Erosion risk mapping

Evaluating the effects of high resolution topographic data in erosion modelling

Master thesis, Geoinformatics 4th Semester 2016

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$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P$$

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Title:
Erosion risk mapping

Theme:
Master thesis

Project Period:
Spring semester 2016

Project Group:
Group 7

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Copies: 3

Page Numbers: 74

Date of Completion:
8th of June 2016

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Abstract:

The focus of this project, has been to understand the physical components in erosion modelling. Erosion is a complex process of many environmental parameters. The relationship between these, determine the patterns of redistribution and deposition.
In this project a model has been created based on the RUSLE-principles. This serves as the foundation of a comparative analysis that aims to enlighten the aspects of using high resolution data, to estimate soil erosion. This is important with regards to sustaining a healthy water supply and habitats for several species. The RUSLE model, takes six physical components into account, Precipitation, Soil type, Topographic length-/steepness, Vegetation and Supporting practices. These considerations was the basis of finding whether high resolution topographic data, is applicable in erosion modelling.

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Preface

This Master thesis was written on the 4th semester of the GeoInformatics education at Aalborg University Copenhagen, Denmark. It answers the following question:
How is erosion modelling affected by the extent and quality of the inputs?

The University has appointed Professor *Henning Sten Hansen* to support the author in his education and personal development. He has been an inspiration and I wish to thank him for his guidance.

With a focus on computation and statistics within the GeoInformatics field, this project seeks to provide an understanding of technical geographic modelling. This is accomplished by using several different algorithms combined with Map algebra. The output of this model is used for comparative analysis against a pan-european dataset created by the JRC.
The project was about presenting and using the skillset obtained through the GeoInformatics education and the personal interests of the author.

Aalborg University Copenhagen, June 5, 2016

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Disclaimer: All illustrations, figures, tables, graphs and maps found within this report or its appendixes, is produced by the author unless referenced. Comma is used as a decimal separator within this report.

Here follows a table translating the written meanings of several registers, agencies, governmental institutions and more, found throughout the report.

Government	
Den Danske Regering	The Danish Government.
Organisations	
JRC	The European Joint Research Centre
ESDAC	The European Soil Data Centre
Eurostat	European Statistical Department
Danmarks Meteorologiske Institut (DMI)	The Danish Meteorological Institute
De Nationale Geologiske undersøgelser for Danmark og Grønland (GEUS)	Geological survey of Denmark and Greenland
Det Jordbrugsvidenskabelige fakultet - Aarhus University (DJF)	Faculty of Science and Technology
Danmarks Tekniske Universitet (DTU)	The Danish Technical University
Spildevandskomiteens (SVK)	The Danish waste water committee
GeoDanmark	National Danish Geographic assosiation
Agencies	
USDA	United States Department of Agriculture
Miljø- og Fødevareministeriet	Ministry of Environment and Food of Denmark
NaturErhvervstyrelsen	The Danish Agrifish Agency
Technical	
LUCAS	Land Use/Cover Area frame Statistical Survey
Kvadratnet	Danish national grid reference system
RIST	Rainfall Intensity Summarisation Tool by the USDA
NUTS	Nomenclature of Territorial Units for Statistics
FSS	Farm Structure Survey
Law	
GAEC	Good Agricultural and Environmental Conditions
MARS	Monitoring Agricultural ResourceS
Randzonelov	The Danish Buffer zone law
Vandplan 2012	Water plan 2012

Data	
OSM	Open Street Map
GSD	Ground Sampling Distance
LiDAR	Light Detection And Ranging
NDVI	Normalized Difference Vegetation Index
MERIS	MEdium Resolution Imaging Spectrometer
OAA	Object-oriented image Analysis
IWD	Inverse Weighted Distance regression
OK	Ordinary Kriging
Other	
Nitrogen	Nitrogen
Fosfor	Phosphor
Kalium	Potassium
Ammoniak	Ammonia
Pløjning	Tillage
Kultivere	Cultivate
Nedbør	Precipitation
Silt (små jordpartikler)	Silt
Dyrkbar jord og brakjord	arable land
Fluvialmorfologi (erosions processen)	Fluvial
Resultatet ændrer sig med tid	Time-variant
Resultatet ændrer sig ikke med tid	Time-invariant

1 | Introduction

"Soil erosion by water continues to be a serious problem throughout the world, and models play an increasingly critical role in conservation and assessment effort. Improved soil erosion prediction technology is needed to provide land managers, conservationists and others with tools to examine the impact of different land management decisions on on-site soil loss and off-site sediment yield and determining optimal land use. additionally, soil erosion prediction technology allows policy-makers to assess the current status of land resources and the potential need for enhanced or new policies to protect soil and water resources" (Harmon and Doe 2001 p. 145).

Due to several physical processes the landscape is constantly being morphed and affected, on-site monitoring of redistribution and transport of sediments, soil, sand, silt and organic material thereby becomes extremely time consuming and expensive. Unfortunatly this eliminates timely and regular temporal soil erosion monitoring as an economic viable option (Pimental 2006). Soil loss is dictated by several physical parameters some of which are water and wind. Monitoring for soil loss is a critical component in planning and construction of counteractive measures. This is becoming increasingly critical as more stress is introduced to the production facilities.
Increasing demands for agricultural produce is directly linked to the incresing population, according to the World Health Organization, the primary foodsource is the farmlands (99,7%) (World Health Organisation 2004). With the increasing population, demands for higher productivity and farm yield follows, the same amount of acres of farmland therefore needs to facilitate more crops and livestock. Maintaining the high productivity, is furthermore becoming increasingly difficult. Soil erosion is a a contributing factor, governing the production effectiveness.
Several countries has a high agricultural- to urban area ratio, for example, about 62 % of Denmark is farmlands, producing groceries, flour and crops for consumption, animal feed and industrial use (Skriver and Larsen 2013). Danish farms produce food for 15 million people, 3 times the Danish population. In-

creasing plant yield seems an obvious fix, however several physical components limits plant growth, among these are photosynthesis (Vidyasagar 2015; Minnesota Pollution Control Agency 1999). To grow and thrive, sunlight, nutrition and water is needed. Increasing the production can only be accomplished by increasing the amount of available nutritions. Commonly Phosphor and Nitrogen are both used as fertilizers. In their non-gas state, Phosphates and Nitrates are immobile substances, meaning they stay where they are deposited. Physically adding nutrition creates an excess, with landslides, erosion, tillage and water these excess immobile substances are transported and redeposited in areas where they are unwanted.
Continuous physical interference on the soil carries small amounts of dirt, soil and sediments away, with these are Phosphates and Nitrates. The fluvial processes of sediment transport, redistributes these particles to low-lying areas and waterbodies. Here they greatly affect both plants and wildlife. Monitoring of the ground water and drinking supplies, has determined their presence, resulting in unhealthy drinking water (Minnesota Pollution Control Agency 1999; Nielsen 2016b). Phosphor and Nitrogen is therefore candidates of concern. Several initiatives has been evaluated around the world, some easier to implement than others. Natural buffer zones without cultivation around streams and catchments is heavily discussed. This approach is easy to implement and the initiative can be introduced directly by policy-makers (Videncentret for Landbrug 2012).

Many considerations should be taken when evaluating agricultural production, and the dangers imposed on water quality. However the transport of sediments, is often a complex function of several parameters, topology, rainfall, soil types and vegetation, making it hard to predict. In many cases the flow characteristics of soil and sediments should not be generalised or simplified across larger agricultural areas (Morgan 1995; Kronvang and Andersen 2012). This complexity of sediment transport creates a need, to better account for the changing environmental conditions across larger areas. Several models should be investigated to find if they are able to accurately detect the complexity of soil erosion.

Available models uses different data and functions on either a temporal or spatial scale, some are based on observations (Empirical models) and some on mathematically and statistically valid equations (physical models). This report will seek to find a suitable model for modelling soil erosion and evaluate the sensitivity of the model to determine its applicability.

These considerations led to the following problem statement and research questions that this report should seek to answer:

Problem statement
How is erosion modelling affected by the extent and quality of the inputs?

Research questions

- Why should erosion be modelled?
- Which forces and environmental processes are involved in soil erosion?
- How is erosion modelled and applied?
- Who benefits from modelling erosion?

2 | Theory and background

The nature is an object of great attention, the water environments is one of the biggest areas of interest and concern. Water is a critical factor for all living organisms, therefore this valuable resource is monitored and protected, ensuring clean unpolluted water. Many chemicals that exist within the top soil layer are being loosened, transported and redistributed by natural forces. Precipitation and water, wind and several other forces work the land surfaces. These forces are catalysed by several parameters, affecting the rate of erosion (Harmon and Doe 2001). This topic has therefore undergone research, trying to understand the physical and mechanical mechanisms. This research has led to the development of empirical and physical models which will be described in this chapter.

The farms of today are high production facilities, demands for increased performance and productivity has created a need for increaing the farm yield. Synthetic fertilization and gain feeds has been introduced to meet these demands. The increased use of synthetic fertilization, creates an excess not used by the crops, thereby allowing it to be redistributed by natural forces, to unprotected water bodies and natural environments (Petersen and Dietrich 2010). Many countries have experienced big changes in food demand and the production has therefore been increased to accomodate this, typically NPK fetilization has been the most popular (Petersen and Dietrich 2010; Petersen 2010). Being proactive in order to avoid unnecessary amounts of pollution in the water, Governments and Agencies publish environmental plans which include thresholds for the amount of tolerated pollution found in e.g the water environments. This is necessary because the run off from the fields will settle in the lowest lying areas and settle in the small streams and catchments.
NPK is synonymous for Nitrogen, Phosphor and Potassium which are typically introduced to the fields in the form of nitrate or Ammonia (Bjerregård and Hansen 1983). Phosphates is found in some types of ammonia and phosphate rocks. Potassium is typically found in potash or Potassium-sulfate which is a crystaline salt (Bjerregård and Hansen 1983). Nitrates and Phosphates are the largest contributors to the pollution of water. Their particles are bound to the

soil sediments, redistributing them together when affected by the atmospheric environment. In some areas legislation has had an effect to the amount of phosphates being introduced to the soil by the farmers (Naturstyrelsen 2013; Nationalt Center for Fødevarer og Jordbrug 2003). In some high risk areas cultivation free buffer zones has been introduced on farms, to force the excess to settle here, avoiding contact with water (Danmarks miljøundersøgelser 2009; Videncentret for Landbrug 2012).

2.1 Pollution

Crop growth is dictated by several factors, energy, carbon dioxide and water. The energy absorbed by the crop originates from heat and light, this energy then transforms carbon dioxide and water into sugar which is stored in the chloroplasts of the plant (Vidyasagar 2015). Nutrients, nitrite, nitrate, ammonia and phosphor is absorbed by the plant together with water. Farmers can boost the productivity of the crops by increasing the amount of potential nutrients available in the soil, thereby introducing it to the plants. Crops can therefore be grown faster and bigger, increasing the potential yield of a farm.
Nitrogen and phosphor are the two plant nutrients that has the biggest effect on yield and plant growth. Nitrogen's natural state is as a gas, though when bound to Hydrogen it becomes ammonia which is generally found in animal waste. Nitrogen is also found in the atmospheric, where it comprises 78 %. The second important plant nutrient is Phosphor, Phosphor is rarely found as a free element, instead it is often found in its oxidised state as inorganic phosphate rocks (Ganrot 2005). Ammonia and Nitrogen is typically in a gas-phase and will escape the soil if not tilled. This happens gradualy over prolonged periods of time. For this reason atmospheric contamination, is a greater problem when dealing with Nitrogen (Nationalt Center for Fødevarer og Jordbrug 2003; Petersen and Dietrich 2010). Potassium has not been linked directly linked with water pollution yet (Hunding, Schjørring, and Skriver 2016; Naturstyrelsen 2013).
In its solid state, Phosphor will tend to stay with the soil sediments, excess is therefore carried away (Nationalt Center for Fødevarer og Jordbrug 2003). However tillage allows the Phosphate to be ploughed into the top soil, keeping it from being removed by wind, making redistribution by water the main concern.

Of the mentioned chemicals Phosphor stands out, as being the only nutrient not to have a gas-phase. Instead the Phosphates stay with the soil and dirt, making it extremely susceptible to being redeposited by soil erosion and other physical factors. This is what makes phosphor dangerous to the water environments and water supplies. Direct exposure to large amounts of phosphor can become toxic and dangerous over time (Minnesota Pollution Control Agency 1999).

Soil erosion is often triggered or catalysed by rainfall where the infiltration capacity of the soil is exceeded (Hasholt, Kuhlman, and Madsen 1990). When eroded by water, the larger particles of dirt and Phosphor are deposited first, and as the speed of the waterflow decreases the smallest particles are deposited. The finer particles of phosphor are thereby deposited together with silt and clay which have the finest granularity. These deposits of fine particles are easier to erode than larger soil particles, releasing the polluting particles (Morgan 1995; Petersen 1994).
In the water environments, NPK nutrients can cause harm by starving the habitats of oxygen, making the habitat even more toxic (Fog 2001). Several attempts has been made to decrease the pollution, special freshwater plants and animals was introduced to the polluted water areas, they were to use all the surplus nutrients in the water, effectively filtering the environment. In addition, dissolved aluminum or iron was added to the water. The dissolved metal solutions was added to chemically bind the phosphor and force it to settle on the sea floor. This way the water environment could slowly return to a state without pollution (Nielsen 2016a).

Because the transport of phosphor is a complex function of several physical factors, topography, rainfall, soil type, vegetation and land use, attempts to decrease pollution hasn't been successful (Morgan 1995; Kronvang and Andersen 2012). Evaluating areas for high risk spots should be the first priority, next these spots should be sampled and evaluated for pollution. If polluted, initiatives should be introduced to reduce pollution and lastly these initiatives should be evaluated to find if they were successful. Using a screening tool, high risk areas could be determined faster. Modelling soil erosion patterns could thereby potentially foresee problems, allowing the implementation of functioning initiatives to be tailored for a specific use case. Furthermore local Governments could be empowered to act accordingly and strengthen future efforts regarding NPK and pollution.

2.2 Modelling erosion

Several models has been introduced, with the promise of detailed erosion estimates. This enables the user to locate high risk areas prone to soil erosion. The models USLE/RUSLE, WaTEM/SEDEM/EUROSEM, SLEMSA, "The Morgan, Morgan and Finney method" and others, are used to simplify the natural processes, causes and effects, while keeping a high coefficient with real world data. Common to all the models is that they rely on the same basic inputs, however the analysis is in some models based on short durations, others for a longer duration such as a year. The duration modelled can be described as the temporal resolution, high temporal resolution is known as Steady-state models, they compute on each event (Harmon and Doe 2001 ch. 7.3.2). Some models can be implemented spatially, enabling a visual representation on a map, others have more statistical outputs and are not easily referenced spatially. The models also operate on different area sizes, some on upland data, some are more local to a specific field. The outputs are in some cases volumetric, and in some cases differential (Morgan 2005).

Generally there are two types of models, the empirical based model and the physical model. The empirical model is build on large amounts of test data, gathered from areas that have several physical features in common, e.g. rainfall, topography and erosivity. These observed areas should be statistically significant, ensuring a high coefficient with the real world when used and implemented correctly, however when misused they tend to have a very low coefficient, these are also denoted "black-box models. The "white- and grey-box models also include observed events like the flow direction of the water based on topography (Morgan 2005; Harmon and Doe 2001). These soil erosion models was developed to answer relatively simple questions about mean rates of transport, applied primarily to agricultural sites. In the 1970's concerns about off-site impacts of pollution and sediment transport arose, therefore new legislation in the US and western Europe required these parameters to be evaluated. Real temporal modelling was not possible with the empirical models, therefore the focus changed to more physical based models.

The physical model tend to work and explain the real world like a domino effect, if one thing is true then the another thing is also true. These models can be tweaked and fine tuned to specific scenarios thereby making it possible to derive information about the real world from the model. Even though modern state-of-the-art models can reproduce reality with high precision, they're still not ideal, and should be considered as process-based (Harmon and Doe 2001 pp. 119-127).

	USLE/RUSLE	WaTEM	SEDEM	CREAMS	WEPP	EUROSEM	SLEMSA	MMF/rMMF
Originating Country	US	NL	NL	US	US	UK/DK	ZA	UK
Empirical model	X	X	X				X	X
Physical model				X	X	X		
Continous				X				
Precipitation	X			X	X	X	X	X
Soil type	X	X	X	X	X	X	X	X
Topography	X	X	X	X	X	X	X	X
Land cover	X	X	X	X	X	X	X	X
Farming type	X	X	X	X	X	X	X	X
River/flow network		X	X	X	X	X		
Spatial	65 %	80 %	80 %	20 %	40 %	40 %	65 %	65 %
Temporal	35 %	20 %	20 %	80 %	60 %	60 %	35 %	35 %

Table 2.1: Comparison between several models. Sources are in the individual model explanations. The Spatial and Temporal understanding was introduced by the author and is solely based on his understanding of the models, based on various sources

2.2.1 Models

USLE, Universal Soil Loss Equation, is one of the most used models for determining the mass and volume of soil erosion. It was developed by the Institute of Water Research, Michigan State University USA, and has been validated several times, by the US defence department, European governments and NGO's, and has been found to successfully determine the mass of soil erosion on a large scale across Europe. The model was developed on empirical data obtained from 1930 to 1956 from the "Corn belt" in the US, where increased amounts of phosphates where found in both rivers, streams and the ground water (United States Geological Survey 1998). The "corn belt" is a low lying flat area compared to the rest of the United States. The model was published in 1965 and revised in 1978 with a new formula for determining the topographic effects (slope -length and -steepness). RUSLE has previously been introduced in GIS environments and has been validated in many scenarios across the US, Europe, Africa and Asia, it exists as a desktop software suite and as a conceptual formula (Kronvang et al. 2009; Panagos, Borrelli, and Meusburger 2015; Institute of Water Research - Michigan State University 2002; Wischmeier and Smith 1978; Harmon and Doe 2001). Being an empirical model, the developers warn users of assuming USLE is applicable everywhere without extensive testing (Wischmeier and Smith 1978). USLE has had revisions and is renamed RUSLE in the most recent revision.

WaTEM Water Transport Erosion Model, is based on the fundamentals that water will flow to a river network and carry sediments from the uplands, tillage and terracing is then the braking parameters. It implements this in an adapted version of the Revised Universal Soil loss equation (RUSLE) (Oost, Govers, and Desmet 2000). *SEDEM* Sediment Erosion Model, used together with WaTEM to determine flow caracteristics and the sediment mass to establish water- and tillage erosion/deposition rates and patterns (Physical and Regional Geography Research Group, Katholieke Universiteit Leuven 2002).

CREAMS Chemicals/Runoff and Erosion From Agricultural Management Systems, is developed for non point source based pollution and is only applicable to individual fields (Nicks et al. 1980 pp. 1-8). Developed in the US in 1978 it was the successor to the first physical based mathematical model (the Stanford watershed model) and it analysed individual temporal events continously, or sumamrized them daily (Steady-state-modelling) (Nicks et al. 1980 pp. 2-10). Meaning that the model would evaluate every event during a day and summarize the total erosion pr. day, pr. field. It is based on the R, C and K parameters from USLE, not using the slope length and -steepness factors.

WEPP Water Erosion Prediction Project (Flanagan et al. 1995). Like CREAMS this model is a steady-state model computing for each individual event (Harmon and Doe 2001 ch. 7.3.2). WEPP does not use event based data, but instead statistical artificial yearly precipitation and water data, making it highly efficient, but only within a very limited environment (Wainwright and Mulligan 2013 pp. 190-195). This volumetric precipitation assumption is also used in daily calculations and is based on the R parameter calculation from USLE. WEPP was designed to meet the shortcomings of USLE, especially in estimating snow-melt (seasonal changes) and irrigation. The developers came to the conclusion that WEPP were not practical to use, this conclusion was probably also the reason why USLE was revised and is still the most used model.

EUROSEM is primarily event based but also spatial. The EUROSEM model developed by Cranfield University UK, based on a hydraulic model (MIKE) by DHI (Danish Institute of Hydraulics) who specialises in hydraulic based modelling (Morgan et al. 1998). It's a physical model, and it takes a huge amount of parameters, making it impractical to use in most cases, although very accurate. It is by many considered to have the highest temporal resolution (up to 1 minute time steps), which is why it is also called a dynamic model. It shares alot of similarities with the KINEROS2 model which will not be covered here (Harmon and Doe 2001 p. 124).

SLEMSA, Soil Loss Estimation Model for Southern Africa, developed by Stocking in 1981, is another approach that is comparable to USLE. Both USLE and SLEMSA has been utilised and tested with the same data, the results are very comparable (Burrough and McDonnell 1998; Kaiser 1999). Sources suggest that SLEMSA is the most widely used alternative to USLE (Harmon and Doe 2001 p. 121). Mostly used to evaluate the effects of protective measures post-construction and not as an initial assessment tool.

MMF, the Morgan, Morgan and Finney method was developed in 1984, and revised in 2001 based on data from 1950-1990. Based on USLE (Wischmeier and Smith 1978) It models erosion by water and sediments but unlike USLE it seperates them. The model inputs precipitation and volume to determine the transport capacity and energy, and Soil particle detatchment to understand the available soil, these two values are then subtracted. The output values differ from USLE, and are annual or mean annual erosion rates. MMF was developed as a development to USLE, based on the same parameters, however it was meant to take advantage of the advances made within erosion science (Harmon and Doe 2001 pp. 120-122). MMF newer reached the widespread adaptation of USLE, but has been introduced as a plugin to Saga GIS which is used in QGIS (Wainwright and Mulligan 2013 pp. 190-195).

The above models are only a small selection of the most used soil erosion models. The models take different approaches in modelling erosion, the spatially enabled models are perhaps better suited for visualizing data where the temporal models would be better for determining the effects of heavy precipitation and storm events. Common for all the above mentioned models, is the fact that they are based on fluvial processes, they do not consider subsurface overflow and run-off of underground pockets. All of the above models primarily use a combination of vector- and raster data as inputs. Vector- and raster-only based models do exist but are not considered in this report due their very specific use cases and macro scale (Harmon and Doe 2001 ch. 7.3.4). The complexity of physical models requires an expert level of know-how, therefore these will not be evaluated in this report. However, USLE seems to be the origin of several of the other models, its recent revision, great documentation and previous GIS implementation makes it the most logical to explore in this report. The findings of this report, might be applicable to other models, as these in some cases utilize the exact same parameters.

3 | RUSLE

the Revised Universal Soil Loss Equation

Erosion is a process of detachment and transport of soil particles by erosive forces, these forces include raindrop impact and surface runoff from rainfall. The Universal soil loss equation, originally tested and developed by Wischmeier and Smith, was first Published in 1965 and later revised in 1978 with a new equation for determining the topographic effects of the slope-length and slope-steepness, LS factors. RUSLE is used to determine sheet-, and rill-erosion, based on the empirical relationship between several physical forces, the original model USLE has found its way into numerous other models (Kronvang et al. 2009; Panagos, Borrelli, and Meusburger 2015; Institute of Water Research - Michigan State University 2002; Wischmeier and Smith 1978). RUSLE describes a relation between multiple erosive factors, working with and against the soil being loosened, transported and redistributed. RUSLE has been applied extensively in the attempt of modelling the erosive behaviour of our environments, by estimating the amount of lost soil. Soil loss models and empirical studies are being implemented in projects related to water pollution, due to polluting substances that are carried with the eroded soil. Several tests and reviews of both USLE and later RUSLE has been conducted by researchers throughout the previous decades (Wischmeier and Smith 1978; Harmon and Doe 2001; Jones, Kowalski, and Shaw 1996; Roose 1978; Panagos, Borrelli, and Meusburger 2015). The concept of USLE was published with a desktop software suite, and the theory was described in the published model documentation. The concept suggests a correlation between precipitation, soil type, topography and land use, expressed by the following equation:

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \tag{3.1}$$

where:

R	Is Precipitation [Rain].
K	Is Soil type [Erosivity].
L	Is Topographic length.
S	Is Topographic steepness.
C	Is Vegetation and crops.
P	Is Land use [Support practice factor]

After documentation by Wischmeier and Smith (Wischmeier and Smith 1978).

In chapter 2 RUSLE was found one of the most used models for determining the scale of soil erosion. Developed by the Institute of Water Research at Michigan State University USA, RUSLE was originally intended for use in the "Corn belt" in the North and Midwestern USA (Wischmeier and Smith 1978). "The corn belt" is a low lying flat area compared to the rest of the United States. The area is spatially determined by the amount of corn produced on this land. Empirical analysis has led to the understanding, of the fluvial processes involved in soil erosion, this led to the above empirical relationship. Legislation has in many areas been introduced nationally to decrease pollution. Using RUSLE as a screening tool and post-evaluation tool has a widespread adoption, underlining the importance of evaluating RUSLE. This serves to enlighten some of the problems within the model and where inaccuracies are introduced.

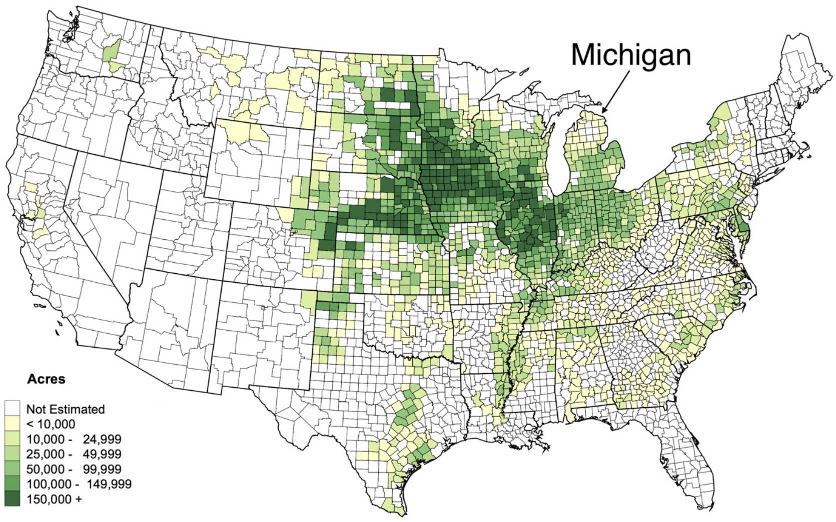


Figure 3.1: Crop yield in the United States, this map shows corn production values from 2010, effectively outlining the area known as "the corn belt" produced by the USDA (United States Department of Agriculture 2010).

Developed upon 10.000 plot-years of run-off and erosion meassurements, RUSLE is based on a huge database ensuring validity within the test environments (Harmon and Doe 2001 pp. 119-145). In the original validation, USLE proved capable of an accuracy up to ±2.5 t/Ha/year on >50% of the evaluated plots, and within ±5 t/Ha/year on >85% of the evaluated plots. In 1978, RUSLE made slight improvements to multiple of the parameters in USLE (Jones, Kowalski, and Shaw 1996 p. 2). The changes included:

R: New and improved isoerodent maps and erodibility index (EI) distributions for some areas.

K: Time-variant soil erodibility which reflects freeze-thaw in some geographic areas.

LS: New equations to account for slope length and steepness.

C: Additional sub-factors for evaluating the cover and management factor for cropland and rangeland.

P: New conservation practice values for cropland and rangeland.

Comparisons between RUSLE and USLE was conducted during the evaluation of US Defence Department lands. RUSLE was found to output 58% less soil loss, 14% higher LS-values and 65% lower C-values, with no change to R and K. On 70% of the tested sites RUSLE gave 50% lower soil loss values than USLE. These numbers does not suggest which model has the most correlated estimation, however RUSLE was found to be more in line with the control measurements (Jones, Kowalski, and Shaw 1996).

Originally intended for use in soil-conservation mapping and evaluation, USLE was based on simplicity and ease of use, allowing quick evaluation compared to other models. The word Universal implies it can be used in all cases, this is not a correct assumption. Being an empirical model it will only be applicable on areas that have high correlation with the original test sites, unless specific measures are taken, to account for the variabilities. Therefore there are several limitations to the use of RUSLE and the empirical relationship it describes. However well suited for use on both cultivated and non-cultivated agricultural lands with vegetation and without extreme topography, it has been validated several times, and was found applicable to use in research and planning of protective measures. However the users must be vary of the limitations of an empirical model before using it.

3.1 Fundamentals

The fundamentals of RUSLE – and most other erosion models used, is the concept of a balance of forces, which affects the case area and acts upon the environment until such balance is restored. In short RUSLE is a simple model stating that mass and energy equals motion, and motion can be reduced by opposing forces. Precipitation loosens the soil, gravity and added energy carries it downhill, several other parameters brake or accelerate this process, until it either stops or ends at the lowest possible elevation, see figure 3.2 (Institute of Water Research - Michigan State University 2002). Precipitation, water and infiltration capacity is the main drivers behind RUSLE, these parameters describe the potential mass and amount of energy and soil that can be set into motion, topography and land use patterns can catalyse, limit or stop the movement (Wischmeier and Smith 1978; Renard et al. 1997; Morgan 2005). The rest of the parameters describe supporting factors that accelerates, stops or slows the process down. The erodibility of the soil, is defined by the soils resistance to detachment and transport. This resistance depends on the disturbance of the soil by water and mechanical processes, tillage etc. and the topographic settings where the soil lies within. Erodibility also changes by the composition of sediments within the soil, granular size, texture, infiltration capacity, moisture, chemical- and organic contents all determine the shear strength of the soil (Morgan 1995 pp. 29-34). Topography is also an important factor in RUSLE, the effect of slope-steepness and -length contributes to erosion by accelerating run-off downhill. Furthermore splash erosion generally fling particles in all directions on a flat surface, on a slope the particles tend to be flung downhill. The relationship between erosion and topography is expressed:

$$E \propto \tan^m \theta L^n \tag{3.2}$$

where:
E, soil loss per unit area, is proportional to the vertical height of the hill tanθ and the slope length L, n and m are scalars used to tweak the equation for varying situations(Zing 1940 and Morgan 1995 pp. 34-35).

RUSLE is unlike other erosion models, not based on the assumption of a closed material net-balance, instead the evaluated case area is assumed to have infinite amounts of soil, that can be affected given enough added energy (Agricultural Production Systems 2016). Wischmeier and Smith suggests that the eroded soil is either decelerated enough to stop, or it is not, allowing the transport of soil to continue until it slows down enough to deposit the sediment (Wischmeier and Smith 1978) . The amount of soil lost or gained on a given area is therefore not dependent on the amount of soil available on nearby areas. This is true because only the evaluated area is taken into concern, therefore RUSLE results will vary based on size and topographic connections between evaluated case areas.

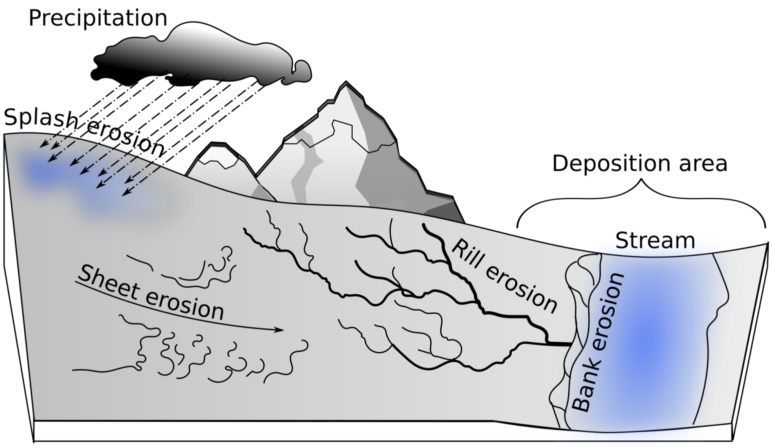


Figure 3.2: The fundamental erosion model proposed by Wischmeier and Smith, the figure has been created by the author.

To ensure validity of the model, RUSLE has been evaluated for use in multiple environments. In 1978 the original USLE was validated in the more humid environments of West Africa (Roose 1978). 50 plots of land, topographically similar to the "Corn Belt" (with moderate to flat and level slopes), varying in size between 100 m^2 to 5000 m^2, was analysed. Static measuring devices were placed to gather control samples. USLE was found, to not be applicable to dry regions, due to low correlation with the short but intense bursts of rain, and the low soil water content. However in the vegetated Sahelien zone, with longer and more moderate bursts of rain and higher soil water content, RUSLE was found applicable on the red ferrallitic soils, but should not be used where high amounts of clay is present (Roose 1978 pp. 68-71).
Again in 1996 RUSLE was validated on a large scale across all US defence areas by the US Defence Department and Colorado State University, this research led to calculating the effects of sheet and rill erosion from rainfall (Jones, Kowalski, and Shaw 1996). The lands of the US Defence Department consists of primarily sparsely vegetated rangelands. Natural resource managers wanted to implement an erosion model to find high risk areas. They tested the WEPP model and RUSLE. Contrary to the Water Erosion Prediction Project (WEPP model), RUSLE does not explicitly consider water runoff or each of the individual erosion processes, detachment, transport, and deposition seperatly. The

research done, suggested that the input data should be standardized since it in some cases needed to be heavily modified before use. However it was concluded that once the input data was standardized the model was straight forward to implement and gave reliable outputs and produced accurate erosion estimates on rangelands and agricultural lands, compared to control samples. It was also suggested that an initial conservative approach would be to use RUSLE to locate trends in erosion at particular locations, thereby giving the user an indication of relative changes in soil loss at each particular site. When using absolute output values, the number of sample sites should exceed a value of statistically validity to minimize variance and allow for a spatial extrapolation with a high level of confidence. This research considered the implementation of the RUSLE to produce defensible results leading to the implementation in future planning (Jones, Kowalski, and Shaw 1996 p. 7).
Geosciences Magazine published research from 2015 of a large scale validation of RUSLE in the European union. This research was conducted by the European Commission, Joint Research Centre, Institute for Environment and Sustainability (Panagos, Borrelli, and Meusburger 2015). Using a new pan European DEM raster with a GSD of 25 m the researchers claimed a better evaluation of areas with more topographic variation when using RUSLE (only areas with up to 50% slope steepness was evaluated). The GSD value is however not the same as vertical accuracy along the z-axis, the research used a DEM with a vertical accuracy of 2,9 m RMS. Topographic steepness and amount of soil lost does not have a linear correlation, studies by (McCool et al. (1987)) found that soil loss is an exponential function that greatly increases when slope steepness is above 9%. However on agricultural land, slopes rarely exceeds this value, therefore RUSLE was found applicable with no modification here. The EU-countries generally had low LS-factors, being similar to those found in the corn belt. The main findings of the European research was made when comparing the maximum and minimum LS values to that of the previous study by Bosco (Panagos, Borrelli, and Meusburger 2015; Bosco et al. 2015). The research suggests a that a high-resolution DEM can produce local LS-value estimations, more accurate than a DEM of lower resolution (Panagos, Borrelli, and Meusburger 2015 pp. 123-125).

3.2 Criticising RUSLE

Being the the most widely accepted and utilized soil loss erosion model for over 30 years, it has received several points of criticism as well as praise. RUSLE has fundamental flaws and limitations, this section aims to investigate the criticism the model and its derivative program has received. Designed and intended as a method of predicting average soil loss annually by sheet- and rill-erosion, the empirical model is most often criticized for its narrow field of applications and usability. However this is partially caused by the general limitations to an empirical model. While RUSLE can estimate long term annual soil loss, it is not applicable for short term modelling and can not be applied to a specific storm event.

As USLE gained popularity it became apparent that the soil-loss ratio (SLR subfactor described in section 3.4.6), gave inconsistent results based on the seasonal cycle. With the revison of USLE, a time-varying SLR based on cropping periods was introduced. The program RUSLE1 implemented the new SLR equation by introducing a new database with a temporal resolution of 24 hours. This database was also used for the P-factor calculation.
The programmers of RUSLE1 misinterpreted the the RUSLE formula and aggregated the values of R, K, L, S, C and P over a year before multiplying them together. This approach yielded invalid results. The correct implementation should take the form:

$$A = (R{\cdot}K{\cdot}L{\cdot}S{\cdot}C{\cdot}P)+(R_1{\cdot}K_1{\cdot}L_1{\cdot}S_1{\cdot}C_1{\cdot}P_1)+(R_{\dots}{\cdot}K_{\dots}{\cdot}L_{\dots}{\cdot}S_{\dots}{\cdot}C_{\dots}{\cdot}P_{\dots}) \quad (3.3)$$

The RUSLE factors are determined for each change/event and then added together. The difference in RUSLE output between the two approaches could vary up to 30% (Morgan 1995 p. 153).
As several other weaknesses where found in the RUSLE1 program, it was deemed unsuccessful in implementing RUSLE for erosion risk planning. The RUSLE2 program were to correct the issues in RUSLE1. The new program were ready for testing in 1996 but was not released until 2001, after careful investigations by the *U.S Natural Resources Conservation Service*.
The primary changes where downplaying the roles of the individual parameters of RUSLE and focusing more on the overall relationship. The original USLE concept described all of the USLE factors as independent except K, C and P, who are in some areas closely related. RUSLE2 was also able to include depositional zones on a hillslope. This was important as more complex topography could have natural terracing or changing gradients (Morgan 1995 p. 151).
Using RUSLE2, all problems should have been addressed, however if RUSLE is implemented as a separate application or manually integrated into GIS the above should be considered. Furthermore the run-off area (LS) can be represented in GIS as rasterized cell values, each cell should also have information on the flow direction to avoid modelling run-off in the wrong direction.

In order to get reproducable results from RUSLE, the input parameters need

to follow certain criteria. Precipitation has been critizied for being difficult to standardize to a point of reproducibility. This was described by Morgan when evaluating the effects of rainfall (Morgan 1995 ch. 2). Short duration, high intensity storms quickly exceed the infiltration capacity of the soil thereby creating run-off carrying sediments. Long duration, low intensity storms saturate the soil over a longer period of time before allowing run-off. Precipitation from the previous days could also have saturated the soils allowing run-off to occur sooner, these events are not directly integrated into RUSLE. Because of this RUSLE uses a precipitation index based on kinetic energy. EI_{30} is the erosivity index, describing energy and duration.
To be a valid description of precipitation, the EI30 index must be significantly correlated with soil loss, Wischmeier and Smith found splash-, rill- and owerland flow erosion to be correlated to a compound index of kinetic energy (E) and the maximum 30-minute precipitation intensity (I_{30}) (Wischmeier and Smith 1978; Morgan 1995). This approach has later been criticised because the equation used to determine kinetic energy is a simple estimation (see equation 3.5). Secondly, it is not applicable in tropical areas with high intensity rain, and in high altitude areas because of the low rainfall energy. Studies by Hudson, found that erosion is almost entirely caused by rain falling at greater than 25 mm/h, and not by low intensity rain (Hudson 1965). Research by Hudson and Morgan mentions no obvious reasons why I_{30} intensity has been chosen, in fact they mention that the EI_{30} index is merely a function used to correct the fundamental overestimation induced by low intensity rain in RUSLE. Stocking and Elwell came to the same conclusion regarding USLE, thereby only recommending UUSLE to be used on bare or sparsely vegetated soil (Stocking and Elwell 1973). RUSLE introduced a revised calculation method for EI_{30}, several researchers have tried different methods to increase the precision. However it should be noticed that no matter the method, the EI_{30} index must be significantly correlated with soil loss in the specific case area.

Topography is perhaps the most influential factor of RUSLE. Erosion is catalysed by the L- and S-factors, as slope-length and steepness increases, run-off speed and volume follows. The effects of topography is determined by two-dimensional estimations of slope gradient and length, where L represents the potential erodible surface region to an estimated break line on the surface. This value does therefore not directly represent the slope length and should not be misinterpreted as the slope length (Andersen and Heckrath 2015).
As the RUSLE model does not consider the infiltration of the soil, previous precipitation events can be overseen, leading to under-estimating the soil loss. Bank erosion is not determined precisely in RUSLE, model calibration is there-

fore important. Calibrating each factor to a case area is crucial in every model, this is done to reduce the size of the model error. This error is typically denoted epsilon (ϵ), and serves to indicate the offset from a true erosion rate (μ) (Andersen and Heckrath 2015).

3.3 Limitations of use

RUSLE should not be used where there is no soil, in mountainous areas and in urban areas.

RUSLE is not directly suited for modelling soil loss in forests, tropical environments, or where there is exposed soil.

Seasonal changes are not taken into account, smelt water is therefore not part of the equation, for this reason the WEPP project was started.

RUSLE is fundamentally two dimensional within the case area, even though it evaluates topographic features, they only exists as numeric values in the equation.

However the most problematic limitation is, that only the case area is evaluated, resulting in a "hard cut" of the dataset, therefore outside topography, soil and precipitation is not considered when working with smaller plots on the middle of a slope. A plot should never be evaluated alone if it exists as part of a larger topographic feature.

(Nicks et al. 1980; Renard et al. 1997; Dissmeyer and Foster 1981, 1984; Flanagan et al. 1995; Institute of Water Research - Michigan State University 2002).

Rain is the main driver of soil erosion in the RUSLE model, many of the limitations of RUSLE is introduced in modelling this paramenter. The fundamentals in RUSLE dictate a relationship between forces, however most of the interactions happen on the ground. Studies have shown that plant cover can brake the fall of raindrops, thereby reducing the forces affecting the soil particles. Low vegetation primarily hold together the soil, where vegetation above ground works as a shield against the rain. Studies have shown that a canopy height above 7 m does not shield the soil as effectively, this is true because the raindrops reaches close to terminal velocity falling from this height, thereby regaining 90 % of the original energy from the fall. Furthermore the drops falling from the canopy form larger droplets, which is more erosive (Morgan 1995 p.

36). Studies have found that during larger storm events, the erosion is 3 times greater within the forests compared to bare soil (Wiersum 1985). The spatial distribution of the droplets is also modified in the forest, locally the infiltration capacity can therefore be exceeded quickly creating run-off. Therefore a modified precipitation parameter should be used in these environments.

3.4 Parameters

3.4.1 R (Precipitation)

The erosive forces of rainfall is described by the amount, and intensity of the rain, these considerations are commonly expressed as the R factor in the RUSLE model terminology. Precipitation data typically originates from meassuring stations, several organisations and agencies has made data available. However these organisations and agencies does not confine their data to a standard. The equipment can also be from different manufacturers, allowing data- and temporal resolution to vary. Furthermore the data is in some cases grouped and categorized by storm intensity or period. Many european countries has a temporal resolution of 60 minutes according to a study on the RUSLE R-factor by Panos Panagos (Panagos et al. 2015b).
The availability of data can be very different from one country to the next, in some cases this forces soil erosion modellers to estimate the precipitation based on data with low temporal resolution, averaging daily-, monthly- or annual data. Studies have been conducted with the purpose of assessing rainfall erosivity in Europe, by using the RUSLE R-factor. Using the highest temporal resolution datasets available from 1541 precipitation monitoring stations within the European union (EU). The precipitation R-factor data values where normalised to values based on temporal resolutions of 30 minutes by linear regression. This effort led to a European rainfall erosivity raster map with a 1 km spatial resolution. The mean R-factor for the EU was calculated to be:

R-factor	Minimum	Average	Maximum
Europe		722	
Northern Europe and Scandinavia	<500		
Mediterranean and mountainous regions			>1000

Table 3.1: Locations of the max, min and average R-values across European areas. Values in MegaJoule (MJ) pr. mm ha^{-1} h^{-1} yr^{-1} (Panagos et al. 2015b pp. 802-806).

The R-factor is synonymous with the kinetic energy affecting the soil, EI30 is the maximum added energy from a rainfall event meassured over a duration equal to 30 minutes. The EI30 value represents the surface run-off and erosion (Renard et al. 1997). R equals the average EI30 energy over a period of minimum 20 years (Renard and Freimund 1994; Wischmeier and Smith 1978; Morgan 2005). The total kinetic energy (E) is the sum of precipitation and the intensity pr. minute of rainfall. Theoretically surface run-off is derived from the volume of water and the sediment detachment is derived from the intensity. Rain droplet size and speed is directly related to the intensity, and are the main factors in calculating kinetic energy (Morgan 2005). To get a good picture of the rainfall within a area, observations from different measuring stations must be collected, grouped and analysed. Only precipitation originating from an event with the following criteria is valid in RUSLE:

- The total amount of rain should exceed 12,7 mm $\sim$ 0,5 inches.
- The event has a maximum intensity of 25,4 mm pr. hour, meassured over 15 minutes, or a total 15 minute precipitation above 6.35 mm (Meusburger et al. 2012 and Meusburger et al. 2012 p. 804).
- A precipitation event of less than 1,27 mm over the period of 6 hours are to be devided into to different events (Renard et al. 1997; Meusburger et al. 2012).

Precipitation records should cover the case area but regional or municipal data is typically used. Generally local variations in rainfall erosivity ($\pm$5 %) can be represented with a single R value. The R value can be constructed from rainfall intensivity data, however this is time consuming. Using the EI distribution calculated as a percentage of the annual value for twenty-four 15-day periods, is also an option. However isoerodent maps typically lists the R factor and this value can be directly integrated.

R is calculated by the following equation:

$$R = \frac{1}{n}\sum_{j=1}^{n}\left(\sum_{k=1}^{m}(E)_k(I_{30})_k\right) \tag{3.4}$$

where:

E	Is the total kinetic energy for every precipitation event k in [MJ ha^{-1}].
I_{30}	Is the maximum precipitation intensity over 30 minutes in [mm h^{-1}].
m	Is the duration of a precipitation event in minutes.
j	Is an indexing number for a year.
n	Is the amount of years.
R	The R factor for RUSLE e.g in [MJ pr. mm Ha^{-1} h^{-1}].

(Renard and Freimund 1994) and (Panagos et al. 2015b pp. 804-806).

E is calculated:

$$E = \sum_{r=1}^{m} e_r \cdot \Delta V_r \tag{3.5}$$

where:

E	Is the total kinetic energy for every precipitation event k in [MJ Ha^{-1}].
e_r	Is the kinetic energy in [MJ Ha^{-1} mm^{-1}].
ΔV_r	Is the amount of precipitation for the minute r in a precipitation event in [mm].
m	Is the duration of a precipitation event in minutes.

(Renard and Freimund 1994) and (Panagos et al. 2015b pp. 804-806).

e_r is calculated in MegaJoules [MJ Ha^{-1} mm^{-1}]:

$$e_r = 0,29(1 - 0,72 \cdot exp(-0,05 \cdot i_r)) \tag{3.6}$$

where:

i_r	Is the precipitation intensity for the minute r in a precipitation event in [mm h^{-1}]

(Renard and Freimund 1994 p. 289) and (Panagos et al. 2015b pp. 804-806).

3.4.2 K (Soil erodibility)

Several physical factors determine the type of erosion induced on the soil. Rill-, Sheet- and Splash erosion is determined by the soil properties. The erodibility of the soil, is defined by the soils resistance to detachment and transport. This resistance depends on the disturbance of the soil by water and mechanical processes, tillage etc. and the topographic settings, slope length and steepness. Erodibility also changes by the composition of sediments within the soil, granular size, texture, infiltration capacity, moisture, chemical- and organic contents

all determine the shear strength. Large soil particles are resistant because of their size requirering more energy to entrain. Smaller particles are resistant due to their cohevesiveness. Silts, clay and fine sand are however the least resistant to erosion. Dry soil behaves like a solid, moist soil behaves like a fluid, requiring less effort to detatch and transport. Land cover, crops and plants also contribute to increase cohesiveness (Renard et al. 1997;Morgan 1995 pp. 29-34).
Shear strength is a value representing the resistance created by cohesiveness, to shearing forces. These forces are exerted by gravity, fluids and mechanical interactions. Exceeding the shear strength of the soil makes it susceptible to erosion. This is the exact same process which starts landslides and avalanches. The fracture line marks the exact spot where the shear strength was exceeded. The soil or snow will slide off, but stay connected because the particles adhesiveness hasn't been exceeded below the fracture.

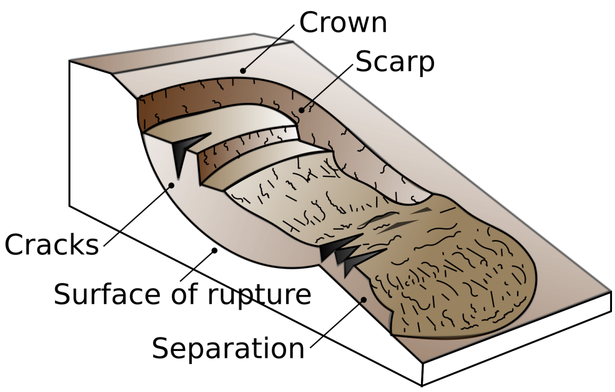


Figure 3.3: Soil erosion, fracture line and shear erosion, own production after (Morgan 1995 p. 30).

The relationship between the soil-binding parameters is in reality very complex and can be expressed:

$$\tau = c + \sigma \tan \phi \tag{3.7}$$

where:

c	Is a measure of cohesion.
σ	Is the stress normal.
ϕ	Is the angle of internal friction.

(Morgan 1995 pp. 30-31).

The soil binding parameters are not directly used in RUSLE (Morgan 1995 pp. 30-31).

The K-factor is a measure of soil loss pr. unit of R-factor, it describes the erosivity of the soil, the ease of detachment. Different compositions of soil particles has different shear- and cohesive strength. However land cover, crops and plants also contribute to the shear strength (Renard et al. 1997). The fine particles in clay has greater cohesiveness than the larger particles in sand, Silts are easily eroded making them extremely vulnerable to precipitation run-off. The K-factor is calculated based on a standardised situation, where a recently tilled, square bare soil field with sides of 22,13 m and a topographic slope of $5,15^o$ is exposed to different precipitation events. The volume of eroded material is then measured. Plotting this volume and mass of eroded soil in varying conditions of soil composition and temporal extend of a precipitation event, the K-factor is expressed for each scenario (Renard et al. 1997). Annual averages of soil erosion is aggregated over longer temporal periods thereby creating the parameter used in RUSLE.

The K factor represents both susceptibility of soil to erosion and the amount and rate of run off. Soil texture, organic matter, structure, and permeability determine the erodibility of a particular soil.

Soil type	Erodability	K value ranges
Fine-textured	High in clay	0.05 - 0.15
Low course-textured	Sandy	0.05 - 0.20
Low medium-textured	Loams moderate	0.25 - 0.45
High silt content	High	0.45 - 0.65

Table 3.2: (Wischmeier and Smith 1978; Renard et al. 1997).

The K factor can be determined mathematically or by using a nomograph, which is a graph with a series of lines representing different k-values for different scenarios of granularity and soil composition. If possible it is recommended to calculate the K-factor with the following equation, originally proposed by Wischmeier and revised by Renard:

$$K = \frac{2,1 \cdot 10^{-4} \cdot M^{1,14} \cdot (12 - OM) + 3,25(s-2) + 2,5(p-3)}{100} \cdot 0,1317 \quad (3.8)$$

and the textural factor M is calculated:

$$M = (m_{silt} + m_{vfs}) \cdot (100 - m_c) \quad (3.9)$$

where:

m_c	Is the clay content (particle size <0.002 mm) in [%].
m_{silt}	Is the silt content (particle size 0.002 – 0.05 mm) in [%].
m_{vfs}	Is the very fine sand content (particle size 0.05 – 0.1 mm) in [%].
OM	Is the organic matter content in [%].
s	Is the soil granularity [from s=1 (fine) to s=4 (blocky or massive)].
p	Is the soil permeability class [p=1 very rapid to p=6 very slow].

After documentation by (Agricultural Production Systems 2016 ch.3 p.74) and (Wischmeier and Smith 1978; Renard et al. 1997; Panagos et al. 2014b).

3.4.3 Topography

An important factor in modelling soil erosion with RUSLE, is the effects of slope gradient and slope length. These parameters are evaluated separately but often denoted as one LS-factor.
Topography affects soil erosion, both L- and S-factors expresses the ratio of soil loss compared to an evaluated square plot with sides of 22,13 m. The L-factor decribes the erosion ratio compared to a square plot with a gradient of 5^o (Morgan 1995 p. 66) (see section 3.4.5). The S-factor is an erosion ratio compared with that of an identical field, but with a specified slope angle of 9% ($5, 15^o$) (Clark Univeristy 2016).

3.4.4 L (Topographic length)

In many areas including the corn belt, the effects of topography on soil erosion has been discussed several times. The L- and S-factors has been implemented to account for environments with varying topography, making the RUSLE assessment more accurate, however in near flat conditions they are not needed due to their value of 0, which would neglect their impact on the RUSLE equation (Wischmeier and Smith 1978; Renard et al. 1997; Morgan 2005).

L is defined as the horizontal distance from the ridge, to the point where sediment is deposited. This point can be hard to determine since the sediments only stops when opposing forces balance the kinetic energy in the sediments, or the sediment transport reaches a barrier, stream or a canal where further transport is impossible.

L is calculated as:

$$L = \left(\frac{\lambda}{S_l}\right)^m \tag{3.10}$$

where:

λ	Is the horizonthal projection of the slope in [m].
m	Is a variable slope length exponent.
S_l	Is the side length of the RUSLE model plot unit [22,13m after section. 3.4.2].

After documentation by Morgan and Renard (Morgan et al. 2011 ch. 8).

m is calculated:

$$m = \left(\frac{\beta}{1+\beta}\right) \tag{3.11}$$

where:

β	Is the slope-length exponent related to rill erosion by raindrop impact.

After documentation by Morgan and Renard (Morgan et al. 2011 ch. 8).

beta is calculated:

$$\beta = \frac{\left(\frac{sin\theta}{0{,}0896}\right)}{3,0 \cdot sin\theta^{0,8} + 0,56} \tag{3.12}$$

where:

θ	Is is the slope angle.

After documentation by Morgan and Renard (Morgan et al. 2011 ch. 8).

When run off, soil, land cover, and management conditions indicate that the soil is highly susceptible to rill erosion, the exponent (m) should be increased. This is true for steep, freshly prepared construction slopes. In cases where the soil is highly susceptible to rilling, doubling the value of β is advised. In conditions where inter-rill erosion occurs and in cases of consolidated soils without tillage, m should be decreased by halving the β value. On rangelands with smelt-water and on cultivated soils dominated by surface flow, the constant value of m = 0,5 should be used (McCool et al. 1989; McCool, George, and al. 1993).

3.4.5 S (Topographic steepness)

The Slope steepness factor was estimated empirically, the evaluation was conducted on a standardised plot unit of 22,13 m squared with 9% gradient (McCool et al. 1989; McCool, George, and al. 1993). However this testing methodology did not consider the many different terrain formations and topographic relationships. In fact, this simplification introduces a need to subdivide an area area into smaller plots if it has a multiple- or complex-slopes that meet. This can be visualised:

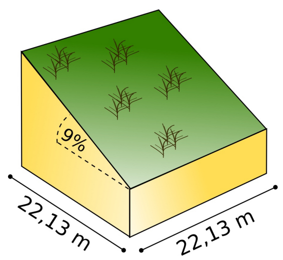


Figure 3.4: The plot on which determining the empirical effects of slope steepness was conducted, figure is own production.

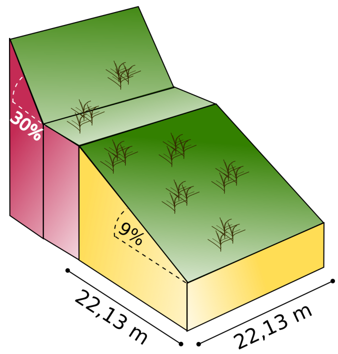


Figure 3.5: A more detailed plot, showing the limitations of the empirical research for determining the S-factor in RUSLE, figure is own production.

The topographic relationship is not described in RUSLE and must be integrated by using various GIS tools. This can be visualised by subdividing a case area into smaller blocks, each color represents a different gradient, the arrows represent the topographic connection and flow directions.

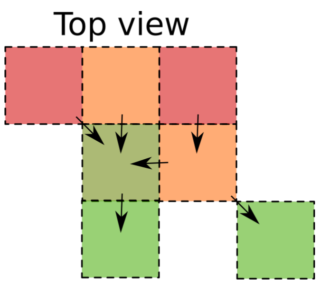


Figure 3.6: Various topographic relationships can occur on a single plot or a plot can be a part of a greater relationship, colors represent gradient and arrows represent flow directions. This figure is own production.

In section 3.4.3 several parameters used in determining the relationship between soil erosion and topography, were discussed. Three sets of equations for determining the effect of slope steepness has been introduced with the revisioned USLE model.

For slopes where run off isn't a function of slope steepness:

$$S = 10,8 \cdot sin\theta + 0,03 \tag{3.13}$$

where:

θ	Is the slope angle [θ <9%].

For use where the gradient is less than 9%, after documentation by Wishmeier, Morgan and Renard (Morgan et al. 2011 p. 144).

$$S = 16,8 \cdot sin\theta - 0,50 \tag{3.14}$$

where:

θ	Is the slope angle [θ >9%].

For use where the gradient is greater than 9%, after documentation by Wishmeier, Morgan and Renard (Morgan et al. 2011 p. 144).

$$S = 3,0 \cdot (sin\theta)^{0,8} + 0,56 \tag{3.15}$$

where:

θ	Is the slope angle where: [Slope Length <4,6 m].

For use where the slope length is less than 4,6 m, after documentation by Wishmeier, Morgan and Renard (Morgan et al. 2011 p. 144). Described in section 3.4.3.

Equation 3.15 furthermore applies to environments, where water can drain freely from the slope end. It is assumed, rill erosion is insignificant on short slopes and inter-rill erosion is independent of slope length.

For use when the soil has been freshly tilled and is thawing. Making it primarily subject to fluvial surface flow:

$$S = 10,8 \cdot sin\theta + 0,03 \tag{3.16}$$

θ | Is is the slope angle [θ <9%].

For use where the gradient is less than 9%, after documentation by Wishmeier, Morgan and Renard (Morgan et al. 2011 p. 144).

where:

$$S = (sin\theta/0,0896)^{0,6} \tag{3.17}$$

where:

θ | Is is the slope angle [θ >9%].

For use where the gradient is greater than 9%, after documentation by Wishmeier, Morgan and Renard (Morgan et al. 2011 p. 144).

A third set of equations is available for complex environments with multiple convex- or concave surfaces. These are rarely used and will not be discussed in this chapter, they can be found in *Handbook of erosion modelling 1st edition ch. 8* (Morgan et al. 2011 ch. 8).
In environments with heavy precipitation, Hudson and Jackson verified the effects of steepness to be greater than slope-length (Hudson and Jackson 1959). Later Gabriels confirmed this (Gabriels, Pauwels, and Boodt 1975). These studies found that slope-steepness and soil loss has a curvilinear relationship, that varies by the topographic concavity and convexity. Therefore McCool suggests the following:
It can be assumed that rill-erosion is insignificant on slopes shorter than 4,6 m (15ft), and that inter-rill-erosion is independent of slope length (McCool et al. 1989; McCool, George, and al. 1993). Wischmeier and Smith suggests that on slopes longer than 4,6 m, rill-erosion potentially can carry more run-off, therefore this should be taken into account (Wischmeier and Smith 1978;Morgan 1995 p. 35).

RUSLE evaluates the slope effect on runoff and erosion by mechanical disturbance in the C- and P-factors. These factors describe land cover, vegetation and support practice factor which includes tillage, terracing etc. The Soil loss estimation of topograhy increases more with steepness, than with slope length, therefore it is advised not to underestimate this (McCool et al. 1987).

3.4.6 C (Vegetation)

Soil erodibility (K-factor) is partially affected by Vegetation (C-Factor). The distinction between the two factors and the values used for each, can be difficult to determine precisely. However old crops and roots that has been tilled and is degrading underneath the top soil layer should be considered part of the Soil erodibility factor. Live plants and crops will be described in this section (Morgan 2005; Renard et al. 1997; Morgan et al. 2011).

The Vegetation factor (C) is derived as a measure of energy interception and dispersion. This value changes based on many environmental conditions. Time-variant and time-invariant effects are taken into concern when determining the C-factor, making it very complex to estimate (Clark Univeristy 2016). Vegetation acts as a protective layer between the atmosphere and the soil. Vegetation above ground buffers and shields the ground from falling raindrops, braking them, redirecting and dispersing their energy. Low vegetation and grasses add mechanical strength to the soil. Simulated experiments by Hudson and Jackson was conducted by suspending a wire guaze above bare soil, simulating plant material and roots. By exposing the soil to precipitation for a 10 year period, it was concluded that on fine particle soil the erosion went from 127 t/ha to 1 t/ha (Hudson and Jackson 1959). Similar experiments in Italy show a reduction in erosion over 6 years, from 46 t/ha to 4 t/ha, showcasing the importance of vegetation (Renard et al. 1997 ch. 5). However only a few researchers have investigated the importance of changes in land cover percent. Wishmeier and Smith sugested that soil erosion would scale exponentially to a linear change in Canopy cover, this was later veried (Wischmeier and Smith 1978; Morgan 2005).

The C factor is the same used in USLE and RUSLE, reflecting the effects of cropping and vegetation management practices on erosion rates. This factor can be used as a stand-alone parameter, but is frequently used as a comparison of the relative impacts of management options on conservation plans (Renard et al. 1997 p. 146). Renard describes this practice: *"The C-factor indicates how the conservation plan will affect the average annual soil loss and how that soil-loss potential will be distributed in time during construction activities, crop rotations, or other management schemes"*(Renard et al. 1997 p. 146).
Work by Wischmeier and Smith, and Mutchler, indicates that the efftect of vegetation is expressed by several factors, dividing the C-factor into several subfactors (Wischmeier and Smith 1978; Mutchler et al. 1982.

The following method is the method used within the RUSLE1 program developed by Wischmeier and Smith. This approach suggests that the important parameters are:

The impacts of previous cropping and management.

The protection offered by the vegetative canopy.

The reduction in erosion due to surface cover and surface roughness.

The impact of low soil moisture on reduction of run off from low-intensity rainfall.

These parameters is assigned a subfactor value. Together, these values yield an SLR value (Renard et al. 1997 p. 146). Individual SLR values is calculated for each time period where the parameters can be assumed to remain constant. These SLR values can then be weighted by using a fraction of the rainfall- and run-off erosivity EI-value. The weighted values are combined into an overall C-factor value for the case area.

$$SLR = PLU - CC \cdot SC \cdot SR - SM \tag{3.18}$$

where:

SLR	Is the soil-loss ratio for the given conditions.
PLU	Is the prior land-use subfactor, effects of residual crops.
CC	Is the canopy-cover subfactor.
SC	Is the surface-cover subfactor
SR	Is the surface-roughness subfactor.
SM	Is the soil-moisture subfactor.

After documentation by Renard (Renard et al. 1997 p. 150).

The PLU subfactor (prior land-use), expresses the influence on soil erosion from subsurface residual crops and the effects of previous tillage practices. PLU values ranges from 0 to 1.

$$PLU = C_f \cdot C_b \cdot exp\left(-(c_{ur} \cdot B_{ur}) + \left(\frac{c_{us} \cdot B_{us}}{C_f^{c_{uf}}}\right)\right) \tag{3.19}$$

where:

C_f	Is a surface-soil-consolidation factor.
C_b	Relative effectiveness of sub surface residue in consolidation.
B_{ur}	Mass of roots found in the upper inch of soil.
B_{us}	Is mass of incorporated surface residue in the upper inch of soil.
c_{uf}	The impact of soil consolidation on the effectiveness of incorporated residue.
c_{ur}	Is a calibration coefficient indicating the impacts of the subsurface residues.
c_{us}	Is a calibration coefficient indicating the impacts of the subsurface residues.

After documentation by Renard (Renard et al. 1997 p. 153). Work by Dissmeyer and Foster suggests different numerical values for different environments (Dissmeyer and Foster 1981).

The canopy-cover subfactor (CC) is a measure of the effectiveness of reducing the energy of rainfall by a vegetative canopy. Most rainfall braked by a canopy will however eventually reach the ground, but as previously described in section 3.3, the rain drops usually loses most of their energy. The canopy-cover subfactor is given by:

$$CC = 1 - F_c \cdot exp(-0,1 \cdot H) \tag{3.20}$$

where:

CC	Is the canopy-cover subfactor ranging from 0 to 1.
F	Is the fraction of land surface, covered by canopy.
H	Is the distance that raindrops fall after striking the canopy in [Kg].

After documentation by Renard (Renard et al. 1997 p. 157).

The Surface cover subfactor (SC), affects erosion by reducing the transport capacity of runoff water, by deposition in ponded areas, and by reducing susceptible surface area to raindrop impact (Foster and Ferreira 1981 pp. 185-197). The SC subfactor is in many cases the most important factor in determining the SLR values. Surface cover includes non-erodible material, rocks and plant residue. Surface cover is described by:

$$SC = exp\left[-b \cdot S_p \cdot \left[\frac{0,24}{R_u}\right]^{0,08}\right] \tag{3.21}$$

where:

b	Is an empirical coefficient.
S	Is the percentage of land with surface cover.
R	Is initial surface roughness in [in], just before a tillage operation.

After documentation by Renard (Renard et al. 1997 pp. 158-161). Several subequations is needed to calculate this parameter, these are not listed here.

The Surface roughness subfactor (SR) is a function of the surface random roughness. This is defined as the standard deviation of the small changes in surface elevations e.g. non random tillage marks like furrows and tractor tracks. A rough surface effects the run off by having many small barrier for it to pass. During rainfall, these potentially trap water and sediments, therefore rough surfaces erode at lower rates than flat and smooth surfaces (Morgan et al. 2011 ch. 8). These effects are described:

$$SR = exp(-0,66(R_u - 0,24)) \tag{3.22}$$

where:

R	Is initial surface roughness, just before a tillage operation in [cm].

After documentation by Renard (Renard et al. 1997 pp. 160-163).

The Soil moisture subfactor (SM) is defined as the antecedent moisture content (previous aggregated moisture content) for a case area. This subfactor can take different values based on the seasonal conditions and soil type. The SM-factor reflects the changing moisture contents during the seasonal cycle. Dryer fall conditions and more humid winther, spring and summer is taken into account together with root depth and soil depth. SM-values can be obtained from a table as suggested by Renard (Renard et al. 1997 p. 164 and p. 180).

The SM subfactor can generally be determined from figure 3.7, but typically, the SM value can be set to 1 where there is no erosion from light rain or thawing (Morgan et al. 2011 p. 146).

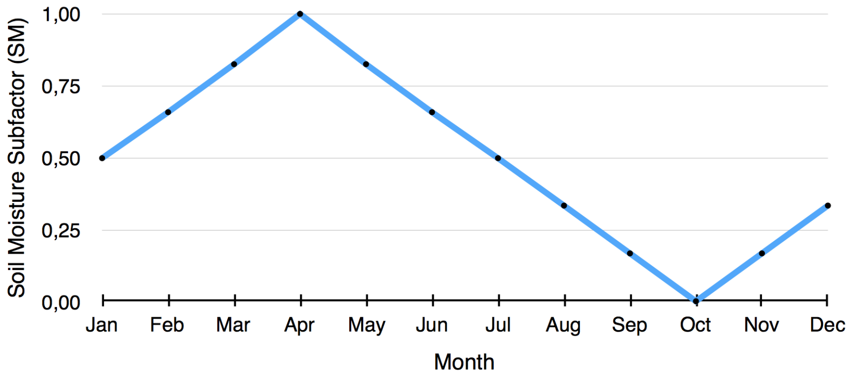


Figure 3.7: Figure of the Soil Moisture subfactor values determined from empirical research as suggested by (Renard et al. 1997 p. 180).

The final C-factor value is then determined by modelling each time-variant temporal event individually using the subfactor equations, and multiplying them together like described in equation 3.18. This leads to:

$$c = \frac{(SLR_1 \cdot EI_1, +SLR_2 \cdot EI_2 + ... + SLR_n \cdot EI_n)}{EI_t} \tag{3.23}$$

where:

SLR	Is the soil-loss ratio for the given conditions.
EI	Is an Erodibility index value for a given events conditions.

After documentation by Renard (Renard et al. 1997 p. 165).

The Vegetation (C) factor represents the effect on run off, from plants, soil cover (plant canopy), subsurface biomaterial and roots, and soil-disturbing activities such as tillage. Both time-variant seasonal changes in plant cover and soil moisture contents, and time-invariant changes (annual averages) are described by the C-factor. Supporting effects of practices like contouring, strip cropping, and terraces are not described here. Several of these Vegetation subfactors can be determined from predetermined tables generated from empirical research on the RUSLE test field. These tables and figures are however not part of this report.

3.4.7 P (Land use)

The land use P-factor can in some cases be difficult to separate from the vegetation factor (C), since both describe the impacts of different management

scenarios.
The P-factor is generally seen as the parameter that emphasises how the management scenarios can change the flow direction and velocity of surface run-off. However the amount of run-off is also part of this parameter, since small catchmnents created by surface roughness is partially determined by tillage and terracing. Traditionally the P factor was meant to be an assesment of impacts from agricultural practices, however the RUSLE1 program, introduced a sub-factor modelling approach for both the P-factor and the C-factor. These sub-factors seperate the effects of contouring, terracing, and subsurface drainage. Multiplied together they produce the overall P-factor value (Morgan et al. 2011 ch. 8).

With the RUSLE revision, the run off is evaluated with regard to sediment transport. This implies that sediments can be contained within run-off and is therefore not calculated as a biproduct with RUSLE. The P-factor is therefore becoming increasingly important, since the run off is influenced by the barriers landscaping introduces. There are four scenarios of deposition.

- There is no run off leaving a slope segment -> All incoming sediment is deposited.
- There is erosion throughout the segment -> No deposition within the segment.
- There is deposition throughout the segment -> All sediment is deposited.
- Deposition occurs at the ridge of the segment -> run off accelerates and erosion is therefore present at the bottom of the segment.

(Morgan 1995 p. 149).

The impacts of deposited sediment throughout a segment makes the P-factor somewhat subjective. The P-factor is meant primarily as a measure of soil resources. Because deposition of sediment does not preserve the soil resource, it is however often kept within the observed plot, preventing erosion in the first place will therefore always be more effective (Morgan 1995 p. 149).

The P-factor relies on subfactor estimations to obtain a P-value for the RUSLE equation.

The Contouring subfactor

$$P_g = P_o + (1 - P_o)\left(\frac{s_f}{s_l}\right)^{0,5} \tag{3.24}$$

where:

P_g	Is the P factor for off-grade contouring.
P_o	Is the P factor for on-grade contouring.
s_f	Is the grade along the contour furrow.
s_l	Is the slope grade.

After documentation by Renard and Morgan (Renard et al. 1997 p. 195; Morgan 1995 pp. 148-149).

Contouring is the process of tilling and strip-cropping perpendicular to the hill slope. This slows dows the run-off, but tends to lose effectiveness on very long slopes. This happens when run-off builds up behind the contour ridges until it overflows and picks up speed. The RUSLE program estimates a theoretical maximum slope length where contouring is effective, this value is references as the Critical slope length (Dissmeyer and Foster 1981). This parameter is therefore also partially dependend on the topography of the case area. The P-factor is then determined as a value of reduction of the erosion estimate for the critical slope length. This implies that only the upslope area is taken into concern in the P-factor, the downslope areas contribution to erosion reduction is therefore not estimated (Morgan 1995 p. 149).

The Strip-cropping subfactor

The RUSLE model, models deposition based on its location on the slope-segment, this is expressed:

$$P_s = \frac{g_p - B)}{g_p} \tag{3.25}$$

where:

P_s	Is the P factor for strip-cropping.
g_p	Is the potential sediment load that would occur if there was no deposition.
B	Is the benefit.

After documentation by Renard and Morgan (Renard et al. 1997 p. 195; Morgan 1995 p. 149).

B can be calculated:

$$B = M \cdot (1 - x^{1,5}) \tag{3.26}$$

where:

B	Is the benefit.
M	Is the mass of sediment deposited.
x	Is the location of the deposition as a fraction of the total distance downslope.

After documentation by Renard and Morgan (Renard et al. 1997 p. 195; Morgan 1995 p. 149).

The Terracing subfactor

Terracing works by breaking hillslope profiles into multiple shorter and flatter profiles, reducing erosion and causing some deposition to occur on the hill slope. This conserves the soil. RUSLE uses sediment yield data for terraces to estimate the amount of sediment deposition, this is done identically to the above strip-cropping subfactor (Morgan 1995 p. 150).

The above methods are all used within the official RUSLE program, however the P factor is often set equal to 1 (Jones, Kowalski, and Shaw 1996). Furthermore, it is like the C-factor, possible to derive the P-factor from a table based on empirical test data. If this method is used, the user should select the value according to the modelled environment (Morgan 1995 p. 67).

4 | Analysis

Denmark has experienced excessive amounts of phosphor in the water environments (Leek and Olsen 2000). In 2012 The Danish Government decided to implement "water plan 2012" which introduced a 10 m perimeter around all streams and lakes with a surface area above 100 m^2. These buffer zones were to be kept free of cultivation (Kronvang and Andersen 2012 and Kronvang et al. 2009 p.12). Danish ph.d. and professor at the Institute for Bioscience, at Aarhus University, Brian Kronvang explains the importance of these zones:
"With heavy precipitation or melting snow, the run-off water transports sediments with it. Phosphates, Nitrates and Potassium are bound to these sediments, therefore they are transported downhill potentially ending up in these water environments. Sheet- and Rill erosion are the primary causes of this. When the transport meets these buffer zones the process slows down, therefore wider buffers are more effective against pollution" (Kronvang 2016).

The introduction of buffer zones was based on the assumption that pollution and soil redeposition is far less complex than in reality (Kronvang and Andersen 2012). Because the transport of phosphor is a function of several parameters, topography, rainfall, soil types, vegetation and land use, the buffer zones would in some areas be too narrow allowing pollution to continue and in other areas be too wide, taking up valuable agricultural land. The buffer zones was a simple and in most cases a very cost effective solution implemented through national planning (Naturstyrelsen 2013; Nationalt Center for Fødevarer og Jordbrug 2003; Morgan 1995; Kronvang and Andersen 2012).

As of January 27th 2016, the Minister of Environment and Food of Denmark announced that the new water plan 2015-2021 would abandon the buffer zones. The "Randzonelov" was therefore withdrawn (Center for Landbrug, NaturErhvervstyrelsen 2016).

Erosion reducing initiatives has been researched by Brian Kronvang, Hans Estrup Andersen and others (Kronvang and Andersen 2012). Work by Kronvang suggests that removing the buffer zones could increase the totalt amount of phosphor in the water environments by 3 to 19 Tons pr. year. This estimation is backed up by international studies on the effects of buffers and domestic studies on rill-erosion from 1994 to 2001. Furthermore the changing climate- and precipitation patterns could potentially increase effectiveness of buffer zones (Kronvang 2016).

In chapter 3 modelling erosion was discussed. The above underlines the importance of understanding erosion patterns in Denmark. Denmark should be evaluated with regards to data availability and the quality of available datasets.

4.1 Data sources

Several sources of RUSLE ready data was evaluated, many of these only describe a single RUSLE factor, making them difficult to compare. In 2015 the European Joint Research Centre (JRC) and the European Soil Data Centre (ESDAC), published reports of their RUSLE research. These reports estimated each individual RUSLE factor for a complete soil loss estimation of the EU member countries. These datasets are described in this section to find if their data is comparable with the highest quality Danish data.
This European analysis is described here:

> www.esdac.jrc.ec.europa.eu/themes/rusle2015
> www.esdac.jrc.ec.europa.eu/resource-type/datasets.

(Panagos et al. 2015b, 2014b;Panagos, Borrelli, and Meusburger 2015; Panagos et al. 2014a, 2015a)

Rain data

Denmark has 66 rain measuring stations (Leek and Olsen 2000 pp. 61-62). These are primarily maintained by The Danish Meteorological Institute (DMI), and in some cases by local institutions and organisations. The data is distributed by DMI but is also available through institutions like DTU (the Danish Technical University) and SVK (The Danish waste water committee). The available datasets differ in temporal extent and frequency, however they are all organized in the same way. The data is distributed as .txt files but are not conformed to e.g. the CSV format, instead the data is arranged in rows and columns. Every row correspond to a precipitation measurement with a 1 minute interval. If no precipitation is measured the column value will be 0.

This means that data can be categorised for each event in between rows with zeroes. Several columns exist, rain intensity can be found by analysing the amount of precipitation pr. minute, amounts are listed in $\mu m\ s^{-1}$ (0,001 mm) this value should be divided by 0,277 or (1000/3600) to get the value in mm h^{-1}. This leads to the total kinetic energy for a given event and the amount of rain gathered. Every event should be analysed and summarized for each year in a 20 year period, this finally yields the R factor value, calculated after equation 3.4.
In 2015 Denmark was evaluated as part of a European RUSLE R-factor research project. This study included the danish researcher Preben Olsen from "Department of Agroecology - Soil Physics and Hydropedology" at Aarhus University. The study was published in 2015 and included detailed raster geo-datasets with a spatial resolution of 1 km^2 (Panagos et al. 2015b). This study utilized all 66 rain measuring stations in Denmark and used least squares linear interpolation to populate the raster in between the measuring stations.
However several points of criticism was expressed:

> The neglect of seasonal erosion indices.
> The low temporal resolution of the data.
> The use of precipitation data instead of rain data in Germany and Austria.
> The differences in temporal resolution between countries.

(Aarhus University 2016; Meusburger et al. 2012).

The above was addressed by the authors, who replied that no current R-factor evaluation has implemented seasonal indexes yet, furthermore the authors indicated that they did indeed use the highest temporal resolution datasets available for the study. Lastly the low R-factor values in Germany and the higher values in Austria (compared to previous studies) was caused by the interpolation method used in the project and not by miscalculations. Using interpolation across the Austrian borders could potentially lower the values of Austria (Aarhus University 2016).

None of the above suggests that the Danish R-factor evaluation could represent miscalculated values. The JRC evaluation furthermore uses the most recent and highest quality Danish data, this should furthermore ensure validity (Renard and Freimund 1994). The data implies a maximum short burst storm rain intensity of 162 mm h^{-1}, and a maximum I30 intensity of 44,3 mm h^{-1} with a standard deviation of 0,99 mm h^{-1}, all values from 2015. These data are presented in Appendix R.

To calculate the R value, the amount of rain in mm and the temporal length should be summarized for every event, creating monthly averages and averaging these on a yearly basis. According to section 3.1 the data should be evaluated for a period of 20 years.

> Rain datasets are available from SVK.
> www.svk28.env.dtu.dk/welcome.htm
> The rain data by (Panagos et al. 2015b) are available from ESDAC.
> www.esdac.jrc.ec.europa.eu/content/rainfall-erosivity-european-union-and-switzerland

The JRC R factors was partially calculated using the RIST tool (Rainfall Intensity Summarisation Tool) created by the USDA (United States Department of Agriculture) (Panagos et al. 2015c). The R-factor data are freely available, however access is only granted after an application describing the intentional uses of the data has been filed through their website.

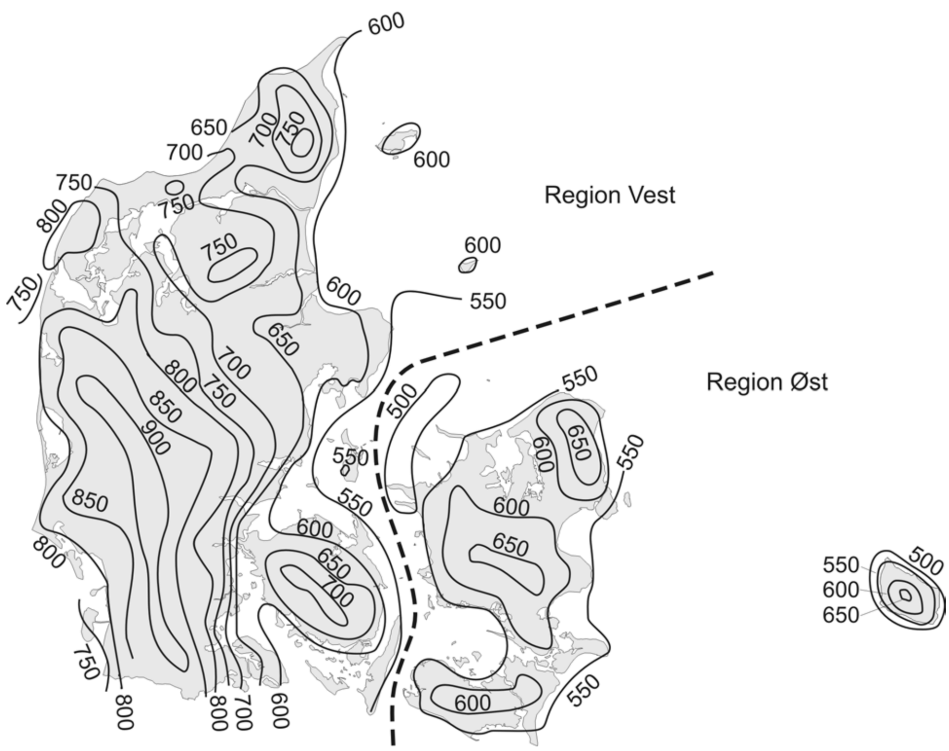


Figure 4.1: Figure of rain in mm pr. year (Spildevandskomiteen 2006 p. 18).

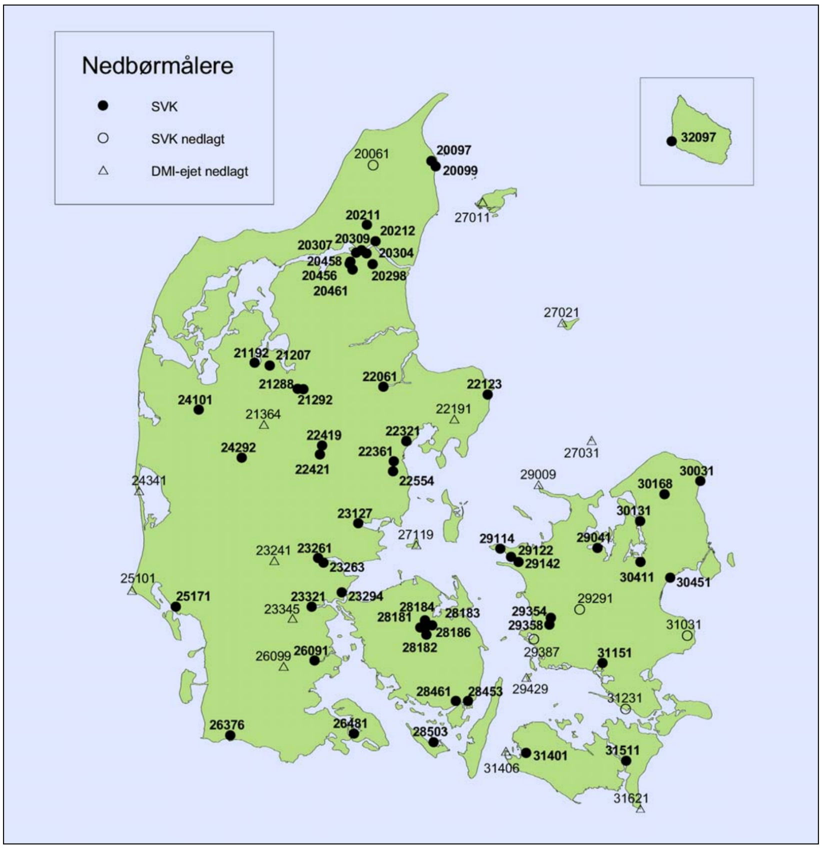


Figure 4.2: Figure of precipitation monitoring stations in Denmark (Nielsen and Cappelen 2005 p. 9).

Soil erodibility

Soil texture, organic content, structure, and permeability determine the erodibility of a particular soil. However several other factors are also indirectly affecting the soil erodibility, this includes mechanical processes like tillage and terracing, described by other RUSLE factors (Greve et al. 2013; Renard et al. 1997;Morgan 1995 pp. 29-34). Rill- and Sheet-erosion are the most common types of soil erosion.
The K-factor is a measure of soil loss pr. unit of R-factor, to determine the soil erodibility the volume and mass of eroded soil is plottet for a precipitation event. This way the K-factor can be expressed for each scenario in a nomograph (Renard et al. 1997). Annual averages of soil erosion is aggregated over longer temporal periods, creating the parameter used in RUSLE.
The K factor represents both susceptibility of soil to erosion and the amount and rate of run-off and can be determined mathematically or by using a nomo-

graph. If possible it is recommended to calculate the K-factor mathematically. Typically table 3.2 can be used to determine the K-factor if a quick assessment is needed.

The Mathematical approach was discussed in section 3.4.2, and equation 3.8, the basic idea is to calculate the K-factor based on the percentages of different elements in the soil composition.
Soil data from GEUS and DJF are not freely available, data from The Danish Agrifish Agency is free but the dataset does not include soil granularity needed for the analysis. However these data was used in conjuntion with LUCAS satelite data to calculate a European K-factor. This work led to an available raster dataset with a spatial resolution of 500 m (Panagos et al. 2014b). These data are available from the JRC and has a standard deviation of 0,009 (Panagos et al. 2014b). The data is presented in Appendix K.

> Data from GEUS, DJF and The Danish Agrifish Agency.
> www.geus.dk/DK/data-maps/Sider/j25-dk.aspx
> www.djfgeodata.dk/datasaml/index.html
> www.jordbrugsanalyser.dk/webgis
> The JRC erosivity data is available from ESDAC.
> www.esdac.jrc.ec.europa.eu/content/soil-erodibility-k-factor-high-resolution-dataset-europe

The K-factor data are freely available, however access is only granted after an application describing the intentional uses of the data has been filed through their website.

Topographic Length & Steepness

The RUSLE topographic-length and -slope factors are often denoted as one topography based RUSLE factor (LS). The equations used for determining these factors was described in section 3.4.3. To ensure a good estimation of erosion, detailed topographic patterns should be visible in the analysed DEM datasets. Such analysis was conducted by JRC and ESDAC researchers in 2015 for the European Union. This led to the availability of a EU wide LS factor estimation. This dataset is described in a article published by geosciences magazine and a repport published by JRC (Panagos, Borrelli, and Meusburger 2015).
The DEM used for the analysis was the current highest resolution dataset with complete coverage of the EU member countries. However several National Agencies has available local datasets with a higher resolution. The Danish Geodata Agency has been acquiring new LiDAR (Light Detection And Ranging) data from aerial laser scannning. This data has a raster resolution of 0,4m which is 62 times denser than the 25m resolution dataset used in this study

(Panagos, Borrelli, and Meusburger 2015; Geodatastyrelsen 2015b).

The LS-factor has been calculated using the high-resolution 25 m DEM with a vertical RMS error of 2,9 m. The study used multiple hydraulic flow algorithm found in the SAGA GIS software, previously the LS-factor was calculated by (Bosco et al. 2015) using a 100m DEM. Visual comparison and analysis of the two datasets indicate that a 16 times increase in resolution resulted in a very different outcome. *"Using a DEM at this scale (25m) for the whole European Union is a significant improvement on past assessments that used 100 m DEMs due to higher input data accuracy, multiple flow algorithm implementation and better representation of the landscape."* (Panagos et al. 2015b p. 124). Overall this new study is able to better capture complex topography and geomorphological changes, leading to a better estimate of soil erosion. The 2015 JRC article specifies a standard deviation of 0,34 for Denmark. (see table 4.1)and a mean LS-value of 0,32 (Panagos, Borrelli, and Meusburger 2015 p. 122).

Country	Mean LS	Standard deviation	Coefficient of variation
Netherlands	0.19	0.20	1.05
Estonia	0.32	0.31	0.96
Denmark	0.32	0.34	1.07
...			
Austria	5.20	5.91	1.14

Table 4.1: LS factors for the EU-countries, Top 3 lowest-value countries and the highest-value country (Panagos, Borrelli, and Meusburger 2015 p. 122).

The LS dataset is available through:

> The JRC topographic data is available from ESDAC.
> www.esdac.jrc.ec.europa.eu/content/ls-factor-slope-length-and-steepness-factor-eu

The LS-factor data are freely available, however access is only granted after an application describing the intentional uses of the data has been filed through their website.

These data is presented in Appendix LS.

Vegetation & crops

The cover-management factor (C) is by many considered the RUSLE subfactor that is the most important real-life parameter in reducing soil loss. This RUSLE paramenter is the only element that can be altered and modified by policy-makers, local governments and farmers at reasonable cost to prevent soil erosion in arable lands. This also prevents the loss of nutrients and polluting particles. Local governments can directly affect the erosion patterns by implementing legislation that eliminates or introduces certain plants or crops. Both the C-, K- and P-factors are in many cases hard to separate numerically, making them hard to determine precisely. This is due to the very complex natural- and mechanical processes of plant-compostation, composition and tillage. Soil erodibility (K) is partially affected by Vegetation (C). Moisture- and biomass contents and granularity of the soil are some of the main working elements in erodibility. Furthermore tillage mixes and distributes plant material and other substances with the soil. As described earlier RUSLE evaluates these parameters separately but they should be considered collectively (Morgan 2005; Renard et al. 1997; Morgan et al. 2011).

The Vegetation factor (C) is derived as a measure of energy dispersion (Clark Univeristy 2016). Above ground vegetation acts as a buffer between precipitation, rain and the soil. This shields the soil from the main impact, however smaller droplets will still act on the soil, therefore erosion is not completely stopped. The C-factor is the same used in both USLE and RUSLE and is frequently used as a comparison of the relative impacts of management options on conservation plans (Renard et al. 1997 p. 146).
This is the reason many governments and researchers have been investigating the effects of different crops and buffer-zones without cultivation. The local governments of the European Union determined that a new pan European research committee should investigate the EU for areas where legislation could help reduce soil loss. This led to the research papers and repport *"Estimating the soil erosion cover-management factor at the European scale"* (Panagos et al. 2014a).

In previous pan European studies, static C-factor estimations where used across Europe, typically 0,2 or 0,335. The new study implements a new approach based on high resolution aerial imagery and regional land use records. This has been named LANDUM.
The C-factor evaluates prior land use, canopy cover, surface cover, surface roughness and soil moisture levels (Panagos et al. 2014a). The LANDUM approach uses different techniques to estimate these sub-factors.

- NDVI, normalized difference vegetation index and general image classification.
- Literature reviews and statistical data on agricultural management practices combined with field trips.

The main objective of this study was determining and estimating the cover-

management factor based on the best- and highest resolution data available, combined with literature and statistical analysis at a national scale for all 28 EU member countries.
This approach left other management-related practices and contour farming, terracing and strip cropping to be evalutated by the P-factor (Renard et al. 1997). The study analysed data from 1990, 2000, 2006 and 2014, 24 years of CORINE data and 10 years of MERIS data (MEdium Resolution Imaging Spectrometer). The data had spatial rasterized resolutions between 100m and 300m. The agricultural statistical data originated from Eurostat and was created using the NUTS (Nomenclature of Territorial Units for Statistics) method on FSS data (Farm Structure Survey). NUTS classifies European areas by population density and summarizes statistics for an area within a threshold. This method summarizes sparsely populated areas within a larger area, potentially lowering the data quality in these areas.

The study led to several detailed raster datasets depicting the C-factor and the effects of vegetation on both arable lands and non-arable lands. Denmark was found to have the highest amount of arable lands, 77% (Panagos et al. 2014a p. 45). The findings of the study did not include wetlands, water bodies, bare rocks, beaches and glaciers. Data will be presented in Appendix C.

> European soil erodibility datasets was obtained through ESDAC.
> www.esdac.jrc.ec.europa.eu/content/cover-management-factor-c-factor-eu

The C-factor data are freely available, however access is only granted after an application describing the intentional uses of the data has been filed through their website.

This dataset specifies a standard deviation of 0,1046 with a minimum C-value of 0,0001 and a maximum of 0,526. The highest individual mean C-factor value was found in Denmark, Hungary, Malta and Romania, indicating larger arable land areas. Denmark and Hungary was also found to have the highest percentages of arable lands (Panagos et al. 2014a p. 48). Furthermore the data used in the study suggested that land-use composition of Denmark, primarily consisted of 18,9% complex cultivation, 17,4% agricultural- and natural land and 40% sparse vegetation totalling 76,3% the rest was infrastructure, urban and suburban areas.

n	Crop type	Share (%) of the total arable land (EU-28)	C-factor
1	Common wheat and spelt	28.5	0.20
2	Durum wheat	3.2	0.20
3	Rye	3.0	0.20
4	Barley	14.8	0.21
5	Grain maize – corn	12.9	0.38
6	Rice	0.6	0.15
7	Dried pulses (legumes) and protein crop	1.9	0.32
8	Potatoes	2.4	0.34
9	Sugar beet	3.1	0.34
10	Oilseeds	5.8	0.28
11	Rape and turnip rape	8.1	0.30
12	Sunflower seed	4.8	0.32
13	Linseed	0.1	0.25
14	Soya	0.5	0.28
15	Cotton seed	0.4	0.50
16	Tobacco	0.1	0.49
17	Fallow land	9.8	0.50

Figure 4.3: Crop types, and C-factor per crop type and area, originates from *"Estimating the soil erosion cover-management factor at the European scale.pdf"* (Panagos et al. 2014a).

Support practice factor

The six parameters of RUSLE have several overlaps in reality, the P-factor is described as the most uncertain of the six (Renard et al. 1997). The P-factor accounts for several physical boundaries, defined both by nature and by mechanical processes such as tillage, terracing and topographic formations. Furthermore stone walls and hedgerows are also interfering with the sediment transport and soil erosion patterns. These should therefore also be part of the model.
Human influences are also a big part of reducing soil erosion. All farmers within the EU must conform to the GAP policy of 2012 and the GAEC policy, (Good Agricultural and Environmental Conditions) defined by the MARS project (Monitoring Agricultural ResourceS). These specify that a farmer is responsible for good agricultural practices and should strive to decrease soil loss and erosion (Panagos et al. 2015a). Different farming practices can however vary greatly even within the EU, therefore there is no definitive strategy to accommodate these goals.

Data for calculating the P-value can be derived from several sources including image classification by remote sensing. Another approach is to use data

from previous studies. In 2015 remote sensing data and data from the LUCAS database was used to analyse the extent of different farming practices and stonewalls. The study also included national data about buffer zones (Panagos et al. 2015a). Several other studies have successfully used object-oriented image analysis (OAA) and Sobel filters to identify physical boundaries and obstacles (Panagos et al. 2012). However such classification process is heavily dependant on high resolution imagery which can be very expensive. The new Danish height model (DEM) could maybe be used for the same process in the future, however this report will not seek to answer this question.
The LUCAS database builds on surveyor data from 2012, which included local ground observations from 270.000 observation points. These surveys included local imagery and landscape observations. The data density of the LUCAS database is 1 observation for every 16 km^2. These data was densified by Inverse Weighted Distance regression (IWD) and Ordinary Kriging (OK) (Panagos et al. 2015a p.28).
The contouring subfactor was determined from a DEM with 25m raster grid resolution. However this evaluation concluded that Denmark has close to zero contouring, probably caused by our "rolling hills" and lack of steep descends.
The study concludes that the most effective boundary is an opposing hill to a downhill flow pattern, a such feature obtains a P-factor value of 0,2. Furthermore the study indicated that 57% of the P-factor value reduction were caused by buffer zones, stone walls only accounted for 38%. This could furthermore serve as proof to the effectiveness of the Danish "Randzonelov".
The average area corrected P-factor value of the EU was determined as 0,9702, Denmark were 0,9843. The United Kingdom (UK) has the lowest value of 0,9528, which was heavily affected by their countless stone walls (Panagos et al. 2015a pp. 29-30). From the data it can be concluded that only Belgium, The Netherlands and The United Kingdom has more buffer zones compared to Denmark in 2012. These data will be presented in Appendix P.

> European support factor datasets was obtained through ESDAC.
> www.esdac.jrc.ec.europa.eu/content/support-practices-factor-p-factor-eu

The P-factor data are freely available, however access is only granted after an application describing the intentional uses of the data has been filed though their website. Distributed as raster format with 1km grid resolution with a standard deviation of 0,0847.

4.2 Summary

The many RUSLE subfactors makes RUSLE hard to use in many scenarios. Furthermore, this possibly creates a very complex model that is hard to verify properly. The use of pre-compiled data is therefore the most time effective method of reproducing a result based on RUSLE. This might however not be the most accurate in every situation, perhaps making it a limiting factor for those who are looking for a quick assessment.

4.2.1 Sensitivity

RUSLE is a composite function of several linear and non-linear equations, this makes RUSLE non-linear. This can be proven by inputting several equally spaced simple numerical values and checking if the outputs are equally spaced. The input data sources described above, yields pre-calculated statistical values for the standard deviations $\sqrt{Var}$. To check the sensitivity of the RUSLE output based on these datasets the composite variance should be found. To find the composite variance of RUSLE it can be assumed that this equals the variance of a series of independent variables:

$$\sigma^2 = a_1^2\sigma_1^2 + a_2^2\sigma_2^2 + \ldots + a_n^2\sigma_n^2$$
$$\Downarrow$$
$$\sigma_A^2 = R^2 \cdot \sigma_R^2 + K^2 \cdot \sigma_K^2 + L^2 \cdot \sigma_L^2 + S^2 \cdot \sigma_S^2 + C^2 \cdot \sigma_C^2 + P^2 \cdot \sigma_P^2$$
$$\Downarrow$$
$$\sigma_A^2 = R^2 \cdot 0,99^2 + K^2 \cdot 0,009^2 + LS^2 \cdot 0,34^2 + C^2 \cdot 0,1046^2 + P^2 \cdot 0,0847^2$$

The Variance indicates the average distance of the data in the distribution from the mean value (μ). The value is a method of observing how the dataset is distributed. A dataset where the data is very close around the mean value has a low variance, indicating smaller fluctuations in the data. If the variance is a product of several independent measurements it can serve as a measure of the general quality of the data. However the datasets are not created on the same base data or with the same procedure, therefore the variance is not directly comparable between datasets.

All of the above indicates that datasets, R, LS and C has the widest spanning data, this could be seen as proof of larger errors within the data. These datasets should be investigated further with regards to their use in Denmark. However the datasets R and C are already based on the highest resolution and quality data available. Therefore the LS factor has the highest potential of improvement, potentially resulting in more accurate RUSLE assessments for Denmark. This data should be remodelled based on the more recent high quality national topographic data. This will be explored in section 4.3.

4.3 Case Area

The new Danish DEM is based on LiDAR laser scanning. The new survey, will result in a dataset consisting of 180 mio. points, the previous available dataset had 20 mio. points. This diffence is equal to a DEM with 4-5 points pr. m^2, allowing the finished dataset to have a 16 times increase in horizontal resolution and 2 times the vertical accuracy. The new DEM data has a GSD of 0,4 m, with a horizonthal accuracy of $\pm$0,15m and a verified vertical RMS accuracy of $\pm$0,05m (Geodatastyrelsen 2015b, 2015a).
The data required for operating the model is extensive, taking up large amounts of space and processing power. Model-run-time is also increased with the amount of data evaluated, therefore a smaller area will be investigated. This allows different model- and data setups to be evaluated without needing to keep the RUSLE algorithm running extensively.

Criteria for the case area:

> Should be covered by the new Danish DEM.
> Should consist primarily of both arable and non-arable land.

A suitable case area is located using GIS software. Land-use should be investigated to find areas most fitting with the RUSLE algorithm, to ensure validity from the model. Furthermore the case area should be available as a subset of the DEM model. The DEM has been split into square subsets with 10 km sides following the outline of the Danish "kvadratnet" (a 100 km^2 national grid pattern). RUSLE should be investigated in a rural area consisting mostly of farmlands, therefore a suitable case area should be determined from the amount of agricultural land within a DEM square. This was accomplished by:

- Import the Danish "kvadratnet".
- Import land-use data from the Danish Agrifish Agency. Data is available as WMS, WFS services and downloadable .SHP files.
- Cut the land-use data using the grid pattern.
- Calculate field geometry size "area" for every field in the land-use dataset.
- Intersect the two layers.
- Summarize the amount of fields within a grid cell and sum the field geometry values.

- Locate the top 10 cells, with highest agricultural area.

Data was acquired from:

> GEUS *www.geus.dk/DK/data − maps/Sider/j25 − dk.aspx*
> DJF *www.djfgeodata.dk/datasaml/index.html*
> The Danish Agrifish Agency *www.jordbrugsanalyser.dk/webgis*
> The Danish Geodata Agency *ftp.kortforsyningen.dk/dhm_danmarks_hoejdemodel/*

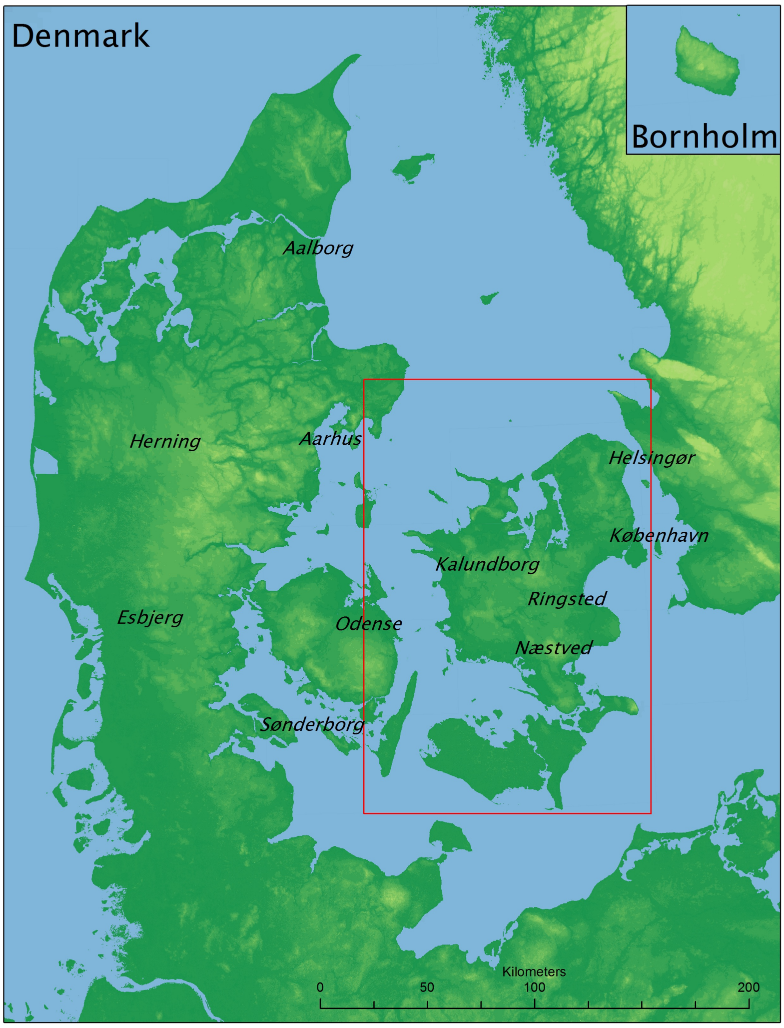


Figure 4.4: The extent of the new Danish DEM dataset Q1 2016, Background map is OSM Topographic WMS.

The technical data acquisition has not been completed for western Denmark as of the first quarter of 2016, therefore the spatial extents of the completed DEM dataset is used as the boundary of the land-use data.
The analysis found 10 cells of interest based on agricultural land, especially the area between Ringsted, Næstved and Sorø municipalities was found suitable for this analysis. The most suited case area is just west of Næstved, located within the DEM subset "DTM_612_66_TIF_UTM32-ETRS89".

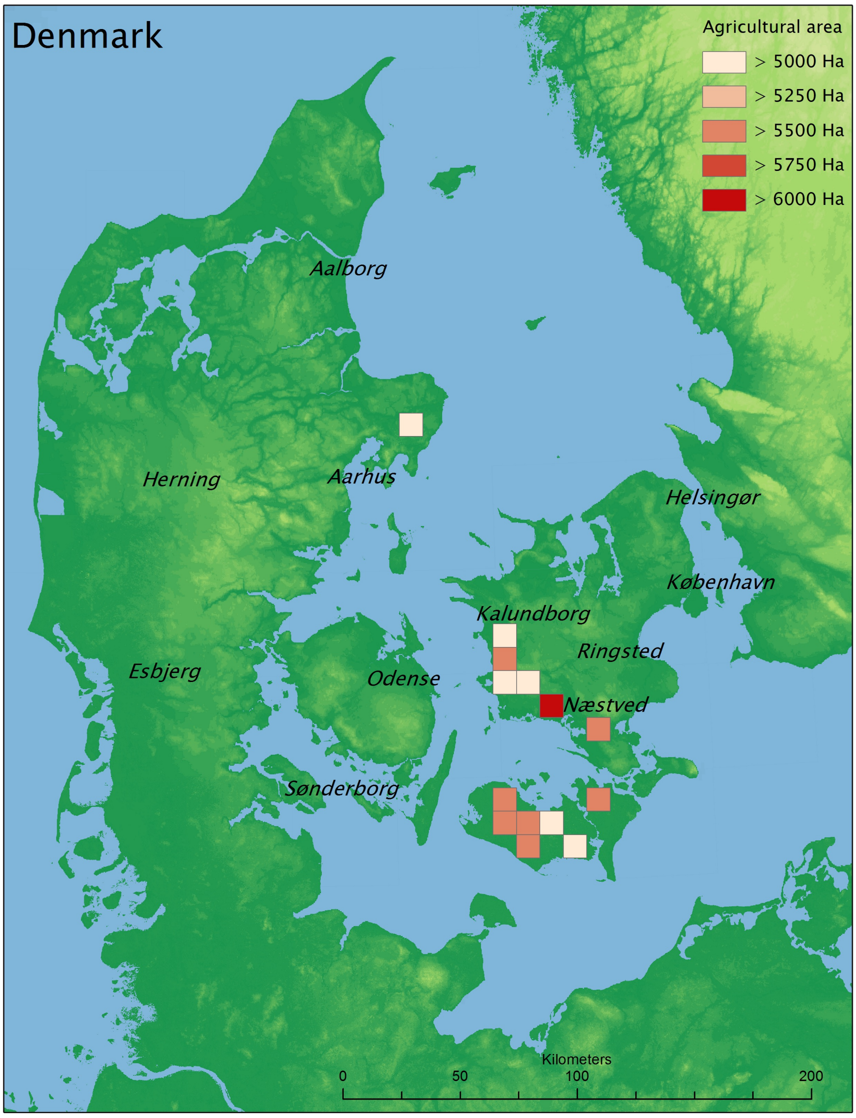


Figure 4.5: The 10 cells from the Danish "Kvadratnet" with the highest agricultural area, the background map is OSM Topographic WMS.

Furthermore the case area has a low percentage of:

> Forests and deciduous areas (~4% or 394,24 Ha)
> Infrastructure (~2% or 189,68 Ha)
> Towns (~2% or 145,02 Ha)
> The remaining areas are open- and fallow fields.

These values were obtained by simple GIS analysis on the GeoDanmark FOT datasets.

4.4 Creating a Danish LS factor

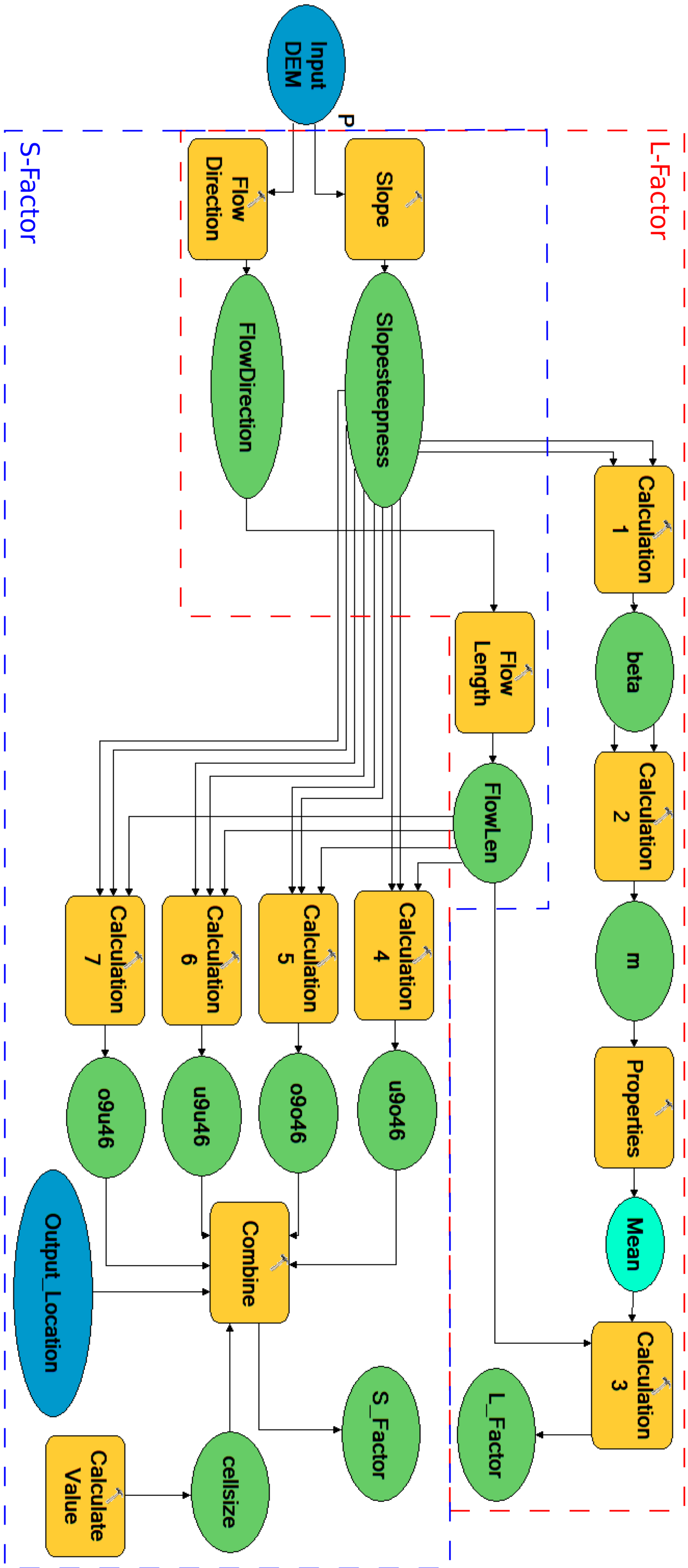
In the previous section a case area was found. This section seeks to analyse the effects of using a high resolution DEM in erosion modelling scenarios. This is determined by analytical comparison between a newly established erosion estimate for the European Union, created by The Joint Research Centre, Institute for Environment and Sustainability and by calculating an L- and S-factor based on the new Danish DEM model. The JRC dataset serves as a baseline for the comparison. The L- and S-factors were calculated using the mathematical formulas described in section 3.4.3, using the data described in section 4.1 and 4.3.
The calculations were performed using the Esri ArcGIS software suite and were developed using the ModelBuilder application, which is an application that automates the creation and visualisation of Python scripts using the Esri ArcPy library.

Disclaimer: ***All figures will also be presented in Appendix A.***

Model Legend

Blue	Data source, input to the model.
Yellow	Process.
Green	Process output.
Turquoise	Temporary output.

Legend describing the coloration of the visual model layout



The complete L- and S-factor model is visualized.

The JRC Dataset is not published as separate L and S factors, instead they are presented in a single dataset, with a single statistical denominator. A comparison of this value is therefore not possible between L factors and S factors, but should be analysed LS- to LS-factor. Furthermore, there exists several differences between the modelling processes for the datasets. The JRC investigated different processing engines for their LS factor, they settled on the hydraulic toolbox found in SAGA GIS, which is part of the underlying framework in QGIS. This choice was purely based on processing speed (Panagos, Borrelli, and Meusburger 2015). Furthermore the JRC team implemented a scalable λ-length value of several fixed values based on the slope of the hill, λ=0,5 for slopes $>$ 5% and 0,2 for slopes $<$ 1%. These values were interpolated between 1% and 5%, this approach requires less calculations, which can save time on large datasets, however this can be less precise. The procedure is described by Liu et al. 2000 and Panagos, Borrelli, and Meusburger 2015 (Panagos, Borrelli, and Meusburger 2015 and Liu et al. 2000 p. 1759).

To compare these model outputs, analysis on raster cell-value level and differences in Minimum, Maximum and Mean values will be described.
This section will walk through the elements of the model and discuss the decisions and logic of the model. The model will be described as two separate independent models the L-part and the S-part. Multiplied together they will form the LS-factor on which this analysis is based.

4.4.1 Modelling the L-factor

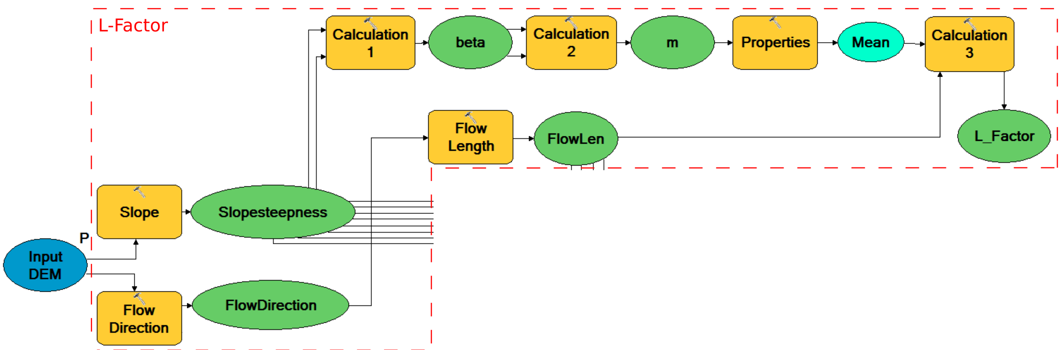


Figure 4.6: The L-factor part of the model.

Input DEM

The first **blue** element in the model, specifies the Input location of the DEM. Before importing the DEM in the model, the user should make sure that the DEM is cut to the correct size of the case area.

Slopesteepness

This yellow model element indicates that a process is being executed. In this case the Slope of every single raster cell is calculated:

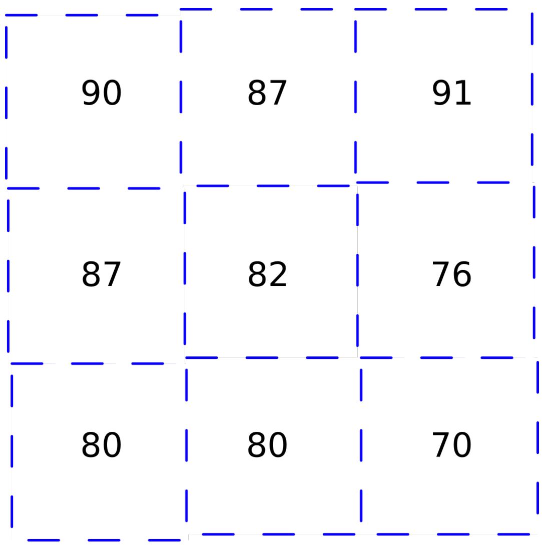


Figure 4.7: A visual representation of several raster cells and their values.

Each cell value is evaluated with regards to its neighbours and the slopes are calculated:

$tan(\measuredangle) = \frac{a}{b}$

$\Downarrow$

$tan(\measuredangle) = \frac{\Delta cell\ value}{horizontal\ distance}$

The output is a new raster with the same spatial extent and resolution but the cell values are now the slope angles to each cell from its neighbours in degrees θ.

beta

This yellow raster calculation model element, outputs the value of beta. this is done with simple mathematical algorithms executed for each individual raster cell:

```
(Sin("%Slopesteepness%"/57.295779513)/0.0896)/(3*Power(Sin("%
    Slopesteepness%"/57.295779513),0.8)+0.56)
```

Here the value 57,295779513 is the conversion factor $sin(\theta/(180/pi))$. This is needed because the ArcGIS environment only uses radians. The rest of the equation is identical to that in equation 3.12. The Power(a,b) command sets value b as the exponent to value a (a^b).

m
This yellow raster calculation model element, outputs the value of m. this is done with simple mathematical algorithms executed for each individual raster cell. The equation is identical to that in equation 3.11.

```
"%beta%"/(1+"%beta%")
```

Properties
This yellow raster calculation model element outputs a single value of **the Mean m value**. The mean m value is used to flatten out some of the great differences caused by the many changes in cell values. This is needed because the high resolution DEM has a tendency to show every little detail which is creating "noise" in the output.

Flow Direction
This yellow model element indicates that a process is being executed. In this case an 8-bit value indicating the Flow Direction of every single raster cell is assigned.
Each cell value is evaluated with regards to its neighbours and the Flow directions is calculated. If there exists several flow paths from a cell, the cell value will be a numeric composite of the values of the flow directions. This is seen by the red arrows that indicate flow direction and the numeric value which represent the sum of the three directional values. This is seen on figure 4.8.

Flow length
This yellow model element assigns a numerical value indicating the Flow Length to every single raster cell. Each cell value is evaluated with regards to its neighbours and the Flow Length is calculated by counting the amount of cells along a flow path, this number multiplied by the cell size and a flow direction angle

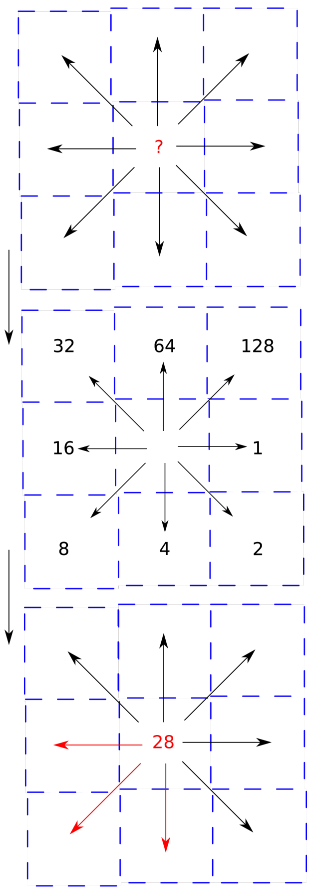


Figure 4.8: A visual representation of several raster cells and their flow direction values.

correction, is then assigned to each cell.

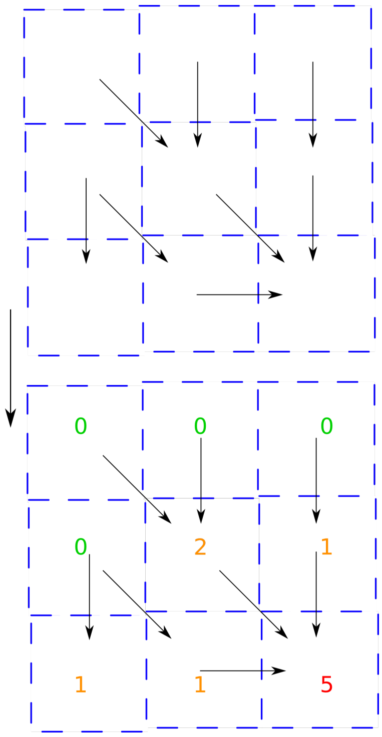


Figure 4.9: A visual representation of several raster cells and the flow length to them.

L

This Yellow final L-factor raster calculation element, outputs the value of L. This is done with a simple mathematical algorithm executed for each individual raster cell:

```
Power("%FlowLen%"/22.13,float("%Mean%"))
```

The equation is identical to that in equation 3.10.

4.4.2 Modelling the S-factor

For calculating the S-factor, the **Input DEM**, **Slopesteepness** and **Flow Direction** is the same used for calculating the L-factor, see section 4.4.1.

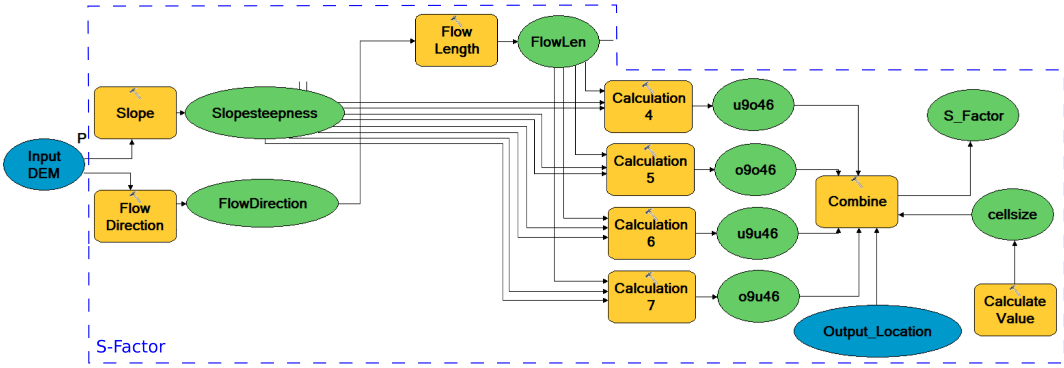


Figure 4.10: The S-factor part of the model.

S

The yellow S-factor raster calculation element combines the values of four parameter based S-factor calculations. These four raster calculations are based on the three equations found in section 3.4.5.

$S = 10,8 \cdot sin\theta + 0,03$	used on slopes above 9%	Equation 1
$S = 16,8 \cdot sin\theta - 0,50$	used on slopes below 9%	Equation 2
$S = 3,0 \cdot (sin\theta)^{0,8} + 0,56$	used on slopes shorter than 4,6 m	Equation 3

These three equations can be written as four algorithms:

θ <9% AND L>4,6 m	denoted u9o46	Equation 1
θ >9% AND L>4,6 m	denoted o9o46	Equation 2
θ <9% AND L<4,6 m	denoted u9u46	Equation 3
θ >9% AND L<4,6 m	denoted o9u46	Equation 3

u9o46

```
Con(("%Slopesteepness%"<5.15) & ("%FlowLen%">4.6),(10.8*Sin("%
    Slopesteepness%"/57.295779513))+0.03,)
```

o9o46

```
Con(("%Slopesteepness%">5.15) & ("%FlowLen%">4.6),(16.8*Sin("%
    Slopesteepness%"/57.295779513))-0.5,)
```

u9u46

```
Con(("%Slopesteepness%"<5.15) & ("%FlowLen%"<4.6),3*(Power(Sin("%Slopesteepness%"/57.295779513),0.8)+0.56),)
```

o9u46

```
Con(("%Slopesteepness%">5.15) & ("%FlowLen%"<4.6),3*(Power(Sin("%Slopesteepness%"/57.295779513),0.8)+0.56),)
```

The Con(a,b,c) statement evaluates statement (a), if TRUE statement (b) is returned, ELSE it returns c which in the above case is null. Null values are better when merging the 4 rasters in the next step. The & symbol is the boolean notation for AND. Again the value 57,295779513 is the conversion factor $sin(\theta/(180/pi))$. This is needed because the ArcGIS environment only uses radians. Furthermore a steepness of 9% is equivalent to a slope of 5,15 degrees, which is needed because the slope steepness algorithm output is in degrees.

Combine

Takes several parameters, **output location**, **cell size** and **the four raster algoritm** outputs. This reveals the final S-factor dataset based on a "mosaic operator" set to MAX, this ensures that if two of the above four datasets has calculated a value for the same cell, the largest cell value will be kept. This ensures that the S-factor value represents a worst case soil erosion scenario, however this implementation has been tested and in zero cases has there been an overlapping cell with this approach.

4.5 Output

The above approach results in two datasets based on the new Danish DEM, these are combined after equation 3.13. As specified the new Danish DEM dataset has a GSD of 0,4m. However this value has been upsampled to 1m, 10m, and 25m resolutions and the LS-factors has been calculated for each, resulting in several interesting observations, visible on figure 4.11 and in Appendix A.

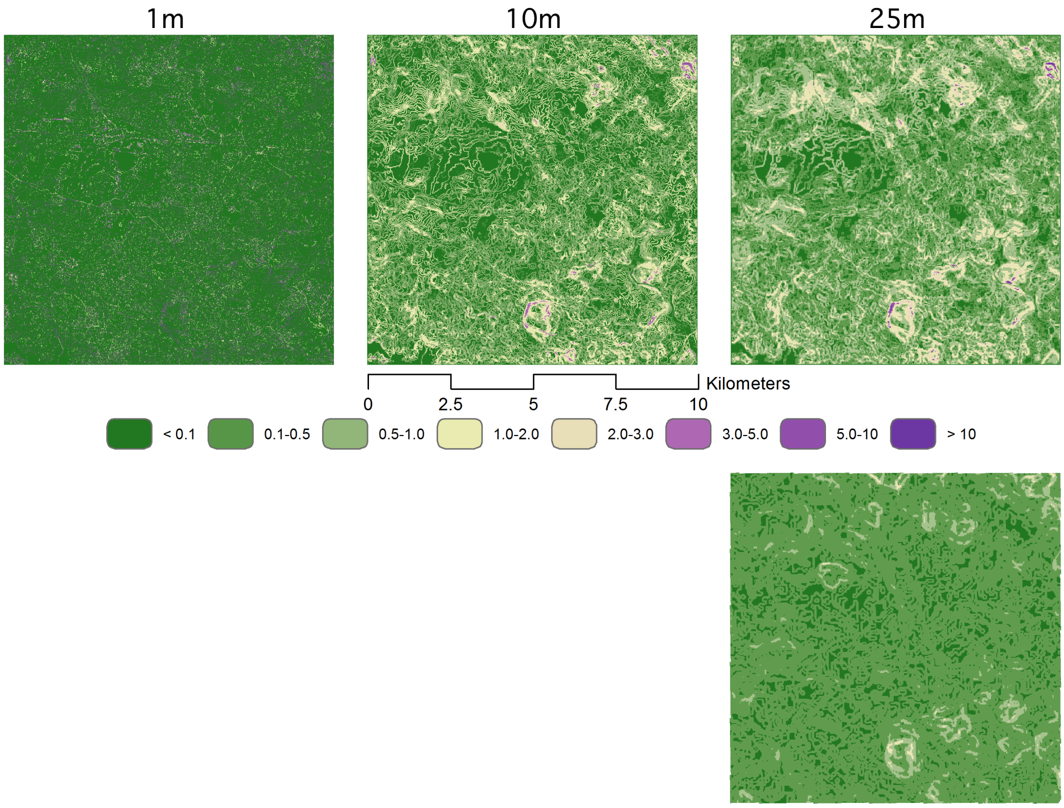


Figure 4.11: A visual comparison of the the data created in this report and the 25m resolution JRC data from 2015 (Panagos, Borrelli, and Meusburger 2015).

The 1m resolution dataset is composed primarily of very low LS-values and has no larger areas with high values. Visually both the 10m and 25m resolution rasters are very similar, the high value areas within the rasters have slightly different extents but are overall identically distributed. However upon closer inspection, the 1m raster shares a few of the same purple high-cell-value areas, indicating that the LS-algorithm did complete normally.
Both the 10m and 25m rasters share many of the same patterns and values as the JRC dataset, however the MAX values differ slightly. The attributes of each dataset is visible in table 4.2.

DEM 1	Cells 100.000.000	Processing 18 min	Std. dev 2,0
	MIN	MEAN	MAX
LS	0,030	0,700	18,270
m	0	0,080	0,751
L	0	1,110	1,532
S	0	0,680	14,140
DEM 10	Cells 1.000.000	Processing 2 min	Std. dev 0,53
	MIN	MEAN	MAX
LS	0,030	0,530	11,070
m	0	0,230	0,697
L	0	1,550	3,140
S	0	0,400	6,780
DEM 25	Cells 160.000	Processing 20 sec	Std. dev 0,41
	MIN	MEAN	MAX
LS	0,032	0,491	6,985
m	0	0,240	0,640
L	0	1,750	3,307
S	0	0,350	3,570
JRC	Cells 160.000	RMS error 2,9m	Std. dev 0,34
	MIN	MEAN	MAX
LS	0,030	0,230	2,290

Table 4.2: Attributes of the output LS-datasets and the JRC LS-factor dataset. The Standard deviations are for the LS-values.

5 Discussion

With the publication of the new JRC LS-datasets, the previous pan European LS-factor was anlalysed by Bosco (Bosco et al. 2015). This previous study had a GSD of 100m, 16 times lower than the JRC data. The differences between them is visualised:

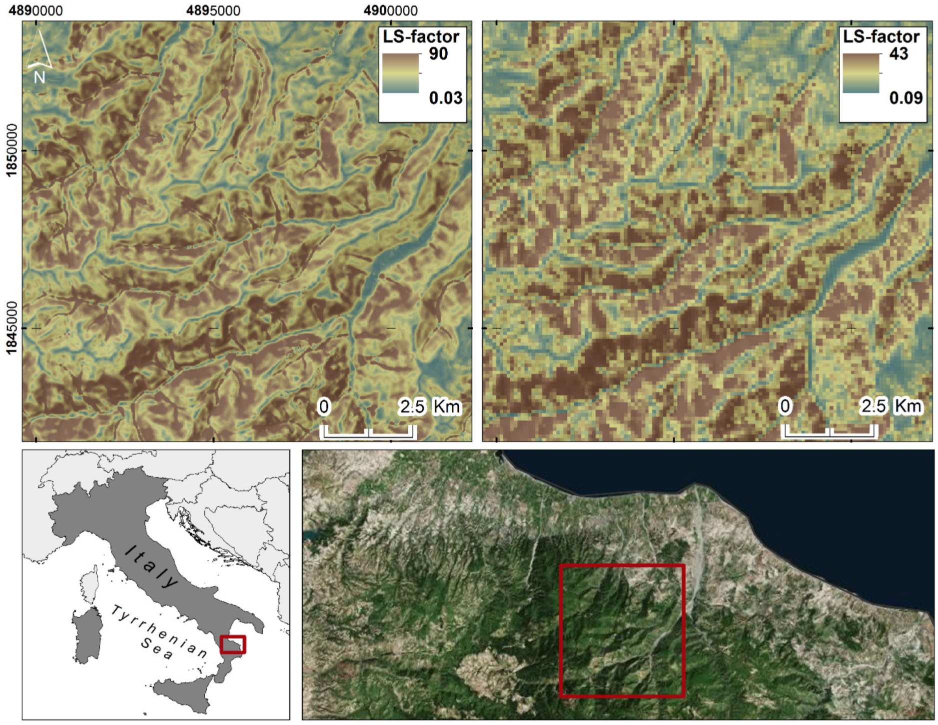


Figure 5.1: Visual comparison of LS-factors between the JRC study (upper left) and the previous pan Europen LS dataset (upper right) (Bosco et al. 2015). Figure from (Panagos, Borrelli, and Meusburger 2015 p. 123). The analysed area is Calabria in Southern Italy.

The map legends shows a change in MIN values from 0,09 to 0,03 and in MAX values from 43 to 90. Furthermore the extents of the high-cell-value areas has been decreased. These elements validate that the larger cell sizes has effectively equalized the greater changes in cell values, caused by complex topography. These areas has therefore not been modelled appropriately. However the near-flat areas in the model area are virtually indifferent, with only minor changes in localized extreme values. The above serves as proof to the greater and more precise applicability of using a higher resolution DEM.

The model output of this report was presented as three different resolution datasets. These datasets was resampled before being introduced to the model, ensuring correct use of RUSLE. The outputs was styled identically to enable visual comparison and was presented in figure 4.11 and in Appendix A.
The first image represents the LS-factor calculated on a base DEM with a GSD of 1m. This output raster consists of very close LS-values, upon closer inspection it is possible to observe high-cell-value areas and patterns in the data that seems to follow infrastructure closely. Several of these high-cell-value areas are located in proximity to the high-cell-value areas of the JRC data, however there is no direct correspondence between cell values. A positive effect of high resolution data, is the presence of small details. In a DEM, these details would include man-made objects and infrastructure. In addition, the small cell sizes have the potential to over complicate very basic topography, making the output very noisy.
The LS-factor based on the resampled 10m DEM, has easily recognizable patterns. These patterns are visually very similar to contour lines, with the areas in between being confined areas with a single LS-value. This visual representation gives the idea of terracing, but in reality terracing is not present in the area.
Lastly the LS-factor of the 25m resampling, is visually extremely similar to that of the 10m resampling, however the "terracing effect" is very limited. The extent of areas and their cell values, follow the 10m resampling and the JRC dataset closely.

The visual differences in the LS-datasets can be explained by table 4.2. Here are several indications to the problems within the 1m LS-raster. As sample size increases the variance between sampled observations should increase, but the variance of the sample mean should decrease. This implies that Standard Deviation should decrease with the increase in sample size, however this is not true for the 1m dataset. Therefore this dataset will be eliminated from further comparison.

To further compare the 10m and 25m LS-datasets they will each be compared to a baseline, the JRC dataset. This is done by comparing each raster on a cellular level $C_{i,j}$ to $C_{i,j}$. This is in practice done using Map Algebra. The differences to this dataset is visualised:

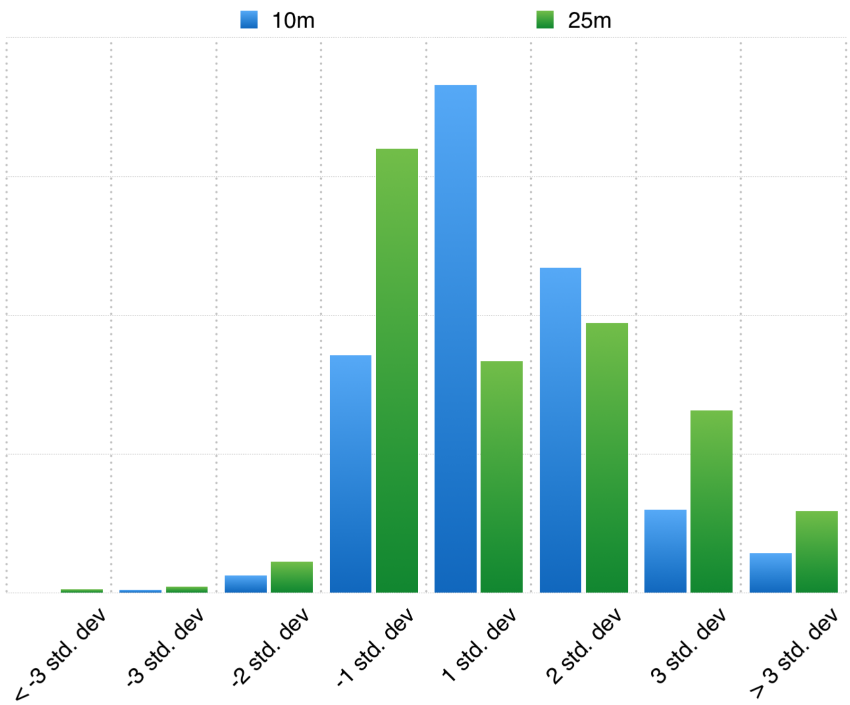


Figure 5.2: Visual comparison of Δ LS-factor values between the JRC-dataset and the model outputs of this report.

Both LS-datasets has very few cells with lower values than the JRC data, indicating that the datasets created in this report has a slightly higher LS-estimation than the JRC data. Both the 10m and 25m datasets, has the majority of LS-values within 1 standard deviation of the JRC data.

Std. Dev	Normally distributed	10m	25m
$\pm$ 1	68%	62%	54%
$\pm$ 2	95%	90%	78%
$\pm$ 3	99,7%	97%	93%

Table 5.1: Control of Normal distribution of the 10m and 25m LS-datasets.

Neither datasets has a tendency to underestimate the LS-factor, this is seen from the non-symmetrical distribution. However this is partially caused by the tendency to overestimate the L-factor and the S-factor in the model outputs for both 10m and 25m datasets. The mathematical relationship of RUSLE multiplies these values together to form the LS-factor, increasing the LS-value exponentially. To be normally distributed the data should follow the values in figure 5.1. The 10m dataset follows this distribution more closely than the 25m dataset, even though the S-factor values of this dataset is much greater, see table 4.2.

The spatial distribution of differences to the JRC dataset is slightly scattered for the 10m dataset:

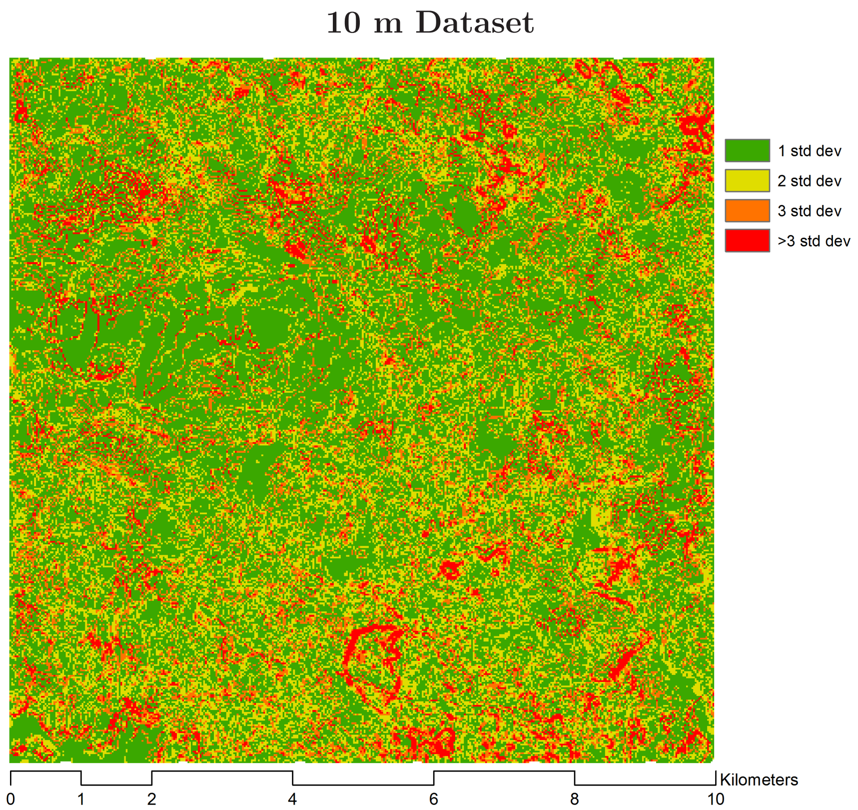


Figure 5.3: Spatial comparison of Δ LS-factor values between the JRC-dataset and the 10m model output of this report.

The spatial distribution of differences to the JRC dataset is grouped around the high-cell-value areas for the 25m dataset:

25 m Dataset

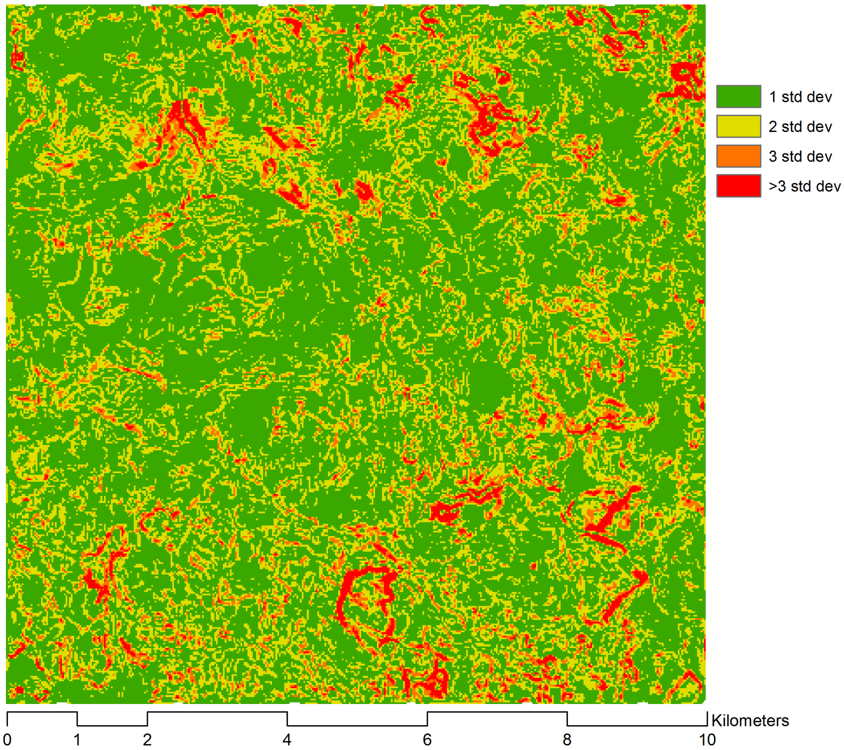


Figure 5.4: Spatial comparison of Δ LS-factor values between the JRC-dataset and the 25m model output of this report.

Calculating the Correlation and Covariance between the 10m raster, the 25m raster and the JRC raster yields the following:

Dataset	Correlation	Covariance
10m to JRC	0,62	0,34
25m to JRC	0,28	0,11

Table 5.2: Control of Correlation and Covariance of the 10m, 25m and JRC LS-datasets.

The above can be summarized:

1. The 10m dataset has visual lines following he contouring of the DEM, these lines are also present in the JRC dataset, however they are slightly overestimated in comparison.

2. The 25m dataset visually looks better, high-cell-value areas has smoother transitioning. However several areas are greatly overestimated.

3. The difference between the 10m dataset and the JRC dataset, follow a normal distribution more closely, but neither 10m or 25m datasets are symmetrical on both sides of μ. Both model outputs has a tendency to overestimate the LS-value, but the 10m dataset is generally closer to the JRC dataset and only does so in 31% of the cells.

4. The 10 m dataset is slightly more Correlated to the JRC dataset indicating a stronger tendency for the datasets cell values to follow each other. Furthermore the Covariance of these datasets indicate slight divergence when comparing the same to two cells in the rasters.

These considerations suggests that the 10m dataset is the most accurate of the datasets created within this report. However it is not possible to derive whether the 10m dataset is an accurate assessment of the model area without in-situ control measurements of sediment transport. Several attempts were made to find the highest resolution DEM that would produce an output LS-factor without noise, 10m where found to be the lowest cell size without significant noise. Furthermore it should be noted that the 25m GSD JRC DEM with a rms error of 2,9m has a potential of introducing a 5,8m error over 25m, this equals a slope-error of 23,2% or 13 degrees. With the 10m GSD DEM used in this report, this slope-error is limited to 1% or 0,6 degrees. The terracing effect in the 10m dataset is perhaps more a visual artefact, than a error within the data. Due to the smaller raster cells these lines in the data consists of a large amount of cells, ensuring a good overlap with the datasets of the other RUSLE factors.

6 | Conclusion

Erosion mapping is a useful tool in locating and assessing areas prone to pollution induced by erosion. Several attempts has been made to estimate erosion risk across differing locations with various challenges both in data-availability and environmental conditions. The most recent large scale evaluation of erosion was conducted by the JRC across all the EU member countries, using the RUSLE model (Bosco et al. 2015). This evaluation was however found to have weaknesses in several of the RUSLE subfactor estimations, Rainfall, Soil type, Topographic length & steepness, Vegetation and Land use.
Of these, Topography was potentially the most inaccurate assessment compared to local or national datasets. The JRC assessment used topographic elevation data with a GSD of 25 m and a vertical RMS error of 2,9 m. This DEM was used solely for its geographic extent, covering all EU member countries. Though several national agencies have higher resolution data available, piecing these datasets together would result in a mosaic dataset with a varying GSD, which is unwanted (Andersen and Heckrath 2015; McCool et al. 1987).

Analysing the effects of a high resolution DEM contra a lower resolution DEM could enlighten **how erosion modelling is affected by the extent and quality of the inputs**.

Erosion modelling outputs are determined to be very influenced by the inputs. In RUSLE, the six factors can increase the model output exponentially. Several of the factors are spatially dependant, RUSLE does however not directly include these considerations. Quality can refer to multiple elements in a dataset, in regards to topography, it can be GSD or cell size but also the accuracy of the data sampling. This led to analysing the RUSLE LS-factor model output for the new Danish DEM and comparing this output to the JRC LS-dataset, which resulted in several interesting observations.
The LS-factor datasets created in this report are successful attempts in estimating the effects of topographic length and steepness, however the precision of the estimation can only be analysed further by comparing it to in-situ mea-

surements. Increasing the resolution and spatial accuracy of the input data was determined by Bosco to enable a more precise estimation of complex topography (Bosco et al. 2015). Using high resolution data it was found that the output datasets in this report could potentially lower the slope-angle error included in the JRC data. Furthermore help visualise the exact extents of high risk areas.

Denmark is however relatively flat compared to other areas of the EU, this means that the relatively small changes in LS-values has no major impact to the complete RUSLE equation. This makes the analysis somewhat redundant, however the analysis also showed that a sub 10m GSD DEM potentially introduces more noise than it enables insight in the fluvial processes. The 25m resolution is therefore a very reasonable cell size, though the input DEM should have a lower vertical RMS error than that used in the JRC study.

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Appendix A

See the following pages for visual examples of LS-data used in the Analysis.

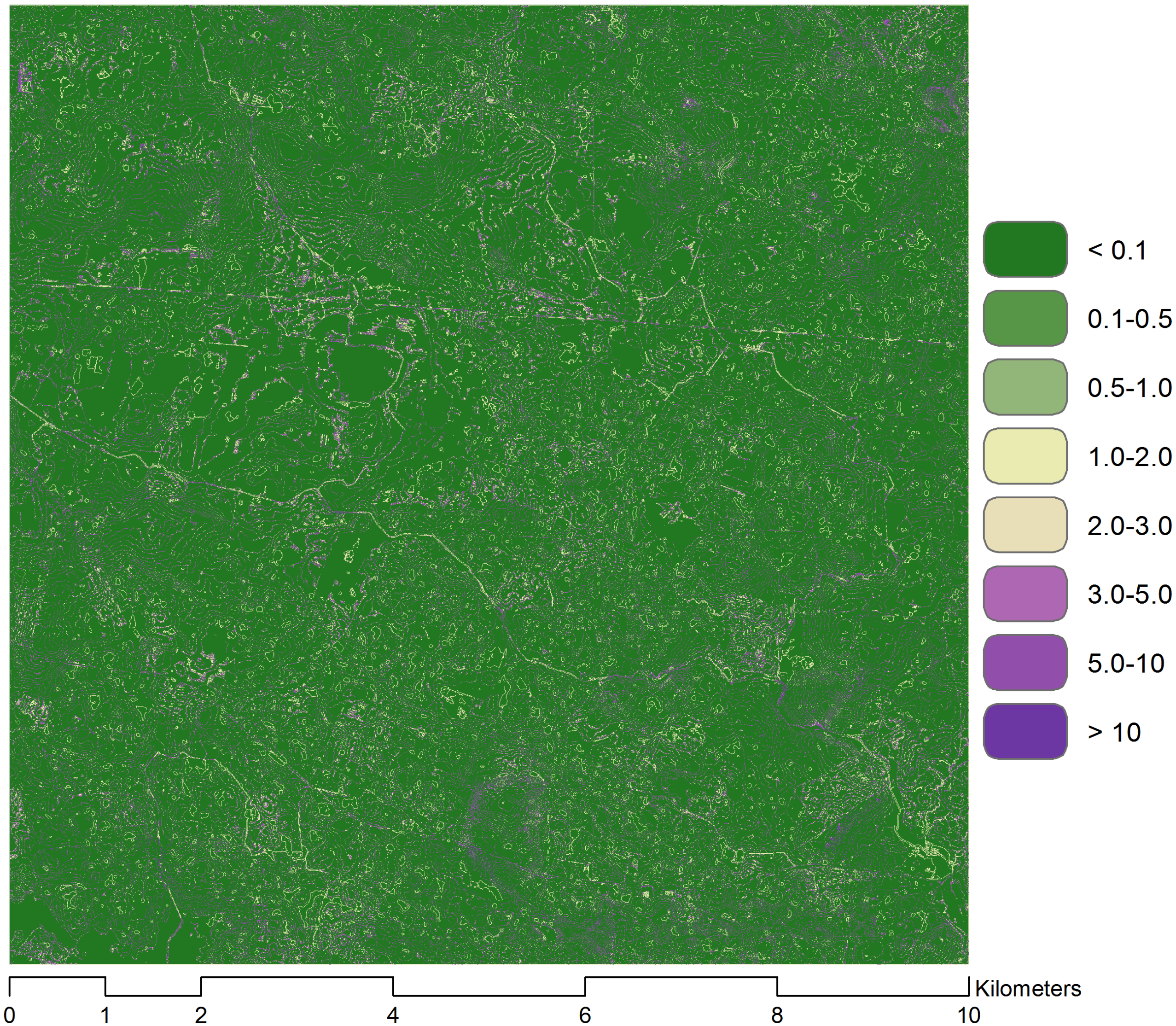

Figure 1: 1m DEM LS-factor see section 4.4.

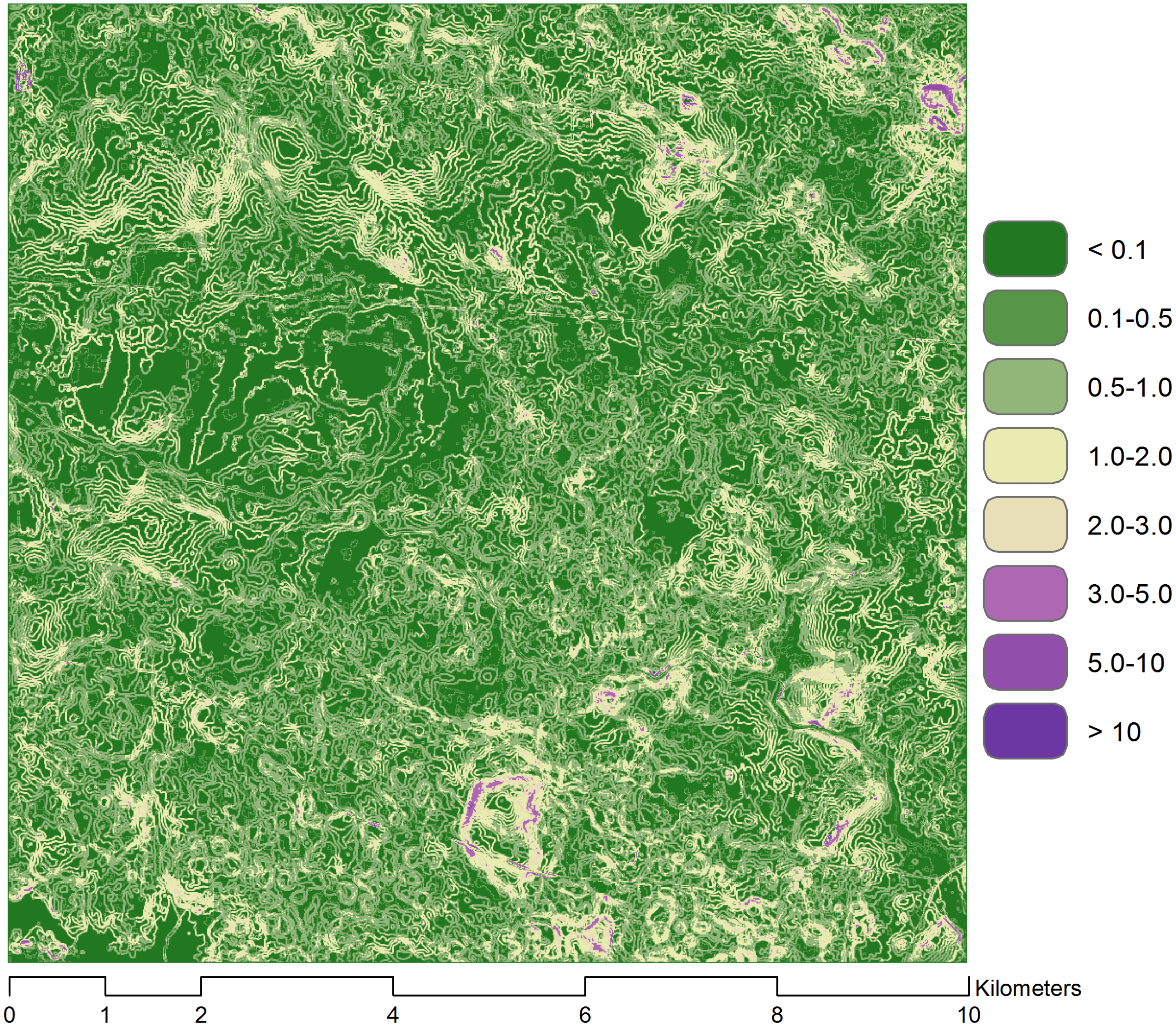

Figure 2: 10m DEM LS-factor see section 4.4.

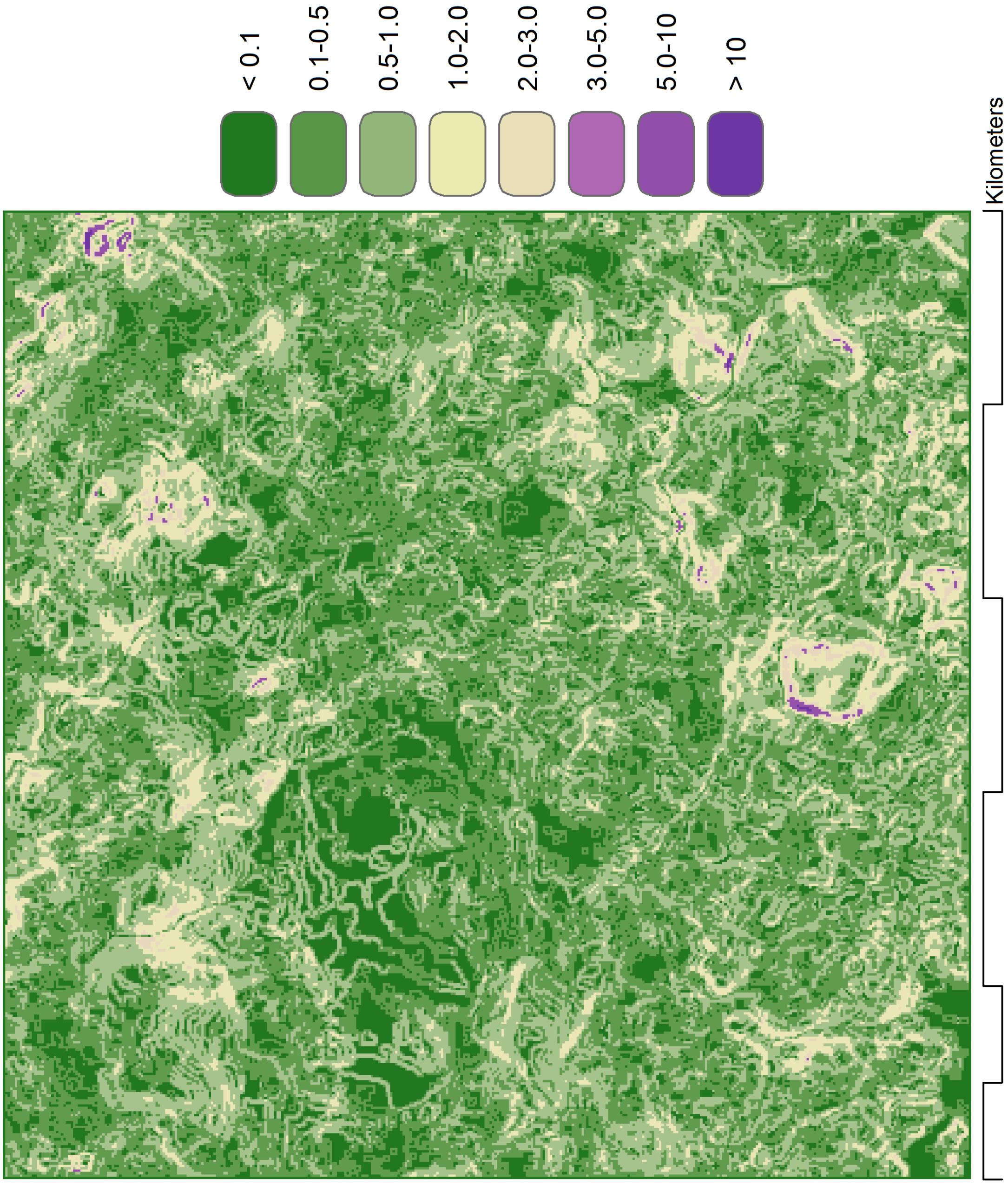

Figure 3: 25m DEM LS-factor see section 4.4.

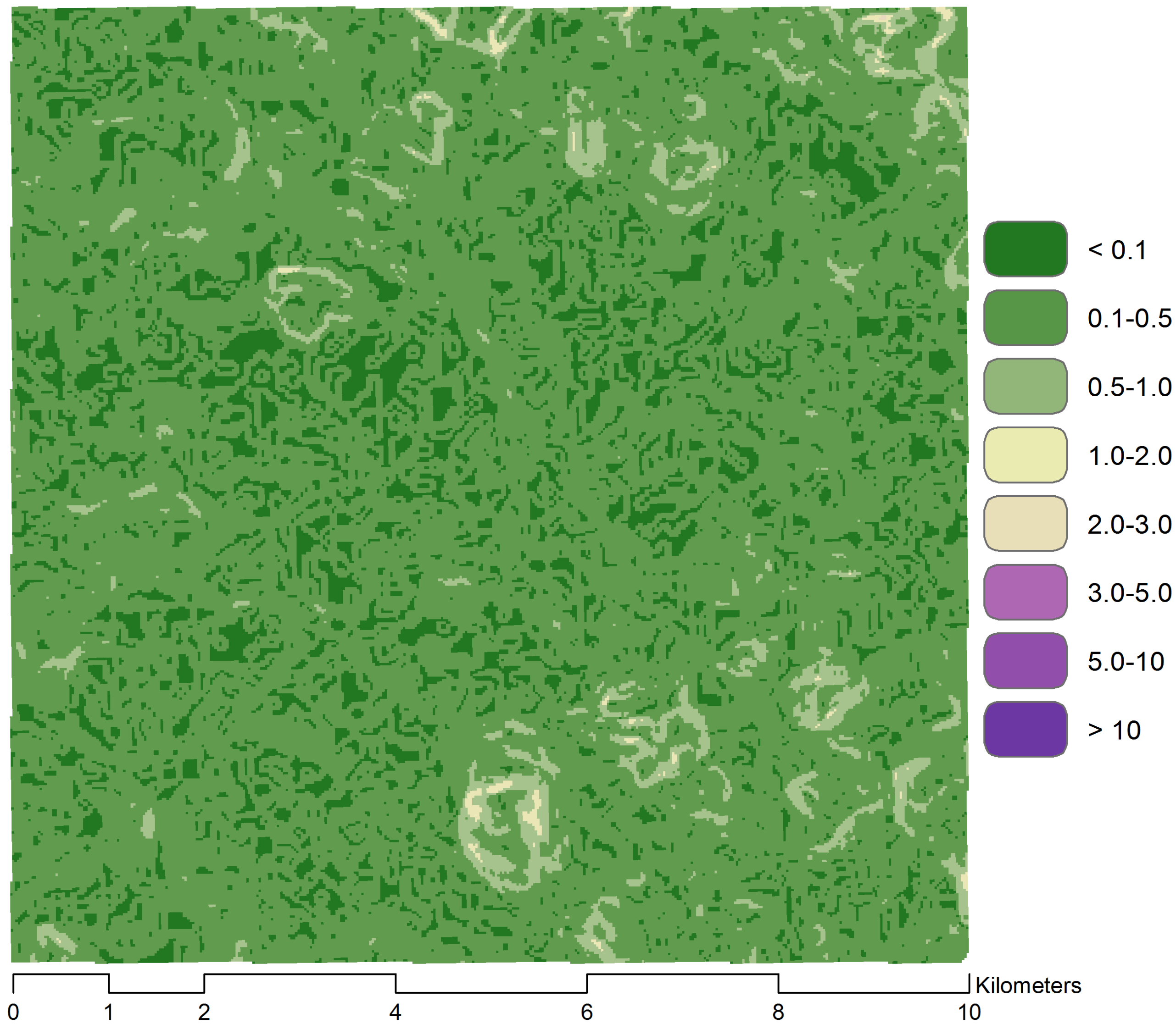

Figure 4: Dataset from JRC styled identical to the datsets created in section 4.4 (Panagos et al. 2015b).

Appendix R

See the following pages for visual examples of R-factor data.

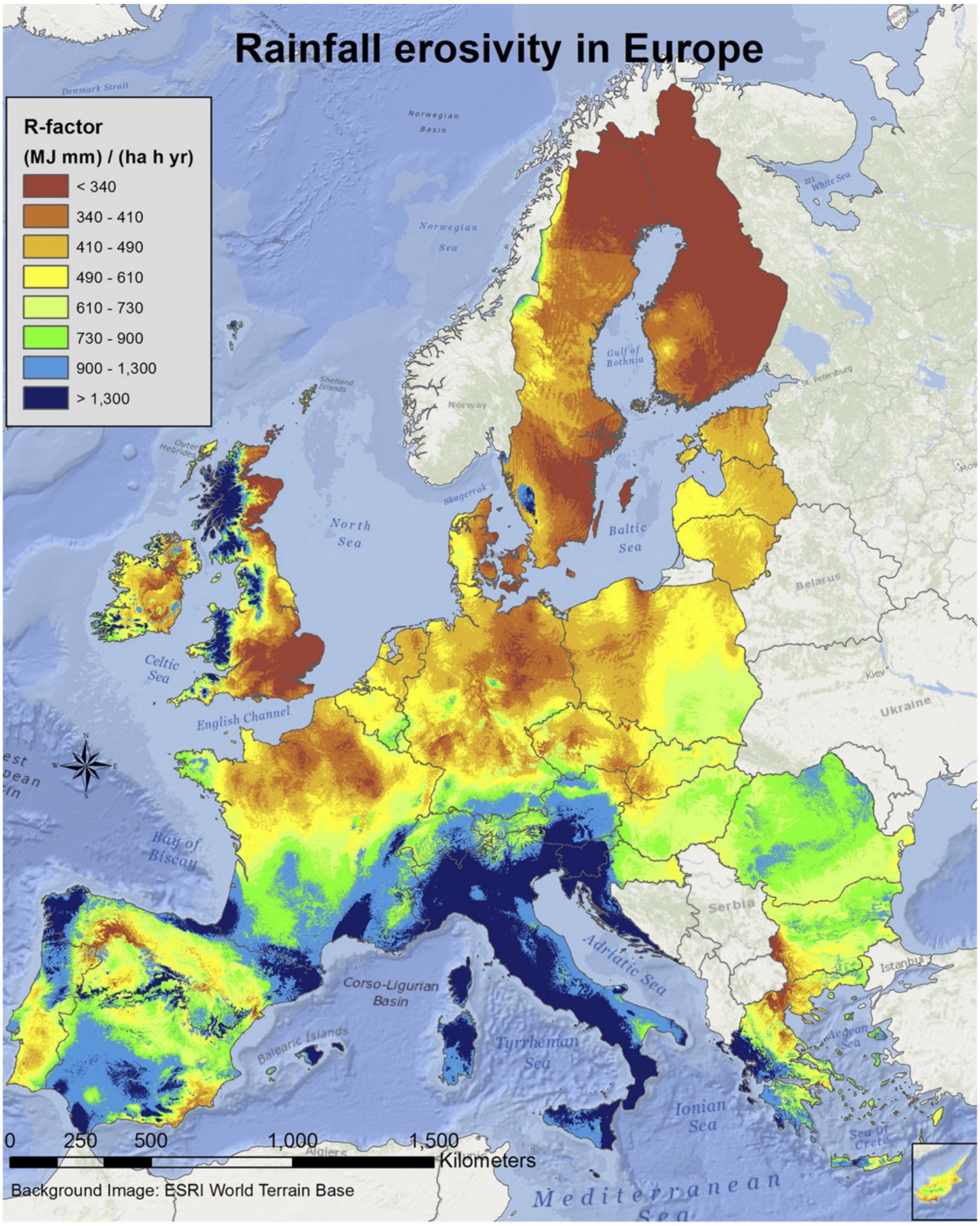

Fig. 2. High-resolution (1-km grid cell) map of rainfall erosivity in Europe.

Figure 5: (Panagos et al. 2015b p. 808).

Appendix K

See the following pages for visual examples of K-factor data.

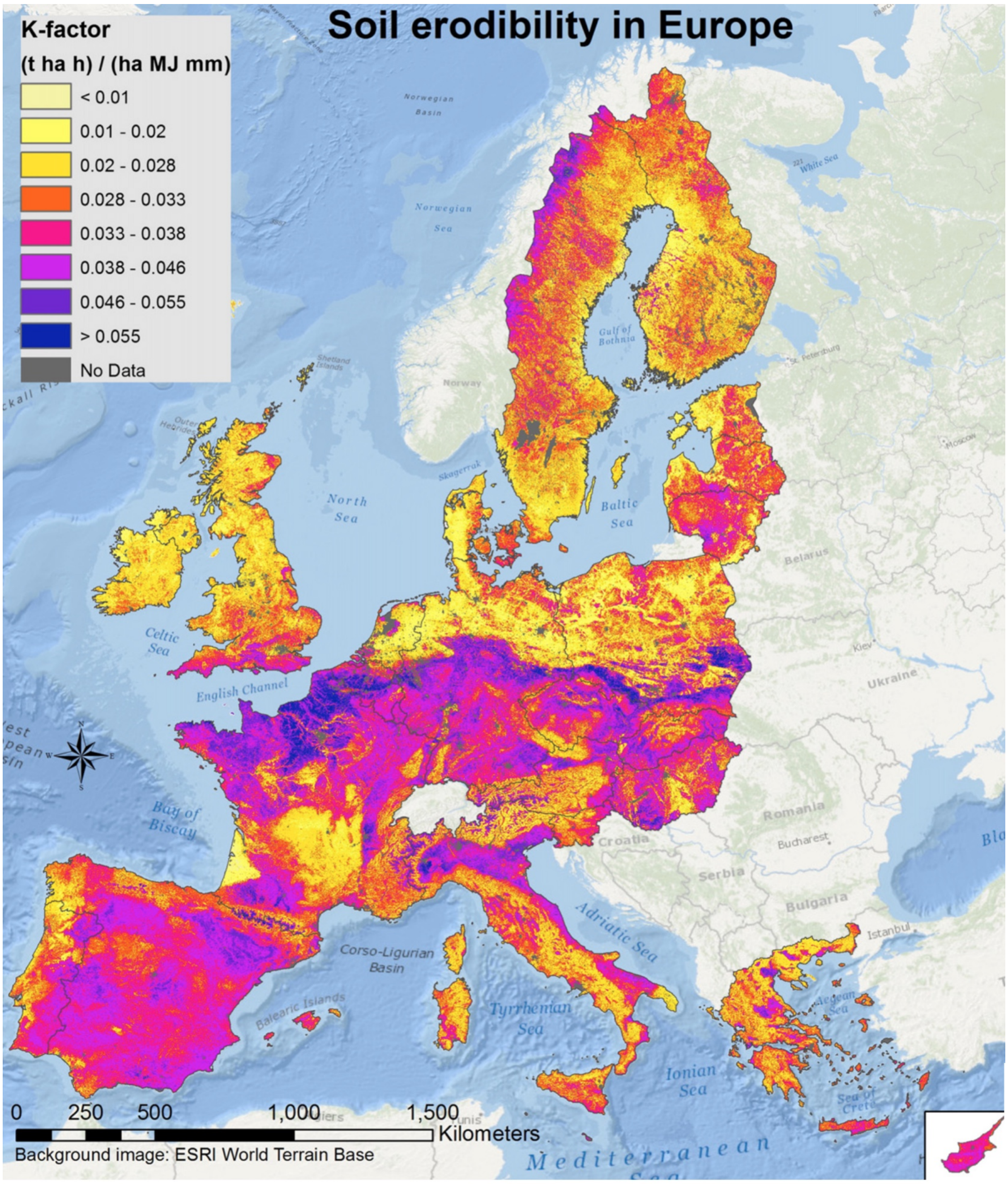

Fig. 2. High-resolution (500 m grid cell size) map of Soil Erodibility estimated as K-factor in the European Union.

Figure 6: (Panagos et al. 2014b p. 193).

Table 5
Comparison of soil erodibility with and without considering surface stone content (K-factor and K_{st}-factor, respectively) per country.

Country		K-factor equation (Eq. (1))		K_{st}-factor stoniness	Reduction due to stoniness (%)
ISO	Name	Mean value (t ha h ha^{-1} MJ^{-1} mm^{-1})	Standard deviation (t ha h ha^{-1} MJ^{-1} mm^{-1})	Mean value (t ha h ha^{-1} MJ^{-1} mm^{-1})	
AT	Austria	0.0321	0.0080	0.0291	9.5%
BE	Belgium	0.0422	0.0092	0.0387	8.2%
CY	Cyprus	0.0362	0.0028	0.0265	26.8%
CZ	Czech Republic	0.0373	0.0076	0.0342	8.3%
DE	Germany	0.0334	0.0102	0.0311	7.0%
DK	Denmark	0.0246	0.0065	0.0225	8.7%
EE	Estonia	0.0254	0.0074	0.0242	4.5%
EL	Greece	0.0298	0.0057	0.0229	23.3%
ES	Spain	0.0368	0.0058	0.0265	27.9%
FI	Finland	0.0273	0.0058	0.0242	11.2%
FR	France	0.0356	0.0101	0.0284	20.1%
HU	Hungary	0.0349	0.0078	0.0337	3.3%
IE	Ireland	0.0234	0.0047	0.0216	7.4%
IT	Italy	0.0322	0.0077	0.0276	14.5%
LT	Lithuania	0.0321	0.0067	0.0309	3.8%
LU	Luxembourg	0.0392	0.0036	0.0345	11.9%
LV	Latvia	0.0290	0.0067	0.0281	3.2%
MT	Malta	0.0381	0.0022	0.0284	25.5%
NL	Netherlands	0.0246	0.0084	0.0236	3.9%
PL	Poland	0.0299	0.0106	0.0285	4.8%
PT	Portugal	0.0333	0.0069	0.0194	41.8%
SE	Sweden	0.0293	0.0068	0.0252	13.9%
SI	Slovenia	0.0313	0.0052	0.0282	9.6%
SK	Slovakia	0.0362	0.0074	0.0321	11.3%
UK	United Kingdom	0.0271	0.0063	0.0241	11.1%

Figure 7: (Panagos et al. 2014b p. 195).

Appendix LS

See the following pages for visual examples of L- & S-factor data.

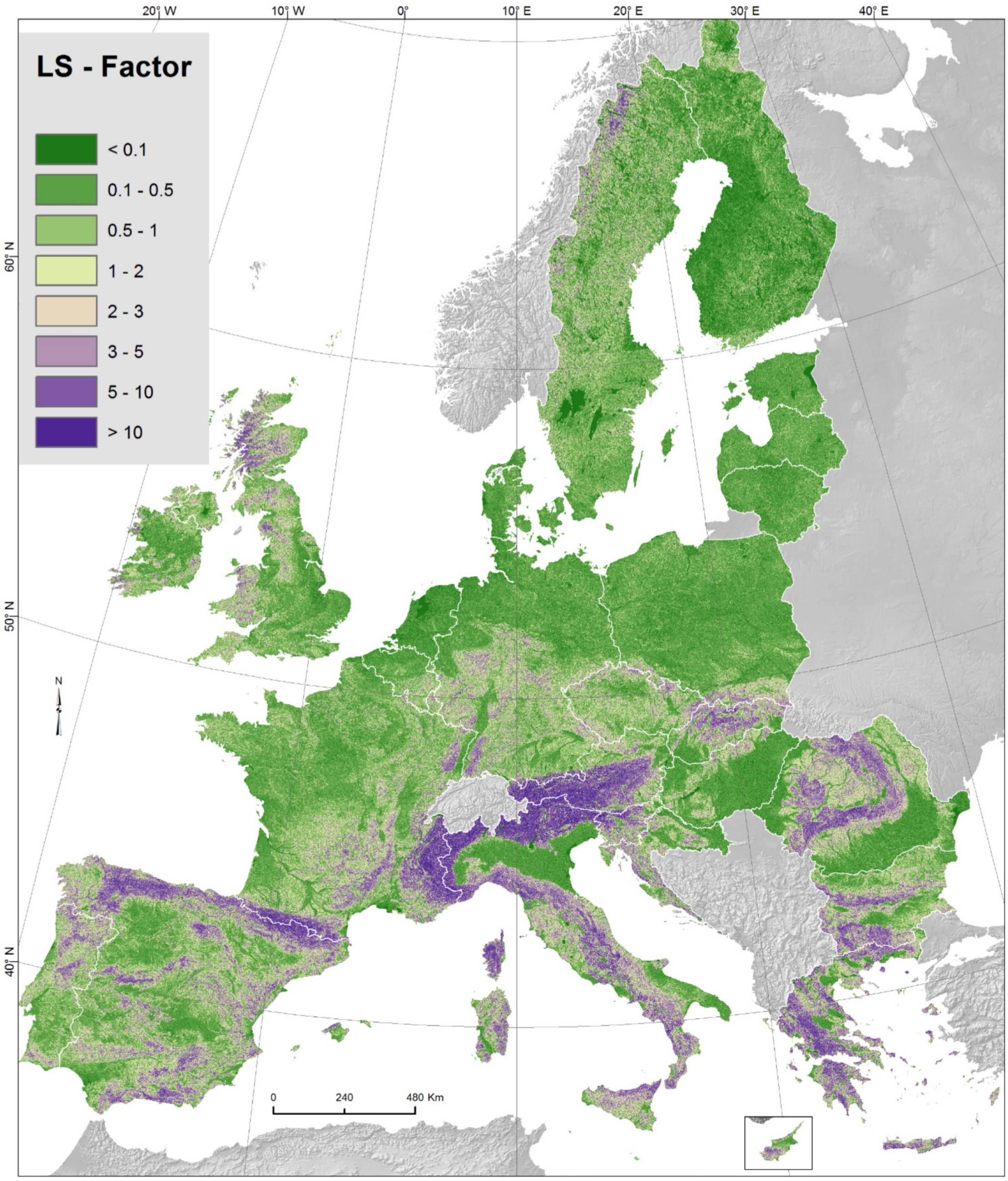

Figure 1. Slope length and steepness factor (LS-factor) in the European Union.

Figure 8: LS factors visualised for the EU-countries, from the original article "A New European Slope Length and Steepness Factor (LS-Factor) for Modeling Soil Erosion by Water" (Panagos, Borrelli, and Meusburger 2015 p. 121).

Table 1. LS-factor statistics per country. More detailed statistics per land cover type can be found in Table S1.

Country Name	Code	Mean	Standard Deviation	Coefficient of Variation
Austria	AT	5.20	5.91	1.14
Belgium	BE	0.68	0.95	1.40
Bulgaria	BG	2.34	3.00	1.28
Cyprus	CY	2.31	2.72	1.18
Czech Rep.	CZ	1.36	1.57	1.15
Germany	DE	1.05	1.64	1.57
Denmark	DK	0.32	0.34	1.07
Estonia	EE	0.32	0.31	0.96
Spain	ES	2.24	2.97	1.33
Finland	FI	0.41	0.64	1.56
France	FR	1.72	3.12	1.81
Greece	GR	3.79	4.05	1.07
Croatia	HR	1.89	2.56	1.36
Hungary	HU	0.59	0.99	1.69
Ireland	IE	1.01	1.54	1.52
Italy	IT	3.63	4.86	1.34
Lithuania	LT	0.35	0.38	1.09
Luxembourg	LU	1.62	1.68	1.04
Latvia	LV	0.39	0.36	0.93
Malta	MT	1.34	1.97	1.46
Netherlands	NL	0.19	0.20	1.05
Poland	PL	0.52	0.86	1.67
Portugal	PT	1.80	2.25	1.25
Romania	RO	2.09	2.82	1.35
Sweden	SE	0.99	1.51	1.52
Slovenia	SI	3.87	4.21	1.09
Slovakia	SK	2.57	2.84	1.11
United Kingdom	UK	1.40	2.02	1.45

Figure 9: (Panagos, Borrelli, and Meusburger 2015 p. 122).

Appendix C

See the following pages for visual examples of C-factor data.

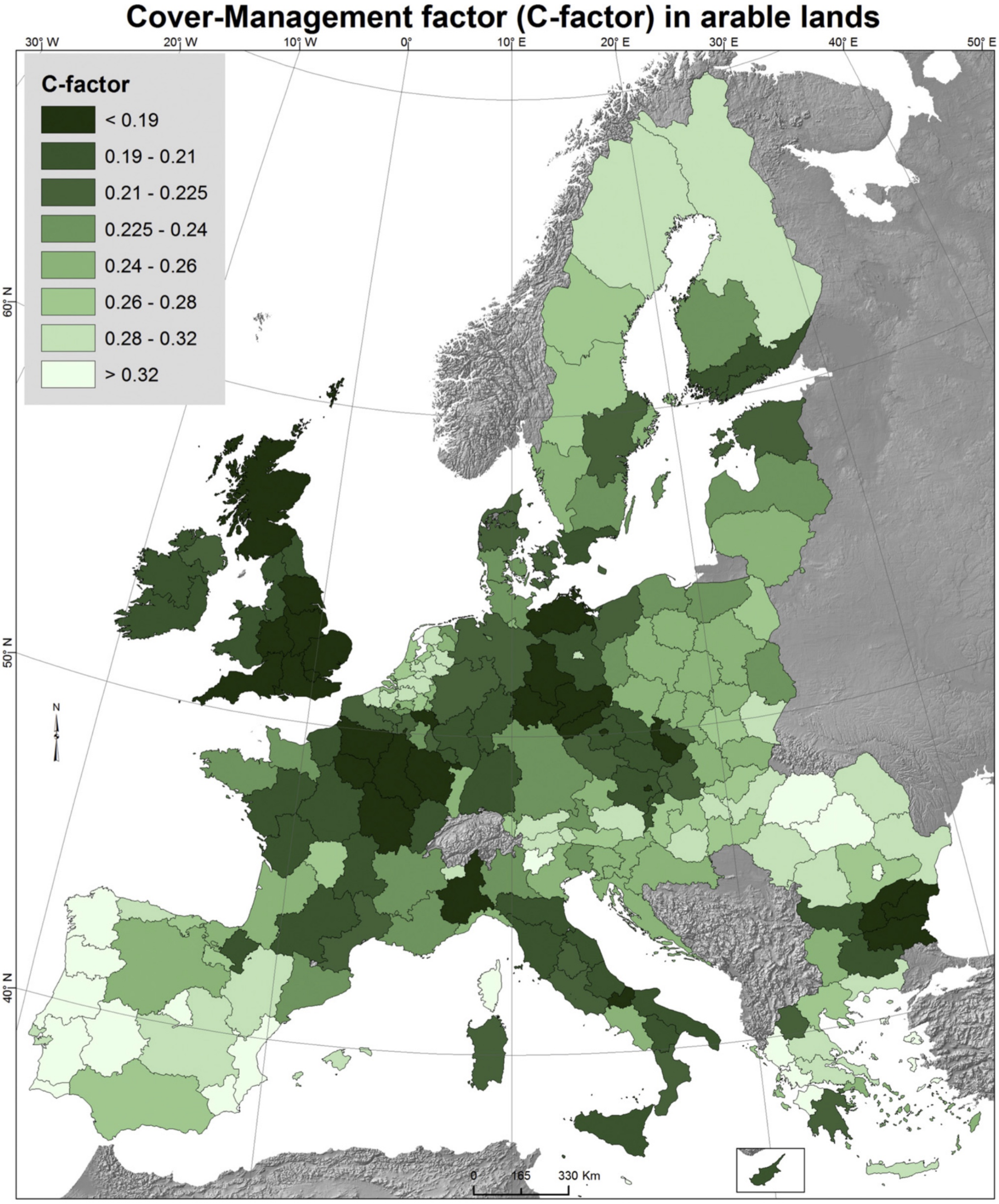

Fig. 1. Cover-management factor (C-factor) in arable lands of the European Union.

Figure 10: (Panagos et al. 2014a p. 43).

Table 5
C-factor per country.

Country	C-factor	Arable lands		Non arable lands	
		C-factor	% Share	C-factor	% Share
AT	0.071	0.218	15.3%	0.045	84.7%
BE	0.121	0.245	27.9%	0.073	72.1%
BG	0.105	0.188	37.5%	0.055	62.5%
CY	0.129	0.193	30.8%	0.100	69.2%
CZ	0.107	0.199	41.1%	0.042	58.9%
DE	0.112	0.200	42.1%	0.048	57.9%
DK	0.178	0.222	72.4%	0.061	27.6%
EE	0.059	0.217	16.7%	0.027	83.3%
ES	0.140	0.289	24.9%	0.090	75.1%
FI	0.023	0.231	6.2%	0.010	93.8%
FR	0.108	0.202	30.3%	0.068	69.7%
GR	0.111	0.280	17.5%	0.075	82.5%
HR	0.075	0.255	7.5%	0.061	92.5%
HU	0.188	0.275	58.3%	0.066	41.7%
IE	0.082	0.202	9.6%	0.069	90.4%
IT	0.119	0.211	30.4%	0.078	69.6%
LT	0.121	0.242	36.5%	0.051	63.5%
LU	0.082	0.215	13.4%	0.061	86.6%
LV	0.070	0.237	16.4%	0.037	83.6%
MT	0.151	0.434	1.7%	0.148	98.3%
NL	0.133	0.260	26.4%	0.088	73.6%
PL	0.140	0.247	47.3%	0.043	52.7%
PT	0.123	0.352	14.8%	0.083	85.2%
RO	0.150	0.296	38.5%	0.058	61.5%
SE	0.032	0.237	8.1%	0.014	91.9%
SI	0.057	0.248	5.8%	0.046	94.2%
SK	0.106	0.235	36.5%	0.032	63.5%
UK	0.099	0.177	32.2%	0.062	67.8%

Figure 11: (Panagos et al. 2014a p. 46).

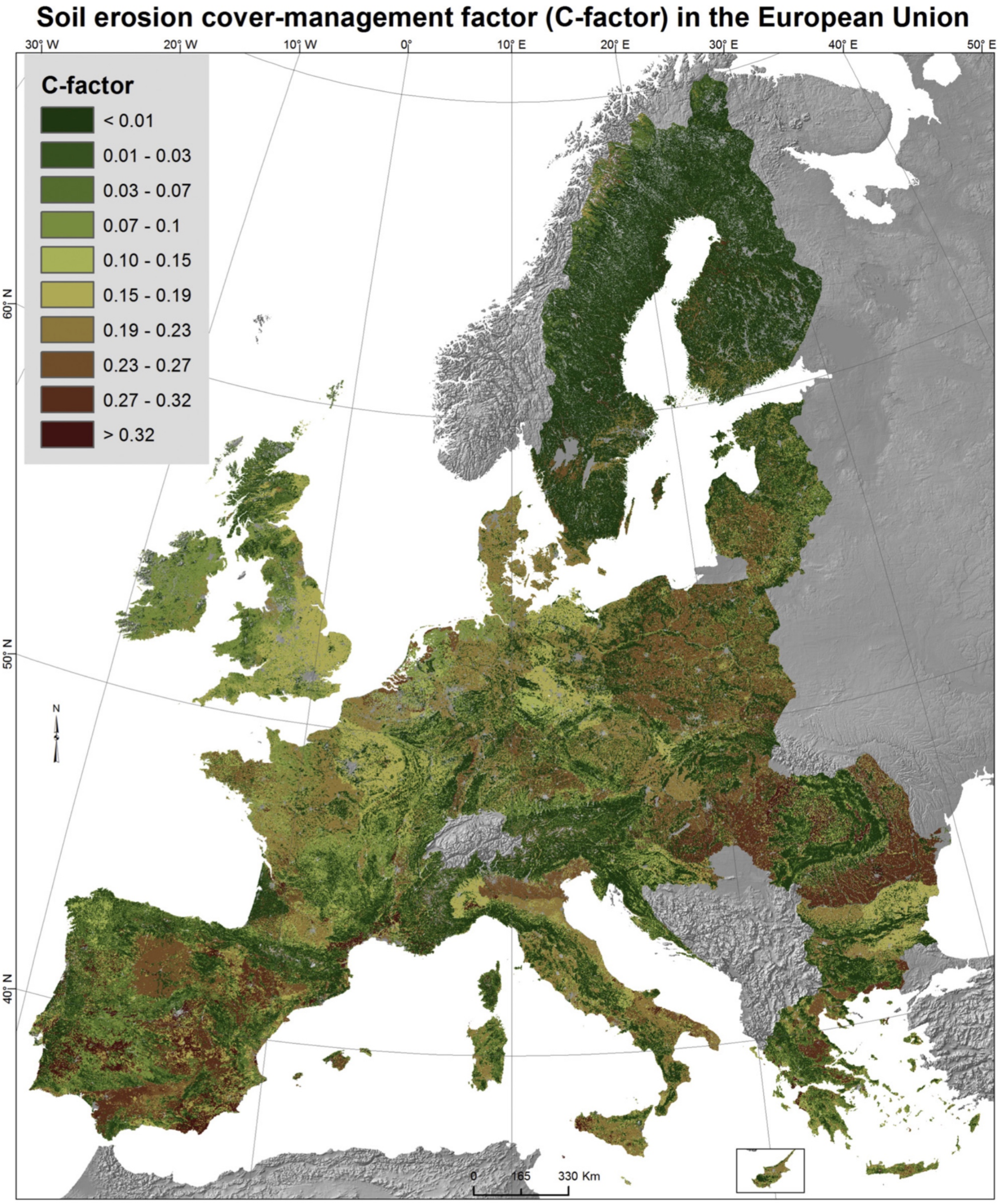

Fig. 3. C-factor map of the European Union.

Figure 12: (Panagos et al. 2014a p. 47).

Appendix P

See the following pages for visual examples of P-factor data.

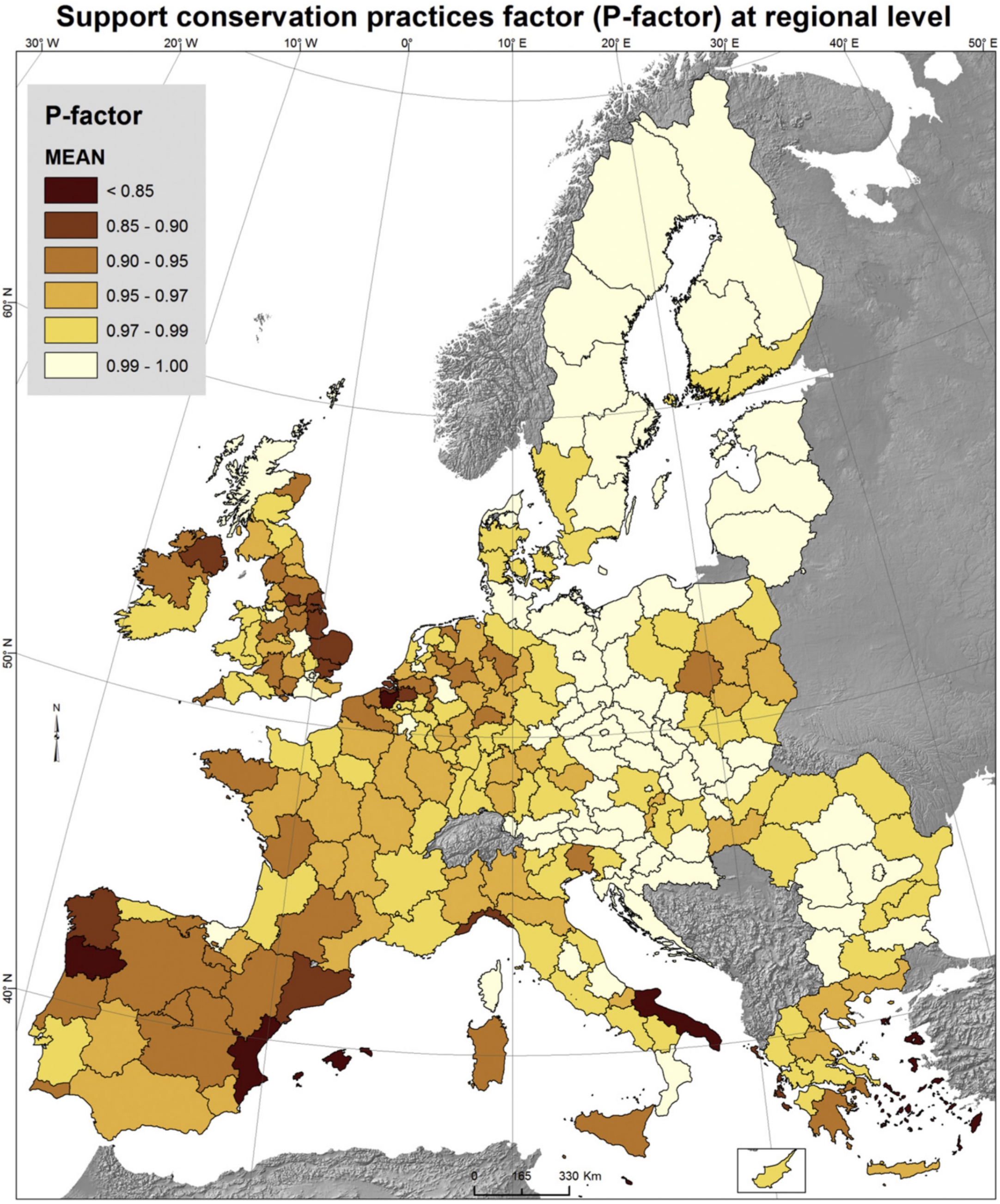

Fig. 3 – Mean *P*-factor at regional (NUTS2) level in the European Union.

Figure 13: (Panagos et al. 2015a p. 31).

Table 6 – Support practice (*P*-factor) and sub-factors per country.

Country	P_c (contouring)	P_{sw} (stone walls)	P_{gm} (grass margins)	P-factor
AT	1	0.9996	0.9887	0.9883
BE	1	0.9998	0.9467	0.9465
BG	1	0.9999	0.9912	0.9911
CY	0.9909	0.9828	0.9991	0.9730
CZ	1	0.9999	0.9983	0.9982
DE	1	0.9998	0.9784	0.9782
DK	1	0.9999	0.9844	0.9843
EE	0.9995	0.9998	0.9996	0.9989
ES	0.9926	0.9580	0.9778	0.9293
FI	1	0.9998	0.9943	0.9942
FR	1	0.9935	0.9691	0.9627
GR	0.9939	0.9676	0.9883	0.9502
HR	1	0.9999	0.9995	0.9994
HU	1	1	0.9840	0.9840
IE	1	0.9738	0.9952	0.9690
IT	0.9992	0.9786	0.9725	0.9519
LT	1	0.9999	0.9980	0.9980
LU	1	0.9991	0.9725	0.9716
LV	1	0.9999	0.9995	0.9995
MT	0.9993	0.5299	0.9915	0.5251
NL	1	0.9999	0.9561	0.9561
PL	1	0.9999	0.9781	0.9781
PT	1	0.9245	0.9921	0.9178
RO	0.9948	0.9999	0.9950	0.9898
SE	1	0.9976	0.9984	0.9961
SI	0.9999	0.9919	0.9940	0.9860
SK	1	0.9999	0.9986	0.9985
UK	1	0.9878	0.9647	0.9528

Figure 14: (Panagos et al. 2015a p. 29).