nachtergaele *et al.* (; GoR (2004a); Karamage *et al.* (2016c)) the agriculture system in Rwanda is rudimentary with minimum soil conservation measures. Therefore, the present study has used slope and contouring because in our study area there is no management but just contouring or relief. Therefore, in the present research, a P value of 0.55 was assigned to slopes of 0.0 - 7.0 in our study area, a P value of 0.60 to slopes of 7.0 - 11.3, a P value of 0.80 to slopes of 11.3 - 17.6, a P value of 0.90 to slopes of 17.6 - 26.8 and a P value of 1 to slopes of 26.8 >.

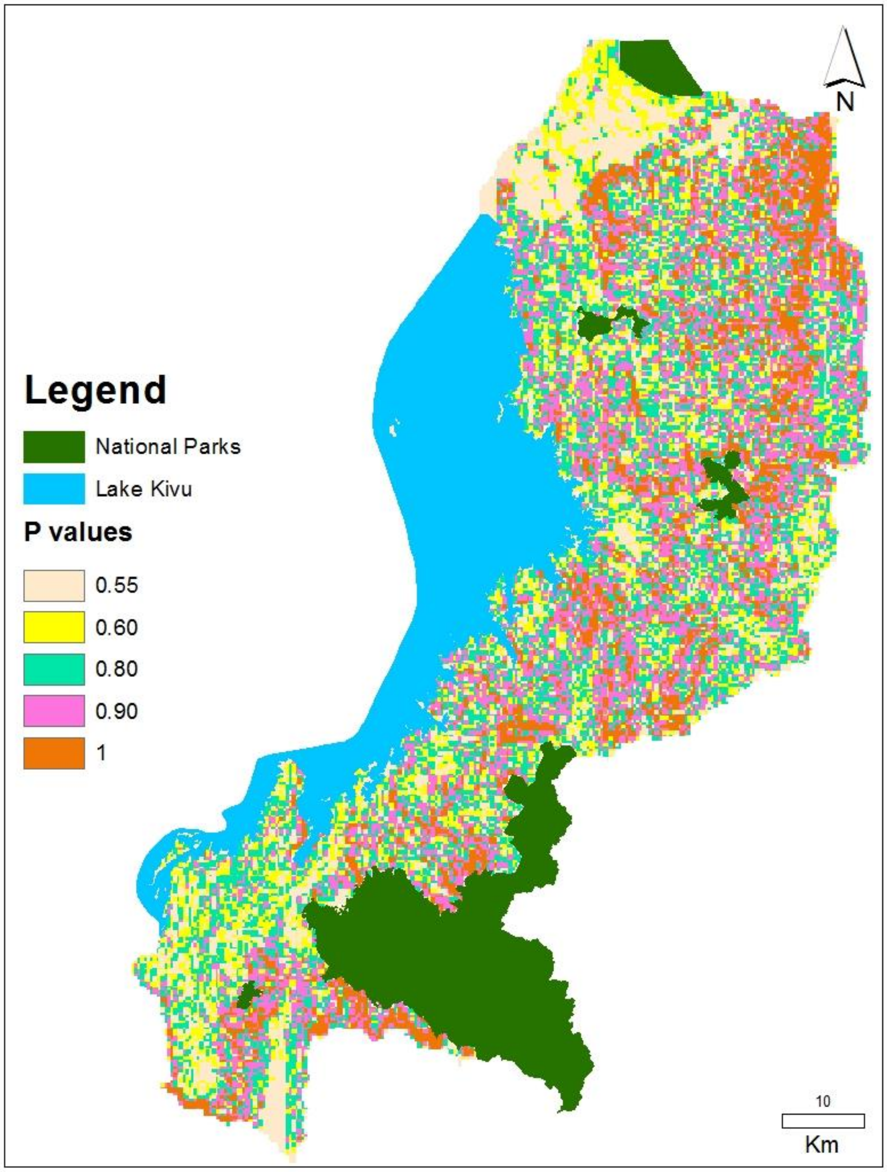


Figure 12: Erosion control practices Map

Figure 12 above indicates that high P values meaning inadequate soil conservation practices are spread across western province except in the North-West of the province. Extremely inadequate soil conservation practices with P value of 1 cover 13% of the area under cultivation while areas of very inadequate conservation measures cover 25% of the area under cultivation. In fact, most of the cultivated land has steeper slopes that are not protected according to the recommended erosion control measures in Rwanda (GoR 2004b).

4.2.6 Soil erosion rates in 2000 and soil erosion rates in 2015

In this section, the spatial distribution of soil erosion in 2000 and in 2015 will be presented and commented.

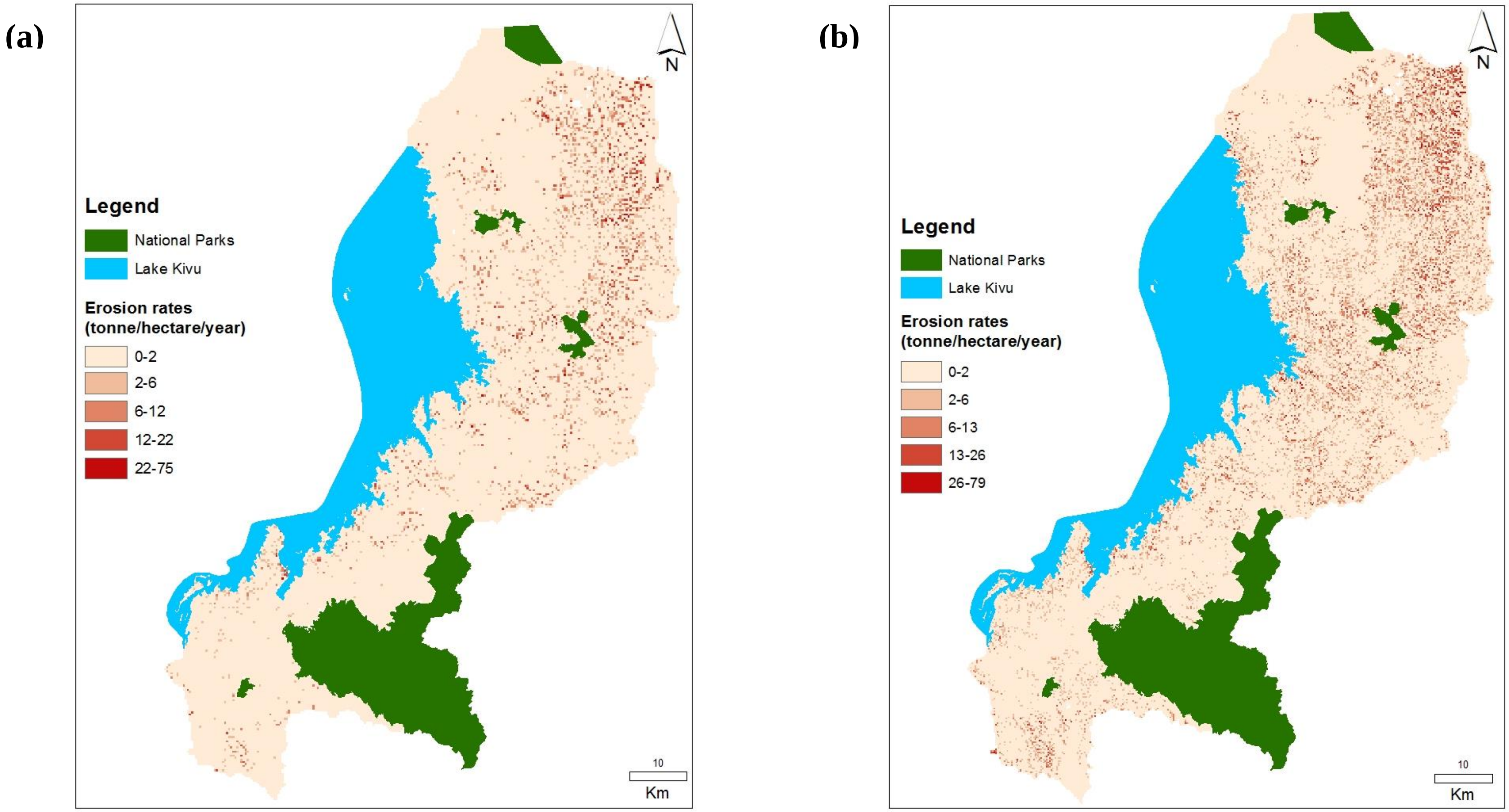


Figure 11: Erosion rates in year 2000 and in year 2015

According to Figure 11a, soil erosion rates ranged between 0-75 t/h/y in 2000 with higher rates concentrated in the North-East of the Western Province. Unlike Figure 11a which reveals soil erosion concentrations in the North-East only, Figure 11b points out the presence of soil erosion in all the parts of the province with more concentrations in the North-West, North-East, in the center and in the South of Western Province. Kagabo *et al.* (2013) found a mean annual soil loss of 40 t/ha/year on plots in the North-West of Rwanda, one of the regions which are seriously affected by soil erosion in Rwanda and which is adjacent to our study area. Comparing erosion rates in Figure 11a and Figure 11b, we can affirm that soil erosion has increased more in terms of spatial coverage rather than in intensity. This finding is consistent with the findings of Rukundo *et al.* (2018) who also found a spatial increase of soil erosion in the whole Rwanda from 135Mt in 1990 to 712Mt in 2010.

We suspect that one of the reasons why soil erosion rates found by the present research are not consistent with soil erosion rates found by UNEP (2011) is that UNEP (2011) excluded the P factor in their USLE model in order to produce a "worst-case scenario". Yet, management practice may be one of the most important factors affecting erosion in many cases(Grimm *et al.* 2001). On the other hand, soil loss results of the present study do not agree with the soil loss rates found by Karamage *et al.* (2016c) and (Karamage *et al.* 2016a) because the latters relied on Global rasters from the Global Land Degradation Information System (GLADIS) database of the Food Agriculture Organization(FAO)(Nachtergaele *et al.*) whose R values seem to be very high compared to the precipitations known in the western part of Rwanda and we suspect that this might have led to overestimation of the soil loss results given that rainfall erosivity can contribute up to 80% of soil loss(Renard & Freimund 1994).

The levels of soil erosion rates found by the present research are high compared to the tolerable level of 10 t/year/hectare in tropical areas(Morgan 2009; Bamutaze 2015). Therefore, it is imperative to modify RUSLE management practices in croplands of the western province of Rwanda. For example: Increasing the organic matter level will decrease the susceptibility of the soils to erosion; constructing terraces or farmable berms will reduce the slope; selecting crop types, tillage practices, rainy season cover crops and the application of solid manure will increase the crop cover and thus decrease the impact of rain drops on soils; selecting a farming method that reduce the erosion potential of the runoff (Vessey 2003).

It should be recognized that this modeling results only estimated the soil erosion risk of Western Province of Rwanda rather than actual soil loss. In fact, RUSLE use empirical relationships and therefore can only be considered valid within the range of experimental conditions from which it is derived(Renard & Freimund 1994). At a larger scale, resource and data limitations on the one hand, and large regional variability in factors on the other, make a quantitative assessment of soil erosion in most cases impossible and results rather reflect broad patterns of relative erosion potential (Claessens *et al.* 2008). Only a few studies in East Africa actually undertook calibration and/or validation of the model, and never beyond the watershed/sub-basin level.(Gachene 1995; Lufafa *et al.* 2003; Cohen *et al.* 2005).

Moreover, although the RUSLE model is considered as a leading model in soil erosion assessment, the data available to derive some of the RUSLE parameters constitute a major limitation for maximizing the accuracy and harmonizing of the RUSLE processing methods worldwide. The model-based approach implies uncertainties in the calculation of each factor and this disadvantage is common among all approaches produced with model-based methods (Van der Knijff *et al.* 1999; Van der Knijff *et al.* 2000)

4.2.7 Erosion ratio and trend of erosion between 2000 and 2015

In this section, the trend of soil erosion in the Western Province of Rwanda in the period between 2000 and 2015 is shown. Areas where soil erosion has increased, areas where soil erosion has not changed as well as areas where soil erosion has decreased are presented.

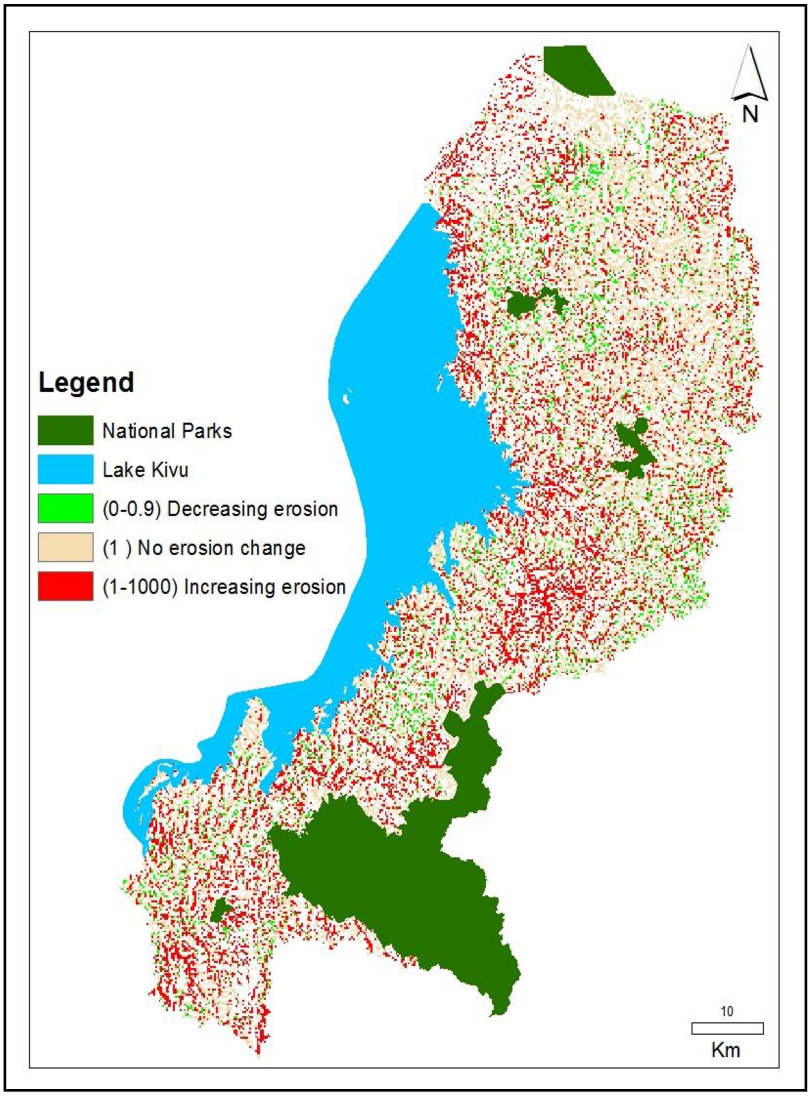


Figure 12 above is the result of the division of erosion map of 2015 over the erosion map of 2000 and classification of the results into decreasing, not changing and increasing in order to find out the trend of erosion in Western Province between 2000 and 2015. Calculations show that soil erosion has been decreasing on 10%, has not changed on 54% and has been increasing on 36% respectively of the total area under cultivation in western province. reliefweb (2008) is also for this view whereas it shows that at least 37.5 percent of land in Rwanda needs to be managed before being cultivated.

Figure 12: Ratio and trend of soil erosion between 2000/2015

Therefore, we deduct that soil erosion is still increasing in Western Province contrary to (GoR 2011a) who once stated that in 2010 soil erosion would have been eradicated in Rwanda. This trend of increasing soil erosion in Rwanda has just been also found by Rukundo *et al.* (2018) who found that 59.8% of soil was being exported from Rwandese cropland in 1990, 73.1% in 2000 and 82.2% in 2010. This increase in spatial coverage of soil erosion is suspected to have been caused by the conversion of a half of forestland (from 49.76% in 2000 to 24.88 % in 2015, see Table 5) into cropland (from 45.36 % in 2000 to 66.51% in 2015). Morgan and Duzant (2008) found that in terms of soil erosion by water, the vegetation cover gives more prominent effect than soil properties. Moreover, (Kosmas *et al.* 1997; García-Ruiz 2010; Pacheco *et al.*

2014) found that soil erosion has a strong correlation with land use, even stronger than the relation between soil erosion and rainfall variability or slope.

The gradual spatial increase of soil erosion found by the present research (Fig. 11b) is due to the scarcity and overexploitation of land resources, which resulted in substantial deforestation accompanied by poor practices of agriculture activities on steep slopes that are susceptible to soil erosion (Mukashema 2007; GoR 2012b). Soil erosion is still prevalent even though the government of Rwanda repeatedly encourages farmers to improve land management and promote installation of terraces and ditches to control erosion.

4.3 Spatial Temporal Distribution of NDVI as a proxy of crop yield

4.3.1 NDVI in 2001 and NDVI in 2015

The NDVI distribution pattern for the two different time series selected for same period of the year present changing trend with increase/decrease between 2001 and 2015, as illustrated in Figure13 below.

(a)

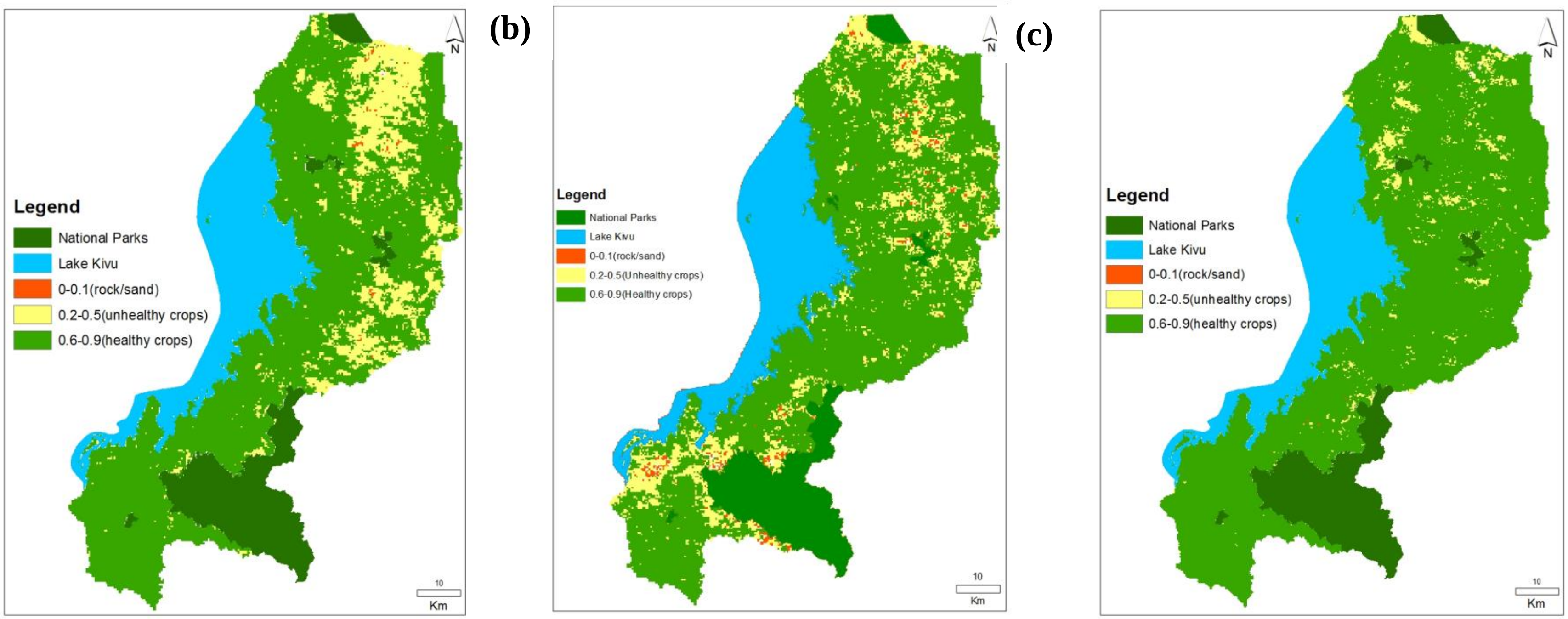


Figure 13: (a) NDVI in May 2001. (b) NDVI in May 2008 and (c) NDVI in May 2015

Based on NDVI values classification of Simonetti *et al.* (2014), Figure 13a indicates that in 2001 unhealthy crops were located in the North in the Central-Western parts of the study area covering the major part of Nyabihu District and many parts of Karongi and Ngororero Districts. Few available data for Karongi District allow us to suggest that this might have been the cause of the reduction in agricultural production in some major staple crops in the Karongi between 2001 and 2008 as indicated in table 7 bellow. This idea is supported by Lal (2001) who argue that soil erosion causes an estimated production loss of 10% for cereals, 5% for soybeans, 5% for pulses and 12% of roots and tubers and it should be reminded that the priority crops in Western province include: maize, beans, wheat, rice, Irish potato, banana and cassava (GoR 2017).

Crop type	2001(in tons)	2008(in tons)
Banana	59,699	18,341
Irish potatoes	29,523	6,793

Table 7: Production of some staple crop in Karongi District
Source:(Donovan et al. 2002; NISR 2009)

Based on the same classification, Figure 13b indicates that healthy crops have increased in 2008. Figure 13c indicates that in 2015 healthy crops have increased in almost all the parts of the province and have even replaced the unhealthy crops which were located in the North in the Central-Western parts of the study area covering the major part of Nyabihu District and many parts of Karongi and Ngororero Districts. This result coincide also with the results of Ndayisaba *et al.* (2016) who found that in the period of between the year 1990 and the year 2014, 81.3% of the country's vegetation has improved while 14.1% of the country's vegetation degraded , from slight (7.5%) to substantial (6.6%) deterioration. Results of Figure 13b are also in line with (Donovan *et al.* (2002); REMA (2015a)) which declare that between 2000 and 2015, agricultural production in Rwanda almost doubled with most of the increase occurring since 2008 driven by the impacts of the Crop Intensification Programme (CIP) and land consolidation (which has affected about 27 per cent of households) and increased fertilizer use (which rose from 6 kg/ha to 29 kg/ha on cropland).

4.3.2 Estimate of crop production ratio and trend between 2000/2015

Figure 14 below illustrate the result of the division of NDVI map of 2015 (see Figure 13b) over the NDVI map of 2001 (see Figure 13a) and the classification of the results into decreasing, not changing and increasing in order to find out the trend of NDVI (crop production) in Western Province between 2000 and 2015.

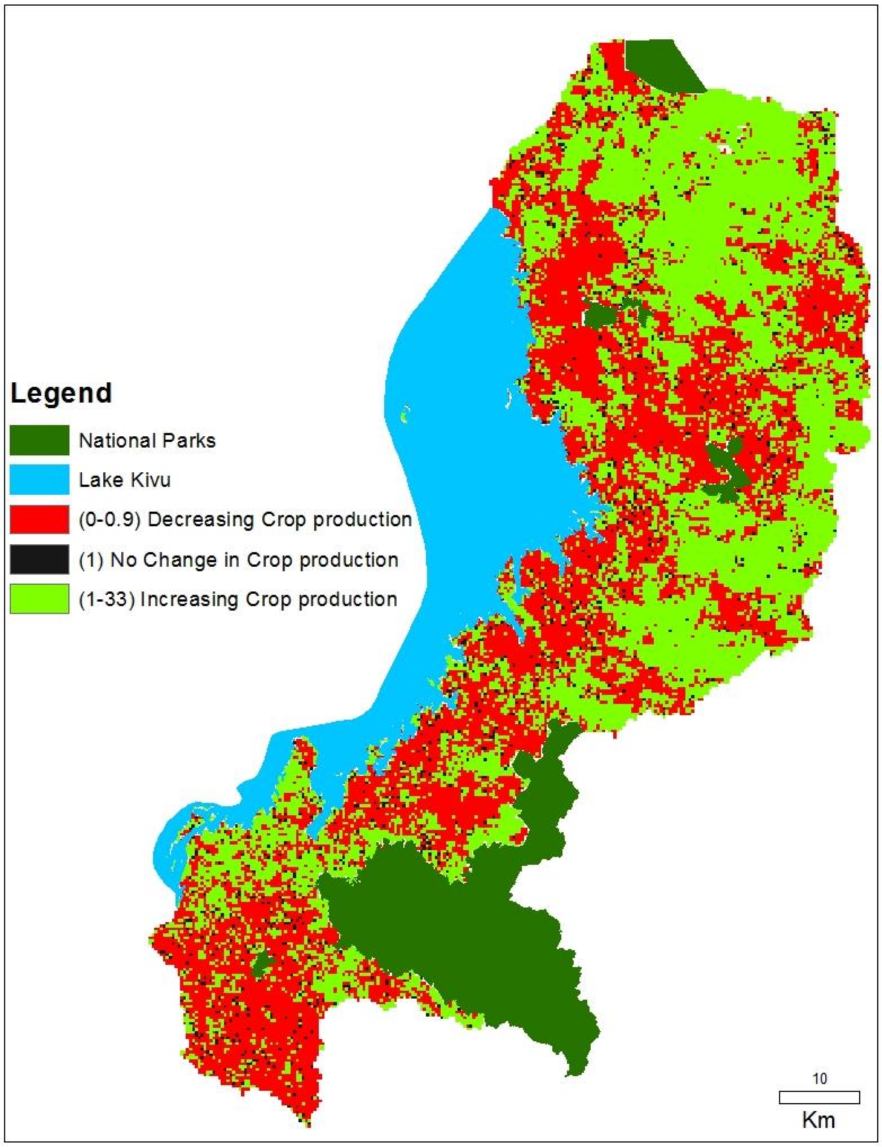


Figure 14: NDVI (crop production) ratio and trend between 2000/2015

Calculation made on figure 14 is detailed in Table 8 bellow.

Trend	Percentage
Decreasing	46%
Constant	3%
Increasing	51%

Table 8: Trend of NDVI between 2000 and 2015

4.4 Interrelation between crop production and soil erosion

Tradeoffs between ecosystem services emerge as situations in which one service increases at the cost of another one (Swallow *et al.* 2009; Raudsepp-Hearne *et al.* 2010; Jessop 2014). The reverse of trade-offs are ***synergies***, which can be defined as situations in which both services increase. Situations where both ecosystem services decrease are called ***traps or loss*** (Bennett et al. 2009; Swallow et al. 2009; Haase et al. 2012). By producing ecosystem services maps to estimate where ecosystem services are produced, areas where ecosystems are stressed emerge and clarify difficult trade-offs being made at the local level (UNEP 2005). Figure15 bellow presents the spatial distribution of the different interrelations between agricultural production ecosystem services and soil erosion control ecosystem services in the study area.

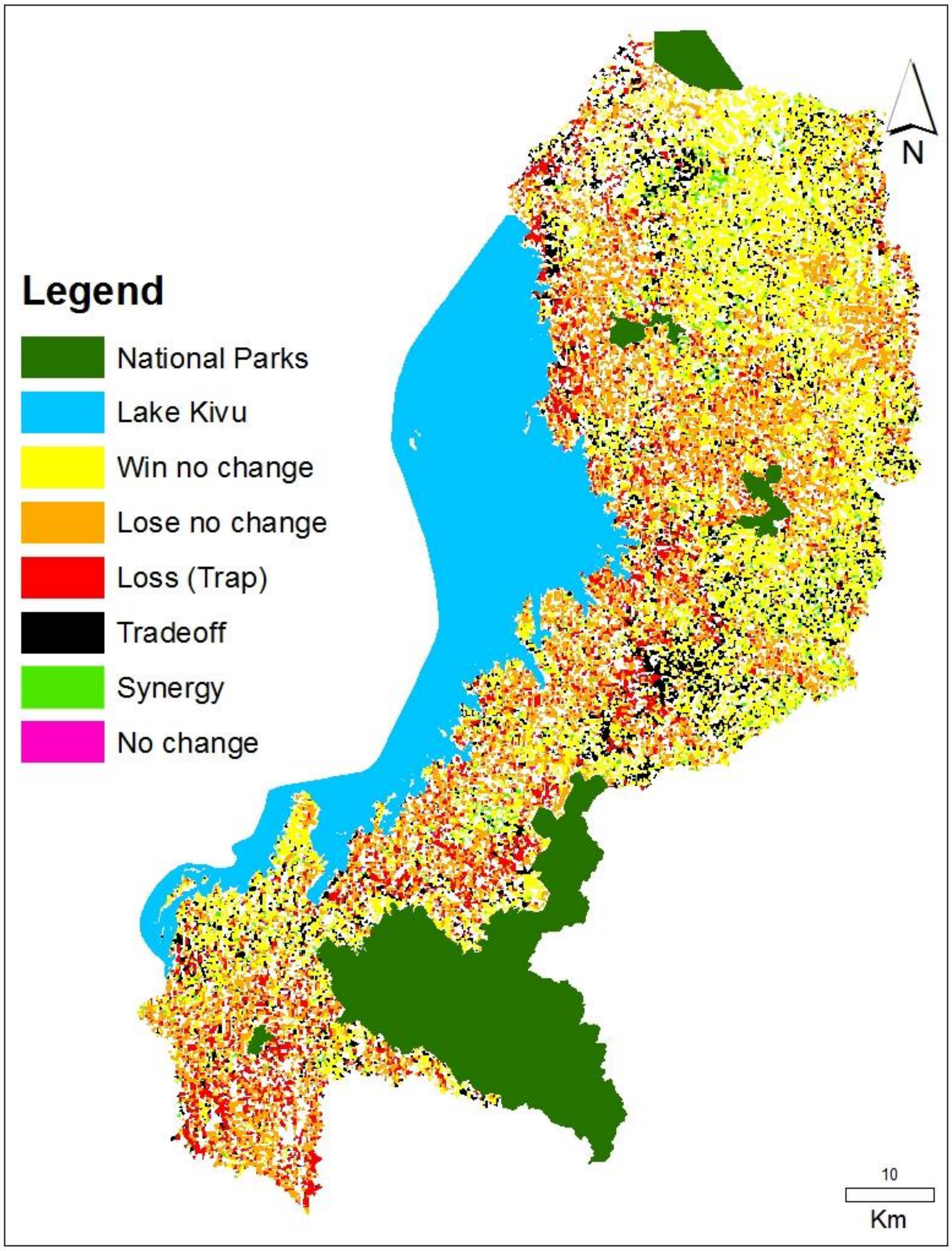


Figure 15: Interrelation between crop production and soil erosion

Interrelation	**Area in Square Kilometer**	**% in Western Province**
Synergy (win-win situation)	252.48	6
Win-no change	1304.48	31
Lose-no change	1052	25
Trade-off	757.44	18
Loss (trap)	799.52	19
No change	42.08	1

Table 9: Areas of ecosystem services interrelations

Figure 15 is the intersection between Figure 14 (NDVI or crop production trend) and Figure 12 (soil erosion trend). It reveals that 6% (see Table 9) of the area under cultivation in western province has been enjoying a situation of increase in NDVI (crop production) and decrease in soil erosion which is also called a *synergy* between provisioning ecosystem services and regulating ecosystem services. We suggest that these are the areas where farmers are able to increase production and invest for the conservation of their soils.

The biggest part which covers 31% (see Table 9) of the area under cultivation has been experiencing an increase in NDVI (crop production) and a no-change in soil erosion and this situation is called *Win-no change* between the above-mentioned ecosystem services. We suggest that soil conservation in these areas can lead to even more crop production. About 25% (see Table 9) of the area under cultivation is enduring a decrease in NDVI (crop production) and constant soil erosion and this situation is often called a *lose-no-change*. More efforts are needed to convert the no-change erosion into decrease erosion and thus trigger increasing crop production.

Conversely, nearly 18% (see Table 9) of the area under cultivation is suffering a situation in which NDVI (crop production) is increasing and soil erosion is also increasing which is also called a *tradeoff* between agriculture production and soil erosion. This is confirmed by REMA (2015a) which says that the increase in agriculture production in Rwanda has been coming with soil erosion. We interpret this by arguing that in order to offset the nutrient losses inflicted by crop production, large quantities of fertilizers have been being applied from 6 kg/ha in 2000 to 29 kg/ha in 2015 in Rwanda on cropland according to (World Bank Group2015). Indeed, according to Pimentel and Burgess (2013) if the soil base is relatively deep, about 300 mm, and if only from 10 to 20 tons of soil is lost per hectare per year, the lost nutrients can be replaced with the application of commercial fertilizers and/or livestock manure. However, according to the same authors, the replacement strategy is expensive for the farmer and the nation in general and usually poor farmers cannot afford fertilizer. Therefore, we think that this increasing agriculture production in these parts of the western province is not sustainable. This argument is supported by Raudsepp-Hearne *et al.* (2009) who discusses that the loss of regulating ecosystem services in areas of high provisioning service production may undermine the sustainability of this production, diminish the possibility of diversifying economic activities, and impact local human wellbeing directly.

Finally, approximately 19% (see Table 9) of the area under cultivation is under a situation where both NDVI (crop production) and soil erosion have been decreasing and this situation is also called a *loss* or *trap* between the two ecosystem services. We conclude that these are the areas of poverty–environment traps where households are caught in vicious cycles of low income, low investment in soil management, soil loss and declines in soil fertility. In these parts, Government interventions are urgently needed to reverse the situation. In fact, in most cases, the initial investment to convert unproductive soil into productive soil in Rwanda is beyond the financial capacity of farmers (Bizoza & de Graaff 2010; Giller *et al.* 2011; Rushemuka *et al.* 2014).

4.5 Implications of the findings of the present research

Findings of the present thesis have implications at different levels, mainly for policy and decision makers, researchers and farmers.

4.5.1 For policy and decision-makers

Results from this study are relevant to the work of a range of the agencies, both state and non-state, concerned with rural development and environmental conservation in Rwanda in general and in the Western Province in particular.

In *Win-no change* areas, investments in soil conservation can lead to even more crop production. In *tradeoffs* areas, farmers should invest a part of their returns in soil conservation in order to make their harvest sustainable. Moreover, tradeoffs should be avoided by planning the land-cover changes. Government special efforts in areas of *traps* or *loss* are urgent to help farmers who are blocked under critical thresholds in production–asset investment relationships. The successful management of *synergisms* is a key component of any spatial development strategy that aims to increase the supply of ecosystem services for the well-being of humans (Haase *et al.*

2012). Appropriate agricultural development, coupled with the promotion of appropriate land and water management practices, appears to be the main pathway to synergies between economic development and environmental conservation (DeClerck *et al.* 2015).

So far in Rwanda, land ecosystem service studies have played a limited role in the management of ecosystems due to the poor integration of ecological and economic or social research. A new approach that can include public participation is needed if Rwanda wants to design and implement suitable and beneficial decisions (Blackstock *et al.* 2010). This can only be attained when there is a better understanding between decision-makers and farmers (Salami *et al.* 2010), given that UNEP (2011) revealed that farmers in Rwanda were reluctant to establish ditches, grass lines and novel practices for soil erosion control due to the lack of knowledge of ecological protection. Family planning to regulate the rate of population growth should be encouraged, as population pressure is the center of the problem (Rukundo *et al.* 2018).

The government of Rwanda needs to create off-farm activities and reduce populations involved in the agriculture sector to mitigate the stress on land resources (WorldBank 2011).

4.5.2 For the scientific community

The Millennium Ecosystem Assessment (MA) did not deliver a fully operational method to implement the ecosystem services concept, which would assist policy makers and provide policy oriented researchers with sufficient tools for taking provisioning of natural goods and services into account (Armsworth *et al.* 2007). As a result, the ecosystem service label is currently used in a range of studies with widely differing aims. This variation presents a problem for policy makers as well as researchers because it makes it difficult to assess the credibility of assessment results and reduces the comparability of studies (Seppelt *et al.* 2011; European Union2013).

An appropriate next step would be to expand the geographic scope of the analysis to other areas in Rwanda especially in the Northern Province where soil erosion is particularly acute (Kagabo *et al.* 2013). Moreover, it would be instructive to increase the number of ecosystem services to include more provisioning services (e.g. timber, livestock, wetland products, forest products, mining products,) and more regulating services (e.g. control of disease vectors, pollination, downstream water pollution,..)

In Rwanda, the measurement of soil erosion is still more of an art than a science, and a wide range of techniques are used to monitor soil erosion (UNEP 2011; GoR 2013). There is a strong need to standardize methods of measurement of soil erosion rates at field, hillside, watershed and regional scales. GoR (2015) proposes that MINAGRI in collaboration with Ministry of Environment (MOE) and REMA develop indicators measuring soil erosion control which will be key to monitor the effectiveness and impact of soil erosion control measures.

4.5.3 For local farmers

Improved land management practices including conservation agriculture practices should be promoted to help reduce sediment yield from all crops. From other work completed in the same region, the use of well-established grass strips or combined infiltration ditches is effective at reducing soil erosion.

CHAPTER 5: CONCLUSION

In the present research, concepts and approaches from Millennium Ecosystem Assessment (MA) were successfully applied to identify areas which are in vicious cycles of low income/low investment in soil management/ soil loss /declines in soil fertility, and areas which are able to achieve higher incomes and investments, maintain soil fertility, and conserve soil on their farms, an approach which has never been used before in Rwanda.

The first research objective was *to assess the spatial-temporal distribution of soil erosion as a regulating ecosystem service in Western Province of Rwanda between the years 2000 and 2015.* Using the Revised Universal Soil Erosion Equation (RUSLE), the soil erosion rates were estimated for the year 2000 and for the year 2015. The map of soil erosion estimates of 2015 were divided over the map of 2000 to find the trend of soil erosion over the period of 2000-2015. The results show that between 2000 and 2015, soil erosion decreased on 10%, did not change on 54% and increased on 36% respectively of the area under cultivation in western province.

The second research objective was *to analyze the spatial-temporal distribution of crop production (using NDVI as proxy indicator) as provisioning ecosystem services in Western Province of Rwanda between the years 2000 and 2015.* The eMODIS NDVI map of the May 2015 was dived over the eMODIS NDVI map of May 2001 to find the trend of crop production over the period of 2000-2015. The results show that between 2000 and 2015 crop production decreased on 46%, did not change on 3% and increased on 51% of the area under cultivation in the western province.

The third research objective was *to study the spatial relationships between crop production and soil erosion in the study area*. Overlay was made between the crop production trend map and the erosion trend map. The results revealed that between 2000 and 2015, 31% of the area under cultivation was occupied by increasing crop production /no erosion change. 25% of the area under cultivation was under decrease of crop production/no erosion change. 18% of that area under cultivation was enduring increasing crop production and increasing soil erosion or tradeoff between the two ecosystem services. 19% of the area under cultivation was suffering a decrease in crop production and an increase in soil erosion which is also called a trap or a loss between the two ecosystem services. A win-win situation consisting of an increase of crop production and a decrease of soil erosion also known as *synergy* between the two ecosystem services occupied only 6% of the area under cultivation. On 1% of the area under cultivation, both crop production and soil erosion did not change.

The fourth research objective was *to recommend strategic interventions for decision and policy-makers on how to allocate agricultural investments and watershed management efforts*. We recommend that in *Win-no change* areas, investments in soil conservation can lead to even more crop production. In *tradeoffs* areas, farmers should invest a part of their returns in soil conservation in order to make their harvest sustainable. Moreover, tradeoffs should be avoided by planning the land-cover changes. Government special efforts in areas of *traps* or *loss* are urgent to help farmers who are blocked under critical thresholds in production–asset investment relationships. The successful management of *synergisms* is a key component of any spatial development strategy that aims to increase the supply of ecosystem services for the well-being of humans.

APPENDIX 1: COMPATIBILITY RESEARCH MATRIX

Research objectives	Research Questions	Data requirement	Acquisition Methods and techniques	Source	Outcome
1. To assess the spatial-temporal distribution of erosion as a regulating ecosystem service in Western Province of Rwanda	1. How erosion rates are spatially distributed in Western Province of Rwanda in the years 2000, 2015? 2. What was the temporal trend of spatial distribution of erosion rates in Western Province of Rwanda??	1. Rainfall erosivity values 2. Soil erodibility values 3. Digital Elevation Model (DEM) 4. Land cover maps of 2000 and 2015 5. Administrative boundaries	1. Collection from concerned offices 2. Online dowload	3. UR-CGIS 4. Regional Center for Mapping of Resources for Development (RCMRD) 5. Rwanda Land Management and Use Authority	Time series Erosion maps Trend map of Erosion distribution in time
2. To analyze the spatial-temporal distribution of crop production as provisioning ecosystem services in Western Province of Rwanda using NDVI as proxy indicator	3.How were NDVI rates spatially distributed in Western Province of Rwanda in the years 2000, 2015? 4.What are the general trends of NDVI been between 2000 and 2015 in Western Province?	1. eMODIS NDVI	Online download	1. USGS FEWS NET Link: https://earlywarning.usgs.gov/fews/product/116#download	Quantified and mapped crop growth distribution
3. To study the spatial relationships between crop production and erosion in the study area	5.Are there some relationships between crop production and soil erosion in the study area?	1. Trend map of Erosion distribution in time 2. Trend map of NDVI distribution in time	Data processing		Quantified and mapped interrelations

4. To recommend strategic interventions for decision and policy-makers on how to allocate agricultural investments and watershed management efforts.					

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