ClimChAlp
Interreg III B Alpine Space

Natural Hazard Report

Chapter 3: Soil erosion in the Alpine Space

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Alpine Space
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List of Acronyms

Abbreviations or Acronyms	**Significance**
AVHRR	Advanced Very High Resolution Radiometer
CLC	Corine Land Cover
DEM	Digital Elevation Model
GIS	Geographic Information System
ICTP	International Centre for Theoretical Physics
IPCC	Intergovernmental Panel on Climate Change
NDVI	Normalised Difference Vegetation Index
REGCM	Regional Climate Model
RUSLE	Revised Universal Soil Loss Equation
SMU	Soil Mapping Unit
STU	Soil Typological Unit
UCA	Upslope Contributing Area
USDA	United States Department of Agriculture
USLE	Universal Soil Loss Equation

1. ABSTRACT

The general aim of our study was an estimation of actual erosion over the whole alpine space and a spatial analysis of soil erosion trends in different IPCC (Intergovernmental Panel on Climate Change) scenarios. A preliminary review of scientific literature regarding soil erosion studies in the Alps was carried out. From this analysis it came out that research experiences studying, by means of models specifically set for mountain areas, soil erosion on the alpine territory as a whole do not exist. Moreover, we found out that few study experiences have been carried out with the aim of deepening the matter of the climate change impact on erosion processes in the Alps with the use of modelling techniques.

This study tries to fill these gaps. The Revised Universal Soil Loss Equation (RUSLE) was applied to the whole alpine space, with a specific setting on mountain areas for slope and rain erosivity parameters. It allowed to produce, with a spatial resolution of 100 m, the map of actual soil erosion and two further maps defining soil erosion rates in IPCC A2 and B2 scenarios. This analysis was carried out by means of the dataset the International Centre for Theoretical Physics (ICTP) of Trieste made us available. It provides daily rainfall values for the years 1960 – 1990 and for the IPCC A2 and B2 scenario 2070 – 2100.

From an integrated analysis of potential and actual soil erosion it comes out the strategic role of cover vegetation in keeping soil losses under control. By analyzing erosion values obtained with RUSLE application, it is evident that almost the whole alpine territory is subject to erosion phenomena. About 32% of the alpine space shows a rather high risk of erosion (> 20 t ha^{-1} yr^{-1}); nearly 50% shows a middle risk (2 – 20 t ha^{-1} yr^{-1}) and the remaining 18% a low risk (< 2 t ha^{-1} yr^{-1}). In the high mountain zone, in particular, more than 25% of the territory is interested by very high erosion rates (> 50 t ha^{-1} yr^{-1}).

From a comparison between actual erosion and soil losses in A2 and B2 scenarios it comes out that our model does not show relevant raises in erosion rates. However, low variations in soil losses rates are observable. In particular, B2 scenario shows a growth of low entity of soil losses over a significant part of the alpine space. In A2 scenario a clear distinction between northern and southern Alps comes out. Northern part should experience a low reduction of soil erosion, whilst in southern areas a rise of soil losses could take place.

On the Italian side of the alpine area, future trends of soil erosion have been investigated taking into account, besides climate data, land use and land cover scenarios. The analysis showed, over the Italian alpine territory, a geographical distribution of soil loss levels similar to the previous assessments. A general very low raise in erosion rates is expected, with an exception for the areas where, according to CLUE-s model simulations, an increase in urban conglomerations and in the extension of forests and permanent crops will occur, to the detriment of arable lands.

2. INTRODUCTION TO SOIL EROSION

Soil erosion is becoming one of the questions that most deserve the attention of the entire world community.

The European Union in the Sixth Environment Action Programme (Environment 2000-2010: our future, our choice. Decision of the European Council and Parliament 1600/2002/CE) ratifies that it is necessary to protect soil against the degradation it is subject to, due to the influence of human actions. Moreover, the same Programme ratified the necessity of a thematic strategy for soil protection to be fixed by the services of the European Commission. This document was written by the DG-Environment of the European Commission with the title: "*Towards a protection strategy of soil in Europe*" (COM (2002) 179). The document takes into consideration eight main threats of soil degradation, three of which are a priority, including the risk of soil erosion.

In September 2006 the thematic strategy was revised (COM (2006) 231 final) and was named as "*Thematic strategy for soil protection*". Meanwhile the framework directive for soil protection was proposed to the European Council and Parliament (COM (2006) 232 final). The thematic strategy estimates that almost the 12% of the European territory, consisting of 115 million hectares, is subject to water erosion.

Erosion is a complex phenomenon which is affected by many factors such as: climate, soil, morphology, soil cover and, last but not least, the excessive human action on the territory.

At present it is estimated that in the Mediterranean region water erosion could affect the loss of 20/40 t ha^{-1} of soil after a single cloudburst, and in extreme cases the erosion could be of even more than 100 t ha^{-1} (Morgan, 1992).

2.1 Driving forces and processes

Superficial erosion is defined as the particles detachment and entrainment from a loose sediment, identified as soil from an engineering point of view. The phenomenon is also known as soil erosion. Erosion regards, in fact, superficial incoherent sediments including detrital ones, soils as indicated by soil or agricultural science and clayey or incoherent sediments of any origin and age (Casati, 1996).

The most important detachment agent is rain, but the complex phenomenon of erosion is influenced also by other important factors. Erosion is basically caused by three kinds of reasons:

- Geological factors (including rocks tectonics or lithology).
- Modelling agents (water, wind, human action).
- Climate conditions (sun radiation, air humidity, atmospheric pressure, temperature, rain type and distribution) (APAT, 2003).

The forces causing erosion are of two types: endogenous (seismic and tectonic phenomena, etc.) and exogenous (phenomenon related to atmosphere, biosphere and hydrosphere); the latter are the first cause of modelling of dry land. Many different factors affect the erosion processes:

climate, soil, morphology, vegetation, agronomic activity, intervention on and settlement of slopes. All these factors are defined as "elementary factors" of the erosion process.

A further distinction can be made between "energetic factors" (precipitation, runoff, slope and slope length, responsible for the entrainment of soil particles), "resistance factors" depending on the soil characteristics (texture, structure, organic substance, permeability, salinity, etc.) and "anthropic factors" (use of soil, agricultural activity, anticorrosive action).

The erosion phenomenon basically takes place when the energetic factors affect the soil that sets against erosion through its resistance factors. Anthropic factors can determine reductions as well as increases of soil loss (APAT, 2003). As a consequence, an estimation of erosion risks is needed as a support to all decisions, in order to put in practice all the necessary interventions aimed at limiting soil loss.

Erosion is a natural process. The anthropication of the territory caused it to be embittered, generating detriments for human and injuries to the environment.

A clear distinction has to be done between damages caused by soil erosion processes at local level (on-site effect) or in places far from the sites where the loss of soil occurs (off-site effect). The following table (Table 1) lists different kind of on-site and off-site erosion damages.

Kind of erosion	On-site damages	Off-site damages
Water	• Loss of organic matter. • Soil structure degradation. • Soil surface compaction. • Reduction of water penetration. • Supply reduction at water table. • Surface erosion. • Nutrient removal. • Increase of coarse elements. • Rill and gully generation. • Plant uprooting. • Reduction of soil productivity.	• Floods. • Water pollution. • Infrastructures burial. • Obstruction of drainage networks. • Changes in watercourses shape. • Water eutrofication.

Table 1: on-site and off-site effects of erosion (Giordano, 2003)

Erosion is a natural process which usually does not cause any major problem. It becomes a problem when human activity causes it to occur much faster than under normal conditions.

2.2 The study of soil erosion over the Alpine Space

A great number of studies have been carried out aiming at an evaluation of water erosion in the alpine territory. In some areas, in fact, the phenomenon is particularly intense and the erosion rates are high. A literature review on the topic has been carried out and it showed that:

- a lot of research has been done to investigate the physical phenomena on which basis the erosion processes take place, in alpine territory as well as in areas with a complex morphology. These studies show how complex the erosion phenomenon is and how it is influenced by environmental factors. Some of these factors are particularly critical in the alpine areas, such as: the reduction in the cohesion due to ice melting (in permafrost soils), particularly intense rainfall and presence of microclimate areas characterised by specific local conditions. All these factors, together with data often lacking, make modelling soil erosion in alpine areas a challenging item. Moreover, it must be pointed out that most of the models usable to estimate erosion over large areas do not take into consideration causes of the process particularly relevant in mountain territories. Even if the most effective cause of erosion is rain it is obvious that, as human can not manage environmental conditions, the erosion process can be limited or increased by means of agricultural and forest actions. As far as soil is ultimately a finite natural resource, its defence is a priority in the view of maintaining satisfactory levels of its functions.
- Do not exist research experiences studying, by means of models specifically set for morphologically complex areas, soil erosion on the alpine territory as a whole. The only existing data are to be found in studies at continental scale as, for example, “Soil Erosion Risk Assessment in Europe – 2000”, (Van der Knijff et al., 2000) or in local studies which are not significant in view of an analysis of soil erosion in the whole alpine space.
- Few study experiences have been carried out with aim of deepening the matter of the climate change impact on soil erosion processes in the Alps with the use of modelling techniques.

Besides the literature review, a census of research institutes and projects related to erosion in the alpine space has been carried out, through focused research and web search. Table 2 and Table 3 list the main bodies, research institutes and projects whose activities and results have been used to build a picture of soil erosion processes in mountain areas.

Acronym	Subject	Focus on Alpine Space	Country
LNSA	Laboratorio Neve e Suoli Alpini	X	Italy
ISSDS	Istituto Sperimentale per lo Studio e la Difesa del Suolo	X	Italy
LaMMA CRES	Centro Ricerche Erosione Suolo		Italy
SISS	Società Italiana della Scienza del Suolo		Italy
ERSAF Lombardia	Ente Regionale per i Servizi all'Agricoltura e alle Foreste		Italy
ERSA Friuli Venezia Giulia	Agenzia Regionale per lo Sviluppo Rurale	X	Italy
UNI BASEL	University of Basel	X	Switzerland
Cemagref	Institut de recherche pour l'ingénierie de l'agriculture et de l'environnement	X	France
UZH	University of Zurich	X	Switzerland
BMLFUW	Federal Agency for Water Management	X	Austria
LTHE	Laboratoire d'étude des transferts en hydrologie et environnement	X	France
JRC	Joint Research Centre – Land management & Natural Hazard Unit	X	Europe
UIBK	University of Innsbruck		Austria
BOKU	University of Natural Resources and Applied Life Sciences		Austria
UNIBE	University of Bern	X	Switzerland
ARPAV	Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto	X	Italy
INRA	Institut national de la recherche agronomique		France
UNI-LJ	University of Ljubljana		Slovenia
APAT	Agenzia per la Protezione dell'Ambiente e per i Servizi		Italy

	Tecnici		
WSL	Swiss Federal Institute for Forest, Snow and Landscape Research	X	Switzerland

Table 2: main bodies and research institutes whose publications have been consulted

Acronym	Project	Website
	Soil Erosion in the Alps	http://pages.unibas.ch/environment/Forschung/Current_projects/Soil_degr_AlpsCA_e_01.htm
	Quantification of Soil Erosion in an Alpine Watershed of Switzerland	
ECALP	ECological soil map of ALPs	http://eusoils.jrc.it/projects/alpsis/MainAlpine.html
PESERA	Pan-European Soil Erosion Risk Assessment	http://eusoils.jrc.ec.europa.eu/Esdb_Archive/pesera/pesera_cd/sect_h4.htm
CORINE	Coordination of information on the environment	http://dib.joanneum.ac.at/alpmon/home.html
ALPMON	Inventory of alpine-relevant parameters for an alpine monitoring system using remote sensing data	http://dib.joanneum.ac.at/alpmon/home.html

Table 3: main projects whose results have been used within the study

The whole set of information collected has been entered in a purposely created database containing scientific abstracts, research projects and institutes related to erosion in the alpine space. The database has been developed using Microsoft Access and has been structured in order to obtain the needed information easily and promptly (

Figure 1).

Figure 1: a database page with information about scientific articles

A file of each article included in the database is available with the complete bibliographical information as well as an abstract. For each institute we made a summary of its main activities. Finally, for each research project general information main objectives and expected or obtained results were entered.

2.3 Modelling soil erosion

2.3.1 Review of soil erosion models

Many methods and models are available to evaluate soil erosion. The models, even if based on some fundamental factors of the erosion process, are different especially in terms of data processing and accuracy of results. As for the latter, models can be classified as follows:

- Qualitative models.
- Semi-quantitative models.
- Quantitative models.

Qualitative methodologies are based on the direct observation of the erosion processes, on air photo interpretation of erosion forms and on the study of the geomorphologic cartography. The soil erosion prediction, in this case, is interpreted as the estimation of its extension in adjacent areas which are similar in terms of pedoclimatic, geomorphologic and land use features. This approach permits to define the different types of risk, but does not provide any data about the quantity (ha yr^{-1}) of removed soil.

The semi-quantitative approach consists of a score-based procedure. On the basis of the best professional judgment, it assigns weights to the determinants of soil erosion proportionally to their relative importance in the erosion process. The main examples of models using a semi-quantitative approach are: the Graviloc Model (1959) and, above all, the P.S.I.A.C. (1968) model. The P.S.I.A.C. model provides a very easy way of use as well as the possibility of identifying rough estimation errors. Its use offers a value of soil erosion in five different intervals. The use of the P.S.I.A.C. model implies the relation between each of the nine parameters (geology, soil, climate, runoff, topography, land use, vegetation, areal erosion, lack of sediment at river mouth) and the corresponding value on the basis of a qualitative evaluation of the physiographic characteristics of the basin (APAT, 2003; ARSSA, 2005).

The more and more complex knowledge of the mechanisms that rule the soil erosion processes permitted to create more and more advanced and reliable models. The quantitative approach is based on the parameterization of the different factors determining erosion. Four different categories of quantitative models exist:

- Empirical.
- Conceptual.
- Physically based.
- Stochastic.

The empirical models are based on observations and on mutual relations, statistically obtained, arising from the analysis of experimental data. They are subject to an inductive logic and can be applied by model calibration. The most important empirical models are: the USLE (Universal Soil Loss Equation) of Wischmeier and Smith (1978) and the RUSLE, derived from USLE.

In 1985, during a meeting, the United States Department of Agriculture (USDA) and other experts in the field of erosion decided to revise the USLE model. They introduced further scientific and technological improvements developed after the release of the USLE manual in 1978. The revision of USLE started just two years later, in 1987, and led to the creation of a new model: the RUSLE. The RUSLE model maintains the base structure of USLE.

Both models consist of a set of equations estimating the soil loss deriving from rill erosion processes (rill – inter rill erosion). The models started from the study of erosion processes concerning a high number of years of parcel observations. The equations they are based on are validated and supported by many scholars (Soil and Water Conservation Society, 1993).

These two models use values referring to the four main erosion factors, such as: climate erosivity (represented by R), soil erodibility (K), topography (LS) and land use and management (CP):

$$\mathrm{A} = R * K * L * S * C * P$$

Even though the structure of USLE has not been changed, the algorithms used to calculate the single factors have been significantly modified in RUSLE. The most relevant improvement introduced by RUSLE consists, perhaps, in the introduction of GIS (Geographic Information System) techniques to determine the erosion factors. Although their limitations (explained in the next paragraphs), they have been largely used, probably because of their simplicity and strength (Desmet & Govers, 1996).

Conceptual models lie somewhere between physically based and empirical models. They are based on:

- physical laws and mathematical equations such as, for example, the continuity equation for water and sediments.
- Empirical relations.

Conceptual models have been focused on predicting sediment yields, primarily using the unit hydrograph concept. Meyer and Wischmeier’s (1969) model (Figure 2) is one of the most important models of this category. It considers rainfall and superficial runoff as erosion agents.

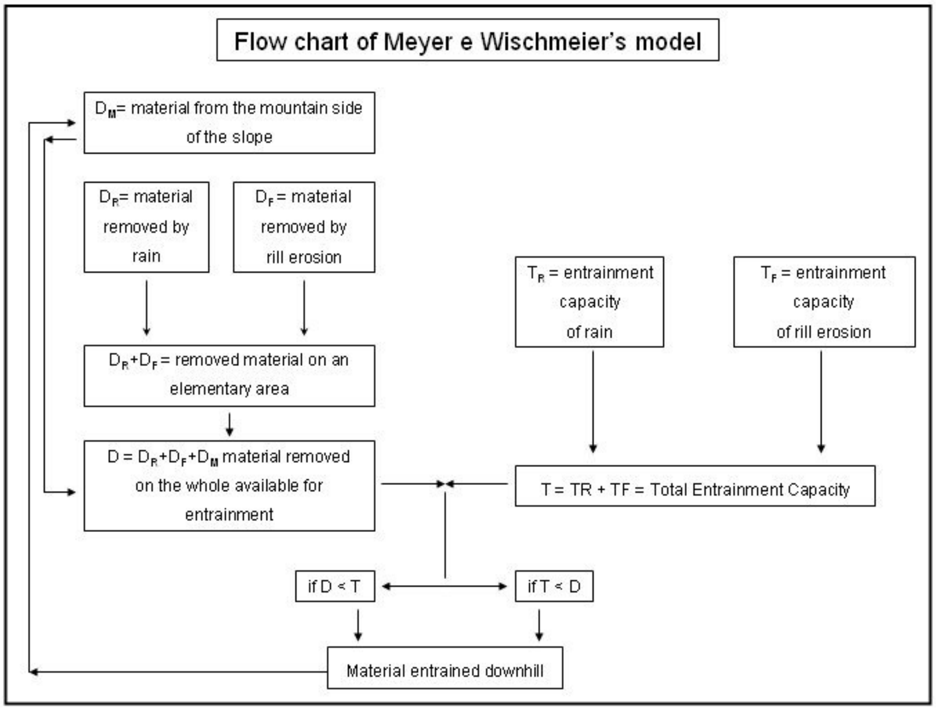

Figure 2: Meyer and Wischmeier's model flow chart

Physically based models try to describe, on the basis of suitable mathematical equations, the essential mechanisms controlling the erosion processes. This kind of models represents a synthesis of the single components causing erosion, including the complex interactions among various factors and their variability in space and time. The result is synergistic, the model as a whole represents more than the sum of the individual pieces. An advantage of physically based models is that they can be improved while deepening the knowledge of natural processes. Among these models, the one with the highest number of studies is WEPP (Flanagan e Nearing, 1995). Developed by the USDA, WEPP is widely used as the USLE successor. WEPP analyses the different processes, both hydrologic and erosive, simulates different elements (climate, wind, etc) and assesses their effects on erosion, using a variable time scale. One of the main limits of this model is that it works on a large scale just on areas having a maximum extension of a few hundreds hectares. Another widespread model is SWATT (EPA, 2002). It differs from WEPP because it works on smaller geographic scales and on annual time scale only. In Europe a physically based model has been recently implemented, EUROSEM. It has been developed on the basis of WEPP but trying to adapt it to the European continent situation.

Even though there is plenty of studies, most of which are still in progress, it is not clear yet whether it is possible to model all the factors affecting soil erosion processes. The complexity of some factors (microbiological, chemical, micro climatic), in fact, could be possibly better analysed through stochastic models. They are used to create random data sequences given in relation to the statistic characteristics of the available data (APAT, 2003).

Models results, compared with values obtained through direct measurements, often provide an unsatisfactory feedback. This is because all models generally need to be set on the specific conditions of study areas. As a matter of fact, soil erosion models basically overestimate the erosion caused by not very erosive rainfalls and, on the contrary, underestimate it in case of extreme events (Nearing et al., 1999). In spite of their limits, the erosion models (a list of the main model is in Table 4) are fundamental to evaluate which factors can be modified by human action and in which way, in order to reduce the phenomenon within sensible tolerability limits.

Soil Erosion Models	**Empiric/Physically based /Parametric**	**Single events/Continuous**	**Field scale/Basin/ Region**	**Data request Low/Medium/High**	**Complexity Low/Medium/High**	**GIS Integration Low/Medium/High**	**Difficulty of use Low/Medium/High**
USLE (Wischmeier & Smith 1978)	E	S/C	F/B	M	M/H	H	M
EPIC/apex/almanac (Sharpley & Williams 1990)	E	C	F	M	M	L	M
RUSLE (Renard et al. 1991)	E	C	F/B	M	L	M	L
AGNPS (Young, R.A. et al. 1989).	E	S/C	F/B	M	L	H	L
MUSLE (Williams, 1975)	E	S	F/B	M	L	L	M
USPED (Mitasova et al. 1996),	E	C	F/B	M	M	M	L
CREAMS (Knisel, 1980)	Ph	S/C	F	H	M	L	H
SWRRB (Arnold et al.1990)	Ph	C	W	M	M	L	L
PSIAC (1968)	Ph	C	L	L	L	M	H
SPUR (Hanson et al. 1992)	Ph	C	F/B	M	H	L	H
SWAT/HUMUS (Arnold et al. 1995)	Ph	C	B/L	M	M/ H	H	M
GLEAMS 2.1 (Knisel, 1993)	Ph	C	F	H	M	M	H
CASC2D (Julien & Saghafian 1991).	Ph	S/C	B	M	M	H	L
MULTSED (Simons et al. 1980)	Ph	S	B	H	H	L	H
ARMSED (Riggins et al 1989)	Ph	S	B	H	H	L	H
WEPP prof/basin (Flanagan & Nearing 1995)	Ph	C	F/B	M	M	L	M

SIMWE (Mitas & Mitasova, 1998)	Ph	S	F/B	M	M	H	M
ANSWERS (Beasley et al., 1980)	Ph	S	F/B	M	M	H	M
KINEROS (Woolhiser et al., 1990)	Ph	S	F/B	H	M	L	M
EUROSEM (Morgan et al.1993)	Ph	S	F/B	H	H	L	M
SHE (Abbott et al.1986a,b)	Ph	S/C	F/B	H	H	M	M
SEMMED (De Jong & Riezebos 1997).	Ph	S	B/L	H	M	M	H
CSEP (Kirkby and Cox, 1995)	Ph	C	B/R	L	M	M	M
MEDRUSH (Kirkby, 1998)	Ph	C	B	H	H	H	M
EROSION3D (Werner et al., 1997)	Ph	S	F/B	H	H	H	M
ACRU (New & Schulze 1996)	E	C	F/B	H	H	L	H
PISA (Bazzoffi,1993; Bazzoffi et al. 1998)	E	C	B	L	L	H	L
AGQA (Ciccacci et al. 1987)	E	C	B	L	L	H	L
CORINE erosion (EEA, 1995)	P	C	R	L	L	H	L
PESERA (Kirby et al., 2004)	E	C	R	H	H	H	H

Table 4: summary of the main soil erosion models features (Bazzoffi, 2002)

2.3.2 A focus on mountain regions

Soil erosion is a matter of primary importance in mountain areas. The analysis of the existing studies on the topic highlights that the main research methodologies have been developed to study erosion in agricultural contexts or hill areas with a mild climate. Therefore, it is difficult to apply these methods in mountain areas, also because of the extremely complexity of the alpine system.

For this reason, some researchers assert that the most common soil erosion models, as USLE/RUSLE or CORINE EROSION, can not be efficiently applied in an alpine environment because they were designed to be used on hilly terrains for agricultural purposes where sheet and rill erosion processes are prevailing. Furthermore, the above mentioned models are not designed to consider some typical erosion processes of alpine areas, as for example the debris flows.

An efficient model to analyse the real morpho-sedimental processes, should in theory be able to:

- minimize empirical factors and be based mainly on physically based factors.
- Use strong calculation methods.
- Combine all factors involved in the process.

A step forward has been made in this direction with the introduction of new-generation models, as i.e. WEPP (de Rosa, 2004). However, as regards the research related to erosion and, in this case, alpine areas erosion, the more used model is USLE (in one of its different versions: i.e. USLE, RUSLE). As a matter of fact, it is the only model in which input data can be obtained in different ways (measurement, estimation, interpolation).

Advanced models, as WEPP, have been and still are less used because they are often less flexible to be adapted to situations that have not already been parameterized before. Furthermore, USLE is a model used on differentiated spatial scales.

Thanks to its undoubted points of strength, some parts of this erosion estimation model have been incorporated in other models, as for instance: CREAMS, AGNPS, SWAT or ANSWER.

Another advantage in the use of USLE is related to its flexibility, it is always possible to set this equation to adapt it to the environment to be analysed.

As for the alpine and, in general, high mountain areas, a new equation for the calculation of the S factor has been proposed. In other words, the equation is used for the calculation of the influence that slope may have on the estimation of soil erosion. That permitted to overcome the difficulties due to its use in complex areas from the topographic point of view, being the equation suitable to analyse slight slope areas.

USLE is, as a matter of fact, a valuable means that has been and still is largely used, nevertheless, a complete development level of the models WEPP or EUROSEM will probably cause its decline. On a large scale the data input accuracy rapidly decreases and, in addition, erosion processes change with scale and models such as the USLE are not able to cope with this.

Due to these difficulties the soil loss absolute values can not be obtained on a large scale with a reasonable level of confidence. Nevertheless, on the basis of a common data set, models such as USLE may be used conceptually to obtain a relative ranking of soil loss risk.

In the last years a series of research have been carried out to compare erosion model predictions of soil loss with measured data. As for USLE, RUSLE and WEPP, results indicate that the three models are operating at the same accuracy level in the analysis of the soil loss processes; anyway, there is a substantial difference in relation to which many researchers indicate WEPP as USLE successor. WEPP is, in fact, the only among the three models to be specifically designed to predict sediment yield.

On the basis of the above mentioned considerations, we decided to use the RUSLE model. The main reason of this choice is that RUSLE has a more flexible data processing system. A further reason is the acquired experience in the application of RUSLE both on local and continental scale. On the contrary, it is useful to highlight the fact that, as already mentioned, the RUSLE model has been designed mainly for agricultural terrains. Its application in alpine areas could hence lead to a overestimated result of the process of water erosion, above all in relation to geomorphologic factors. However, it is necessary to take into account that the main objective of this research is the assessment of the soil erosion in relation to climate change. From this point of view, the analysis of the cartographic printouts should be considered comparative and not absolute.

3. QUANTITATIVE ANALYSIS OF ACTUAL EROSION ON THE ALPINE SPACE USING RUSLE MODEL

3.1 Input data and factors

RUSLE estimates erosion by means of an empirical equation:

$$A = R * K * L * S * C * P$$

Where:

A = (annual) soil loss (t ha^{-1} yr^{-1}).

R = rainfall erosivity factor (MJ mm ha^{-1} h^{-1} yr^{-1}).

K = soil erodibility factor (t ha h ha^{-1} MJ^{-1} mm^{-1}).

L = slope length factor (dimensionless).

S = slope factor (dimensionless).

C = cover management factor (dimensionless).

P = human practices aimed at erosion control (dimensionless).

As spatial information regarding human practices aimed at protecting soil from erosion were not available, to the P factor was set value 1 and, actually, it has not considered.

The procedures used to estimate the different factors are explained in detail in the following paragraphs.

3.1.1 Rainfall-runoff

The erosion factor R, also known as rain aggressiveness factor, indicates the climatic influence on the erosion phenomenon through the mixed effect of rainfall action and superficial runoff, both laminar and rill. For the assessment of the R factor it is possible to use different procedures.

Wischmeier (1959) identified as the best indicator of rain erosivity a composite parameter, EI_{30}. It is determined, for every rain event, by multiplying kinetic energy of rain by the maximum rain intensity occurred in a time interval of 30 minutes.

Wischmeier's procedure consists in computing R factor as the average, on a consistent set of data, of the sum of EI_{30} values for the whole set of rainfall events in a year.

$$R = \frac{1}{n}\sum_{j=1}^{n}\left[\sum_{k=1}^{m_n}(E)_k(I_{30})_k\right]$$

Where:

n = number of years.

mn = number of rainfall events occurring in the nth year.

EI_{30} = product of storm kinetic energy (E) and the maximum 30 min intensity (I_{30}).

For a strict computation of R factor, a huge number of pluviometric data with high temporal resolution (30 min) is necessary. Rain aggressiveness factor probably is, among the different components of the soil loss equation, one of the most difficult to derive, above all because rainfall data with adequate temporal resolution are very difficult to obtain over large areas. Rainfall data we could collect during ClimChAlp project are not enough detailed to apply Wischmeier and Smith's procedure to compute R factor over the whole alpine space.

This is the reason because simplified formulas, with lower temporal resolution, were applied. Many of these formulas use the Fournier's index (F) modified by Arnoldus (1980).

$$F = \frac{\sum_{i=1}^{12} p_i^{\,2}}{P}$$

Where:

p = average month rainfalls.

P = average annual rainfalls.

Other equations, instead, are exclusively based on the average annual rainfalls (P).

$$P = \frac{\sum_{i=1}^{n} p_i}{n}$$

Where:

p_i = i^{th} year precipitations.

n = number of years.

Existing literature is not exhaustive with regard to the algorithms to be applied, with the aim of determining R factor, instead of the Wischmeier and Smith's EI_{30} in the alpine zone. We have hence carried out a deep analysis of some of the mostly used formulas (Arnoldus linear (1977), Arnoldus exponential (1980), Renard and Freimund (1994) - F, Renard and Freimund (1994) – P, Lo et al. (1985), Yu and Rosewelt (1996), Ferrari et al. linear (2005), Ferrari et al. exponential (2005), based on mean annual precipitation or on modified Fournier's Index (Table 5).

Author	Equation
Arnoldus (1980)	$R = [(4.17 * F) - 152]$
Arnoldus (1977)	$R = [0.302 * (F^{1.93})]$
Renard & Freimund (1994) - F	$R = [0.739 * (F^{.1.847})]$
Renard & Freimund (1994) - P	$R = [0.0483 * (P^{1.61})]$
Lo et al.	$R = [38.46 + (3.48 * P)]$
Yu & Rosewelt (1996)	$R = [3.82 * (F^{1.41})]$
Ferrari et al. (2005) – linear	$R = [(4.0412 * P) - 965.53]$
Ferrari et al. (2005) - exponential	$R = [0.092 * (P^{1.4969})]$

Table 5: commonly applied equations to estimate erosivity

With this analysis we intended to evaluate the applicability of these methods, developed in different climatic zones, on the alpine region.

A statistical analysis was hence carried out to estimate the degree of correlation (Correlation Coefficient [R^2] and Root Mean Square Error [RMSE]) between R factor values computed by means of EI30 or using the simplified formulas. The analysis was carried out on rain data with high temporal resolution available for 42 meteorological stations in Veneto region, inside the alpine territory. Data were supplied by ARPAV (Agenzia Regionale per la Prevenzione e Protezione Ambientale del Veneto).

With the aim of computing the correlation between the simplified formulas and Wischmeier's R factor, Pearson (r) correlation coefficient was used.

$$r = \frac{\sum (x - \bar{x}) * (y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 * \sum (y - \bar{y})^2}}$$

Where:

x and y = original data and modelled values, respectively.

$\bar{x}$ = mean original data.

$\bar{y}$ = mean modelled data.

R^2 is the square of the r correlation coefficient. It can be interpreted as the ratio between y variance imputable to x variance.

RMSE can be computed by mean of the following formula:

$$RMSE = \sqrt{\frac{1}{n} * \sum_{i=1}^{n} k_i^{\,2}}$$

Where:

n = the number of location subjected to validation.

k_i = the difference between R estimated and R (EI_{30}).

It soon came out a clear difference between formulas based on modified Fournier's Index and the ones using mean annual precipitations. The latter show higher values of R^2.

A first analysis compared EI_{30} erosivity index with R factor values estimated by means of the simplified formulas. Looking at data distribution (Figure 3), it comes out that all simplified formulas over or under-estimate R factor. Among all the other, with growing over or under-estimations at higher R values, Lo et al. (1985) and Ferrari et al. linear (2005) equations show a systematic over-estimation. Lo et al. and Ferrari et al. linear equations show the highest R^2 and among the lowest RMSE values (Table 6). Compared to Lo's equation, Arnoldus (1980) formula shows a lower RMSE value but its R^2 is inferior and its trend inconstant: the higher are R (EI_{30}) values, the higher are the errors. The maximum error caused by Arnoldus is higher than the Lo's one. All these reasons make the equations proposed by Ferrari et al. linear and Lo preferable in comparison with Arnoldus's formula.

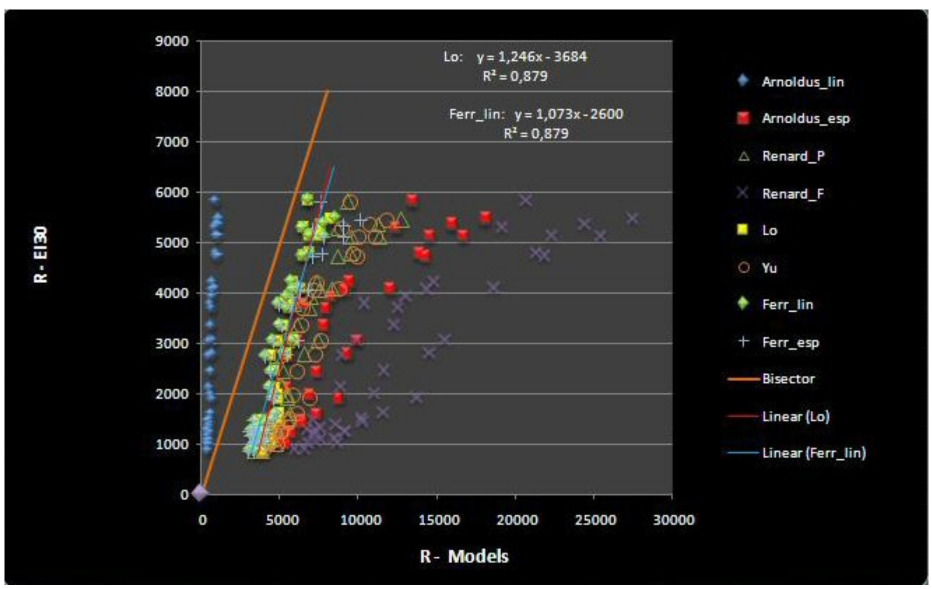

Figure 3: comparison between R factor values obtained with EI_{30} method and simplified formulas

	Arnoldus linear	Arnoldus exponential	Renard P	Renard F	Lo	Yu	Ferrari linear	Ferrari exponential
r Pearson	0.9182	0.9075	0.9292	0.9088	0.9378	0.9146	0.9378	0.9312
R^2	0.8431	0.8236	0.8635	0.8259	0.8795	0.8365	0.8795	0.8672
RMSE	2460	5907	3617	10860	2509	3844	2310	2510

Table 6: r Pearson, R^2 and RMSE values arising from the statistical analysis between R (EI_{30}) and simplified formulas

Ideally, none of the formulas we tested can be considered suitable for a quantitative estimation of erosion on the alpine territory. Unfortunately, the lack of data with adequate resolution got us to apply the best one among them.

Ferrari et al. linear equation shows, with the same R^2, lower RMSE values compared with Lo's formula. In spite of it, we decided to use the latter because pluviometric available data were acquired in Veneto region and we could not determine if they were representative of the whole alpine space. We preferred, hence, to apply Lo's equation which has firm international literature, whereas Ferrari's formula is rather recent.

From simple linear transformations of the adopted formulas it came out the possibility to improve their performances (by linear transformations we mean transformations whose parameters can be obtained by means of the mean square method: that is linear, logarithmic, power, or exponential transformations). By adopting linear transformations, equations showed nearly unvaried R2 values, whereas RMSE values basically improved. As an example, Lo's formula RMSE value 2500 becomes 549.

Due to the limited area the pluviometric data covered and as they were not representative of the whole alpine space, it was not possible to develop a new equation for R estimation.

The rainfall measurement data we used to determine rainfall erosivity factor on the whole alpine space have been provided by the International Centre for Theoretical Physics (ICTP) of Trieste. These data are the output of a prevision model of the climatic change (RegCM, Regional Climate Model), that provides the daily rainfall values for the years 1960 – 1990 and for the IPCC A2 e B2 (2070 – 2100) scenarios. RegCM is a 3-dimensional, sigma-coordinate, primitive equation regional climate model. Version 3 is the latest release. Different reasons explain the choice to use modelled instead of measured data:

- we decided to use dataset sharing the same origin to make more significant comparisons between actual and future rate of erosion.
- Modelled data have homogeneous spatial distribution and accuracy over the alpine space. It warranties to make analysis with the same level of accuracy over the whole study area.

- Last but not least, ICPT data were promptly available at the beginning of the project.

With the use of GIS interpolation techniques and the application of Lo's formula we obtained the current spatial distribution of the erosivity factor R in the Alps (1960-1990) (Figure 4).

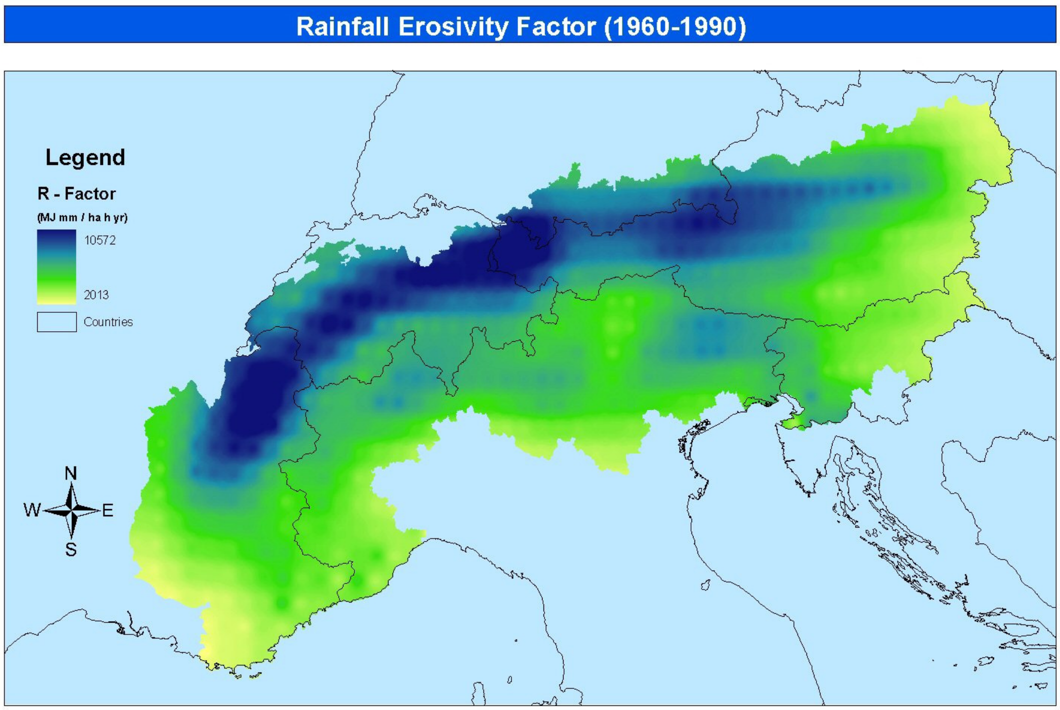

Figure 4: Rainfall Erosivity Factor map (Lo, 1985) based on historic series 1960 – 1990 (MJ mm ha^{-1} h^{-1} yr^{-1})

3.1.2 Soil erodibility

The soil erodibility factor K indicates the erosion tendency of soils. It is defined as the unit erosion index for the R factor in relation to a standard fallow parcel (22.13 m length; 9% slope). On this basis, the value of factors such as length, slope, cultivation and anti-erosion actions becomes unitary. K is usually estimated using the normograph and formulae that are published in Wischmeier e Smith (1978). While these equations are suitable for large parts of USA, they are not ideally suited for European conditions. Romkens et al. (1986) performed a regression analysis on a world-wide dataset of all measured K-values, which yielded the following equation (revised in Renard et al.. 1997):

$$K = 0.0034 + 0.0405 * \exp\left[-0.5\left(\frac{\log D_g + 1.659}{0.7101}\right)^2\right]$$

Where D_g is:

$$D_g = \exp\left(\sum f_i * \ln\left(\frac{d_i + d_{i-1}}{2}\right)\right)$$

D_g is the geometric mean weight diameter of the primary soil particles (mm) and, for each particle size class (clay, silt and sand), d_i is the maximum diameter (mm), d_{i-1} is the minimum diameter and f_i is the corresponding mass fraction.

The database of European soils (SGDBE), in scale 1:1.000.000, has been used to define the soil erodibility factor (Heineke et al., 1998). Texture information in the database is stored at the soil typological unit (STU) level. Each soil mapping unit (SMU) is made up of one or more STU. Due to the type of data concerning the soil texture in the database, some further data processing has been necessary. The processing led to the creation of a soil erodibility value (Table 7) in relation to the texture class (Van der Knijff et al., 2002). For each SMU, a K-value was estimated for all its underlying STU. Then a weighted average was computed, where the weights are proportional to the area of each STU within a SMU. The resulting erodibility map is shown in the following map (Figure 5).

TEXT	Dominant surface textural class				
	(Present in: STU)	% clay	% silt	% sand	K
0	No information	-	-	-	
9	No texture (histosols,...)	-	-	-	
1	Coarse (clay <18% and sand > 65%)	9	8	83	0.0115
2	Medium (18% < clay <35% and sand > 15% or clay <18% and 15% < sand < 65%	27	15	58	0.0311
3	Medium fine (clay < 35% and sand < 15%)	18	74	8	0.0438
4	Fine (35% < clay < 60%)	48	48	4	0.0339
5	Very fine (clay > 60%)	80	20	0	0.0170

Table 7: representative texture parameters for each texture class

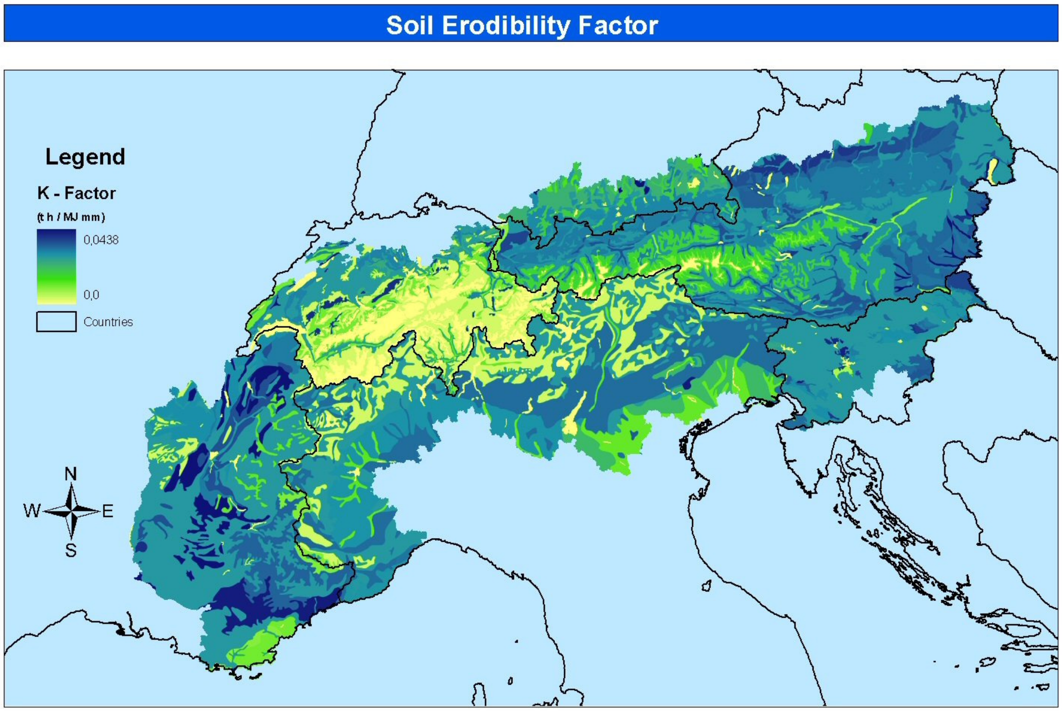

Figure 5: Soil Erodibility Factor map (t ha h ha^{-1} MJ^{-1} mm^{-1})

3.1.3 Slope and Length

The main innovation of the RUSLE model, in comparison with the original model (USLE), is the LS factor. The factor considers the flows convergence and is the result of the combination of the slope (S) and length (L) factors. Many methods have been proposed to improve the calculation of the topographic factor LS, but just in the last ten years a certain accuracy has been reached thanks to the implementation of GIS systems and of digital elevation model (DEM). The L Factor has been substituted by the Upslope Contributing Area (UCA) (Moore and Burch, 1986; Desmet and Govers, 1996), in order to consider the convergence and divergence of the superficial runoff. The UCA area is where water flows in a given cell of the grid. L and S factors have been determined through GIS procedures carried out using the following relation of Moore and Burch (1986):

$$LS = \left(\frac{A}{22.13}\right)^m * \left(\frac{sen\alpha}{0.0896}\right)^n$$

Where:

A = drainage area of a point belonging to a certain cell of the grid.

α = slope.

As suggested by many researchers, the values m and n are considered respectively as 0.4 and 1.3. For the calculation of the LS factor the DEM SRTM (Shuttle Radar Topography Mission) has been used. The accuracy of the DEM is of 90 m.

LS calculation in complex hillslopes is generally problematic for traditional USLE applications, particularly when slope morphology shows great spatial variability (Moore and Burch, 1986; Engel, 1999; Mitasova, 2002). The topographic complexity of the alpine territory, consisting in steep slopes and complex ravine networks, presents significant challenges in estimating the S factor. Therefore, we preferred to modify Moore and Burch's equation. The S factor has been evaluated using Nearing's (1997) formula, that provides more reliable results at high slopes (more than 50%) than those provided by RUSLE, which is used in case of lower slopes.

$$LS = \left(\frac{A}{22.13}\right)^{0.4} * S$$

Where:

$$S = -1.5 + \frac{17}{\left(1 + e^{(2.3 - 6.1 sen\alpha)}\right)}$$

The formula was applied in a GIS environment. A factor has been substituted with the result of the flow accumulation (Flowacc) multiplied by the pixel dimension (cell size). Flowacc consists of the number of cells bringing runoff water to each pixel in the grid.

$$LS = \left(\frac{Flowacc * cell\_size}{22.13}\right)^{0.4} * \left(-1.5 + \frac{17}{\left(1 + e^{2.3 - 6.1 sen\alpha}\right)}\right)$$

The application, in GIS environment, of the above formula brought to the generation of the LS factor map for the alpine space (Figure 6).

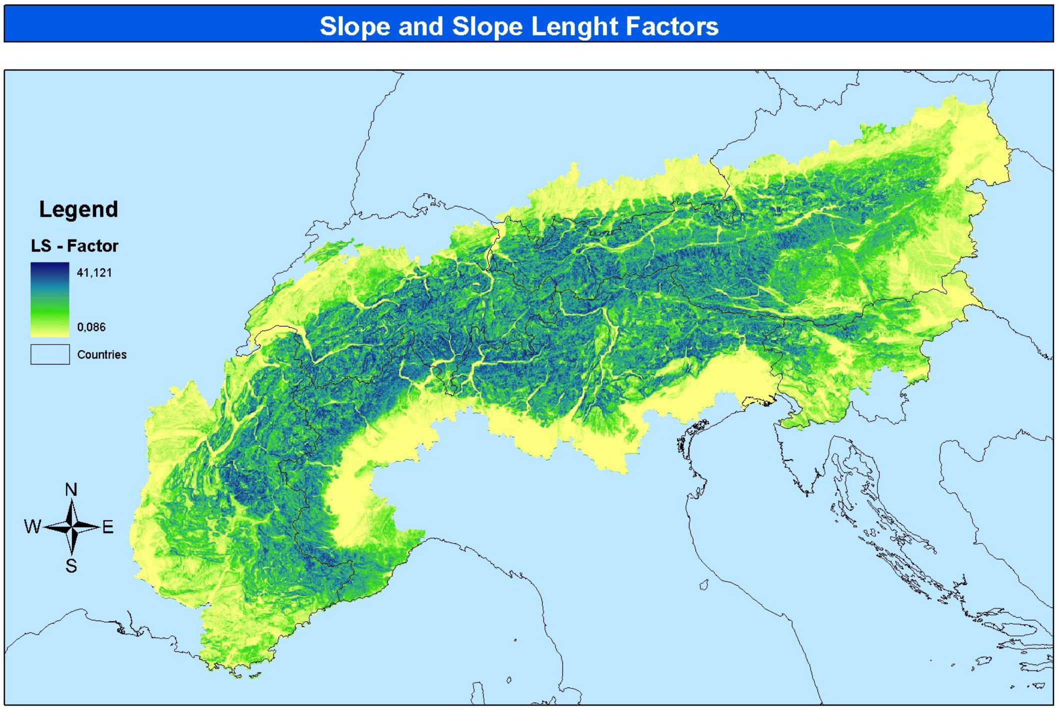

Figure 6: Slope and Slope Length factor map (dimensionless)

3.1.4 Soil cover management

The soil cover factor represents the influence on soil loss of vegetation, terrain cover, agricultural activity, management of agricultural residuals and of soils. The C factor represents the relation between the soil loss in certain agricultural or cover conditions and the erosion that would be obtained from a standard fallow parcel (bare soil). The evaluation of this factor is difficult, because it always depends on changes in terms of environment, cultivations, agricultural activities, residuals management and on the morphology of the plant in the year. The C factor for a certain soil cover typology may have different values. Due to the lack of detailed information and to the difficulties in processing all factors on a large scale, it is difficult to use RUSLE guidelines to estimate the soil cover parameter. Therefore, the average values of literature have been used for this aim (Suri, 2002; Wischmeier and Smith, 1978). The necessary data to establish the C parameter have been provided thanks to the Corine project, a European programme aimed at reproducing maps about soil use, analysing the image of the whole Europe provided by satellite. The calculation of the soil cover factor has been processed using the information layer Corine Land Cover 2000 (CLC 2000) third level. The information layer CLC 2000 is not available for the Switzerland territory. For this area, we decided to use the CLC 1990, in which the Helvetian region is covered. The legends of the Swiss and of the rest of the alpine territory information layers were different. Hence, an intervention aimed at uniforming the data was necessary. To this aim, everything has been traced to the 44 classes of soil use/cover established in the CLC 2000. A C factor value has been assigned to every class, based on literature data (Table 8).

Class ID	Classes	C factor
111	Continuous urban fabric	0.000
112	Discontinuous urban fabric	0.000
121	Industrial or commercial units	0.000
122	Road and rail networks and associated land	0.000
123	Port areas	0.000
124	Airports	0.000
131	Mineral extraction sites	0.000
132	Dump sites	0.000
133	Construction sites	0.000
141	Green urban areas	0.001
142	Sport and leisure facilities	0.001
211	Non-irrigated arable land	0.335
212	Permanently irrigated land	0.335
213	Rice fields	0.335
221	Vineyards	0.550
222	Fruit trees and berry plantations	0.550
223	Olive groves	0.550
231	Pastures	0.010
241	Annual crops associated with permanent crops	0.400
242	Complex cultivation patterns	0.335
243	Land principally occupied by agriculture. with significant areas of natural vegetation	0.100
244	Agro-forestry areas	0.400
311	Broad-leaved forest	0.005
312	Coniferous forest	0.005
313	Mixed forest	0.005
321	Natural grasslands	0.010
322	Moors and heathland	0.010
323	Sclerophyllous vegetation	0.100
324	Transitional woodland-shrub	0.01

331	Beaches. dunes. sands	0.000
332	Bare rocks	0.000
333	Sparsely vegetated areas	0.550
334	Burnt areas	0.550
335	Glaciers and perpetual snow	0.000
411	Inland marshes	0.001
412	Peat bogs	0.001
421	Salt marshes	0.001
422	Salines	0.001
423	Intertidal flats	0.001
511	Water courses	0.000
512	Water bodies	0.000
521	Coastal lagoons	0.000
522	Estuaries	0.000
523	Sea and ocean	0.000

Table 8: soil cover values

The cartographic result is reported in the following map (Figure 7).

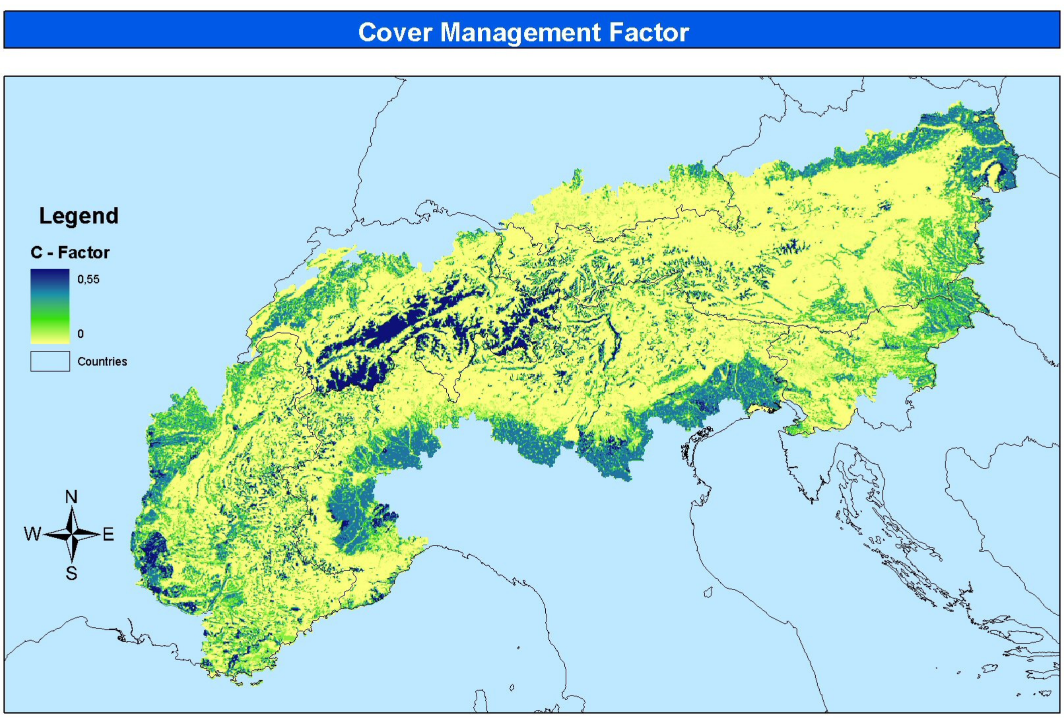

Figure 7: Cover Management Factor map (dimensionless)

Due to the complexity of the territory examined in this work, the approach we used presented some problems. The vast variety of climatic conditions in the alpine areas can cause a large variation both of space and of time in the growing season and in the strength of cultivations. Using a table-based approach, all these factors are not always easy to control. For this reason we made an attempt to use NOAA (National Oceanic and Atmospheric Administration) AVHRR (Advanced Very High Resolution Radiometer) imagery in order to obtain approximate C-factor values. It is a four (AVHRR/1) or five (AVHRR/2) channel radiometer with channels in the visible, near infrared, middle infrared and far infrared parts of the electromagnetic spectrum. The most widely used remote-sensing derived indicator of vegetation growth is the Normalised Difference Vegetation Index (NDVI). We used the Van der Knijff et al. (1999) equation to estimate the C factor starting from the NDVI values.

$$C = \exp\left(-\alpha * \frac{NDVI}{(\beta - NDVI)} \right)$$

Where:

α and β = parameters determining the shape of the NDVI-C curve

The first results we obtained applying this method highlighted the inconsistency of some of the values of the C factor. Van der Knijff (1999) points out that the evaluation of the C factor from NDVI values can be unrealistic, particularly for specific categories such as: grassland and woodland.

Therefore, we decided not to use this method in order to be able to evaluate soil erosion using NDVI values in the future. It will be useful to review the equations available to adjust them correcting possible non realistic values.

3.2 Results and discussion

By integrating the different factors of the RUSLE equation, it was possible to generate, on a GIS platform, the Potential Soil Erosion and Actual Soil Erosion maps (Figure 8 - Figure 9) for the whole alpine space. They define, for each cell of analysis, the quantity of soil (t ha^{-1}) annually lost due to erosion processes.

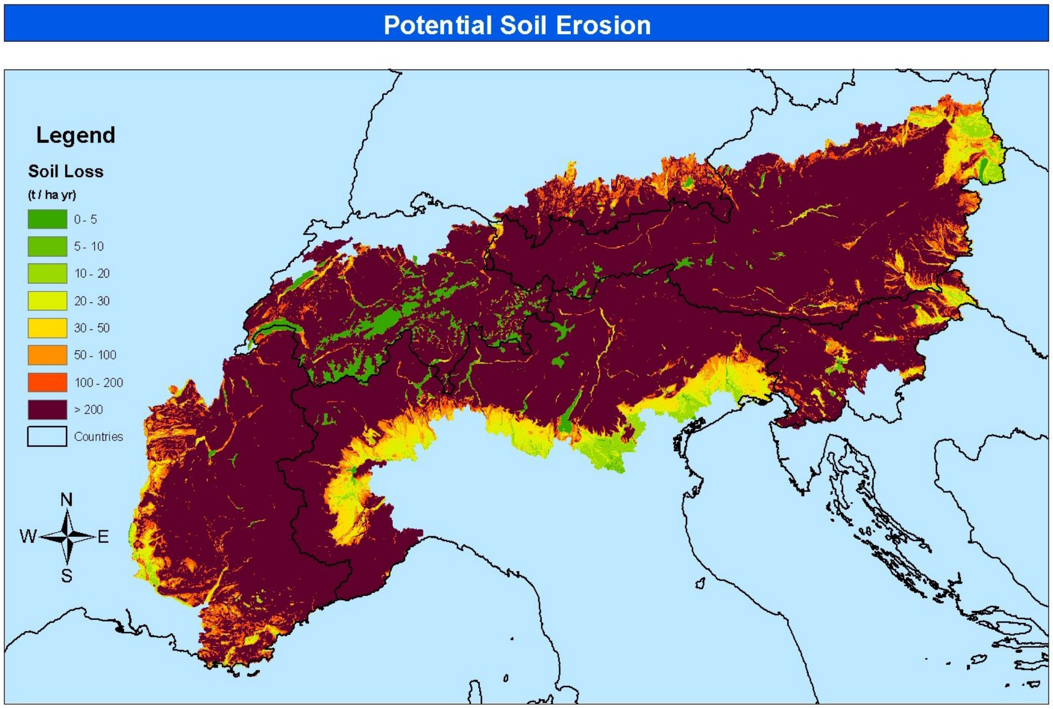

Figure 8: Potential Soil Erosion (t ha^{-1} yr^{-1})

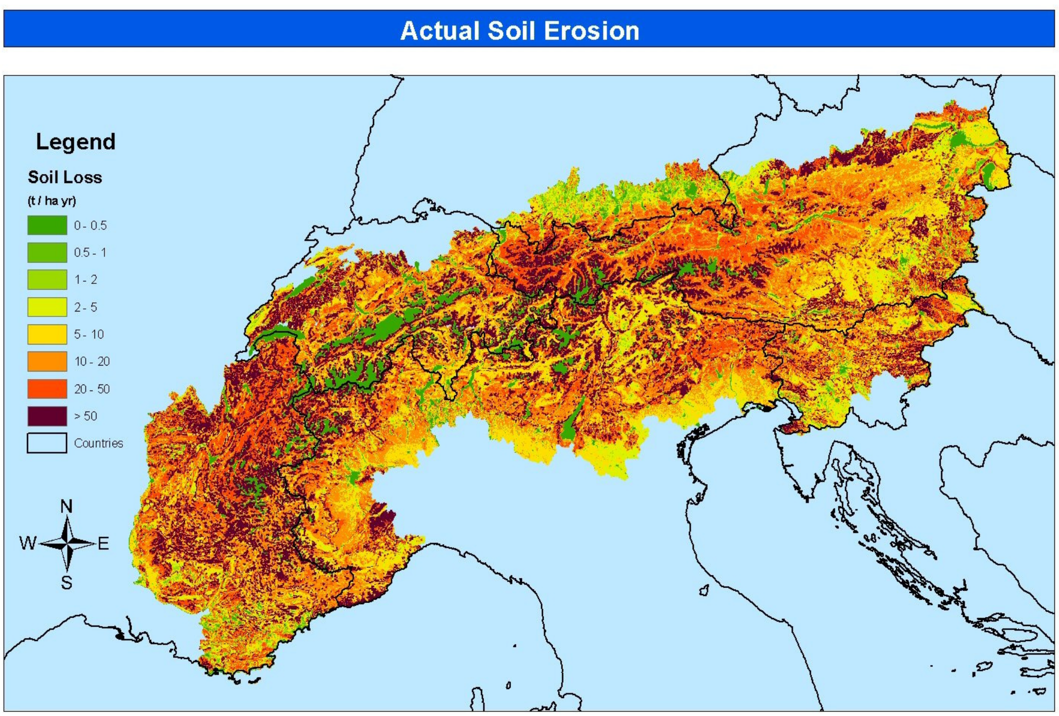

Figure 9: Actual Soil Erosion (t ha^{-1} yr^{-1})

The potential soil erosion map points out the soil loss due to the action of physical factors involved in erosion processes. Hence, it does not consider the action of soil cover. The integrated reading of the two maps show the fundamental role carried out by vegetation in areas potentially exposed to high erosion rates. The mitigating action of soil cover acts reducing kinetic energy drops of water reach the land surface with. It acts on their breaking action and, as a consequence, on translocation of soil particles (splash erosion). Besides, soil cover is a barrier against surface water flowing. This produces a further mitigation of erosive effect (sheet erosion).

By analyzing erosion values obtained with RUSLE application, it is evident that almost the whole alpine territory is subject to erosion phenomena. About 32% of the alpine space shows a rather high erosion (> 20 t ha^{-1} yr^{-1}); nearly 50% shows a middle risk (2 – 20 t ha^{-1} yr^{-1}) and the remaining 18% a low risk (< 2 t ha^{-1} yr^{-1}). Nevertheless, due to the extension of the Alpine Space (the way it has been defined by the Convention of the Alps), it is necessary to carry out a more detailed analysis, linked with geo-litho-morphologic and land use/cover parameters. As it has been previously pointed out slopes, slope length, pluviometric regime and soil cover play a crucial role in the erosive process. The study area was hence subdivided in some classes of landscapes, with the altitude acting as discriminating agent. Elevation shows, at least in the Alps, strong correlations with the other factors previously mentioned. The alpine space was therefore subdivided into four altimetrical zones:

- flat areas (< 300 m above sea level).
- Hill areas (300 – 600 m above sea level).
- Mountain areas (600 – 2000 m above sea level).
- High mountain areas (> 2000 m above sea level).

By analyzing the data relative to the altimetrical zones (Figure 10 and Figure 11), it is possible to notice the relative significance of the different factors of the model:

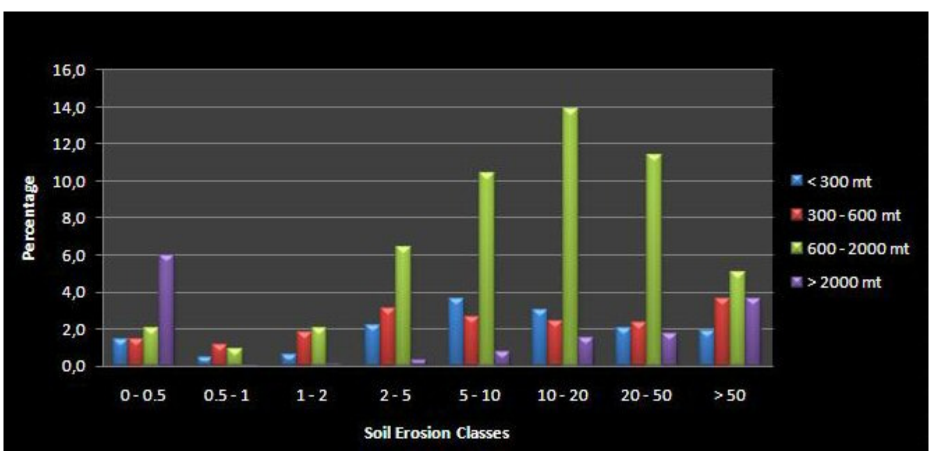

Figure 10: percentage of Actual Soil Erosion in different altimetrical zones

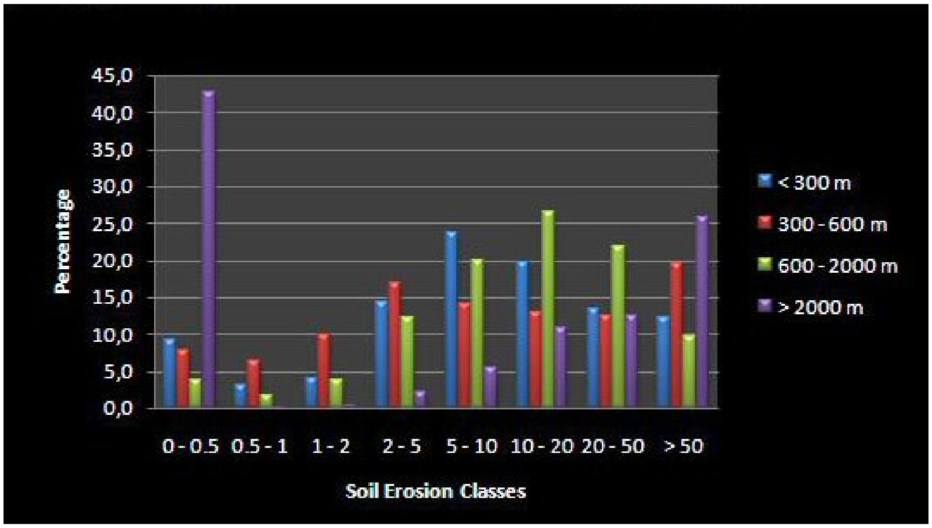

Figure 11: percentage of Actual Soil Erosion within every altimetrical zone

- in the areas below 300 m, nearly the 75% of the territory shows erosion rates lower than 20 t ha^{-1} yr^{-1}. But the remaining 25% is characterized by very high erosion rates. The observation of the C factor map allows to understand that in these areas the role of cover vegetation is low, because the most of these areas are cultivates.
- At higher altitudes (300 – 600 m), the proportion of territory with an erosion rate below 20 t ha^{-1} yr^{-1} diminishes, whilst 20% of the zone shows an erosion rate > 50 t ha^{-1} yr^{-1}. This trend is caused by an increase in slopes which produces very high risk levels in areas with poor cover. On the other hand, the presence of wooded areas contributes in keeping high the percentage of territory with risk level < 20 t ha^{-1} yr^{-1}.
- In the mountain zone (600 – 2000 m) the high presence of forests leaves nearly unchanged, as regards to the lower zones, the percentage of territory with an erosion rate < 20 t ha^{-1} yr^{-1} and allows a reduction of the areas with soil losses > 50 t ha^{-1} yr^{-1}.
- In the high mountain zone, erosion presents a very particular trend. More than 42% of these areas are not subject to soil losses. Moreover, nearly 40% of the remaining territory are interested by very high erosion rates. This is easy to explain with lithologic considerations: at these altitudes, soil is often very thin and bare rocks crops out; but in the areas where soils exist, geo-morphologic characteristics, severe rainfalls and often lacking vegetation cover make them very vulnerable.

After all, without further deepening the item, it is possible to assert that alpine space is, due to its peculiarities, highly vulnerable to erosion risk. But the widespread presence of vegetation cover allows, in a significant part of the territory, to keep it under control and this is the reason because a right management of mountainous region cannot be disregarded.

3.3 Main limits

Erosion assessment in the alpine region, obtained by applying the universal soil loss equation, specifies the quantity of soil yearly moved from a catchment. Every soil particle can undergo different removal and sedimentation cycles. In its way downstream, a huge part of the removed material can sediment due to variations of slope, superficial roughness or land use/cover. RUSLE, which does not consider the sedimentation processes, tends to over-estimate soil loss. Besides, the model is not able to simulate gully erosion, mass movements and riverbed erosion.

The application of RUSLE over the alpine territory, moreover, presented huge difficulties mainly due to problems in finding data. Unfortunately, we were not able to collect the whole set of data necessary for a strict application of the model. We have been often forced to make use of simplified equations, as for R and K factors, or use data with sub-optimal geographic scale, like for C, L and S factors. The simplified equation we used for R factor computation, in particular, though preferable to the other available, tends to over-estimate the measured rates of erosivity and makes scarcely meaningful a validation based on measured data.

These and many other uncertainties propagate throughout the model, resulting in an uncertainty in the estimated erosion rate. Despite these deficiencies and shortcomings, the methodology applied has produced valuable information on alpine soil erosion processes and on their distribution. The spatial analysis, in fact, has allowed the identification of areas which are likely to experience significant erosion rates. More detailed input data and more sophisticated erosion models might warrant a better quantitative estimation of soil losses due to water erosion.

It is however worth noticing that, despite the over-estimation problems, the geographical distribution of soil erosion rates is congruent with the expected results.

4. QUANTITATIVE ANALYSIS OF EROSION TRENDS ON THE ALPINE SPACE USING RUSLE MODEL, IN DIFFERENT CLIMATE SCENARIOS

4.1 Scenarios data

IPCC identified a set of scenarios (Figure 12) based on socio-economic esteems. They will produce an increase in greenhouse gases concentration and, as a consequence, temperatures could raise from 1.4 to 5.8 °C and rainfall regimes change. Every IPCC scenario comes out from different storylines. Each of them assumes a specific course of future development with diverging final conditions. They cover a while range of key future characteristics such as demographic change, technological and economic development.

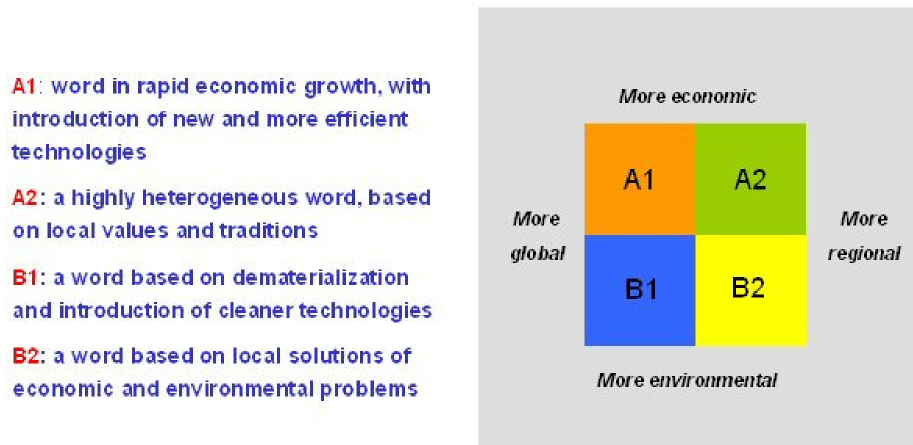

Figure 12: the different IPCC scenarios features

In A1 scenario the world is characterized by a strong economic growth, a decrease, after it has peaked at the middle of the century, in global population and new and more efficient technologies. But this scenario does not warranty on the way the world will develop. The growth, in fact, could be based on the exploitation of different kinds of resources (A1F – fossil fuels, A1T – renewable energies – A1B – both kinds of energies).

A2 scenario is referred to a very heterogeneous world, whose basic feature is the conservation of local identities. Technologic change is slower and fragmented than in other scenarios and economic growth is not very homogeneous. Climatic changes stronger than in other scenarios are foreseen.

B1 scenario shows a demographic trend similar to A1 scenario, but stronger emphasis is given to global solutions for economic, social and environmental sustainability. Raw materials exploitation and energy consumptions are reduced. Specific action aimed at climate protection are not planned.

B2 scenario is based on local solutions for economic, social and sustainability problems. Population is under non-stop growing but with rates lower than in A2 scenario. Economic growth is intermediate and technologic development is slower with respect to A1 and B1 scenarios. This scenario is hence oriented to environment protection and social equity but it focuses on local and regional levels.

4.2 Input data and factors

Climate change potential in raising soil erosion is evident, but it is difficult to estimate. The aim of our study, in the framework of ClimChAlp project, was giving an estimation of the potential impact of changing climate on soil erosion processes inside the alpine region.

The quantitative estimation of soil erosion trends resulting from ongoing climate change was carried out, like for the actual erosion definition, by means of the universal soil loss equation (RUSLE). The factor K, L, S and C layer coincided with the ones used for actual erosion estimation. Lo (1985) formula was instead used to generate new maps of erosivity factor R. To this aim ICTP RegCM A2 and B2 scenarios data were used (Figure 13 and Figure 14).

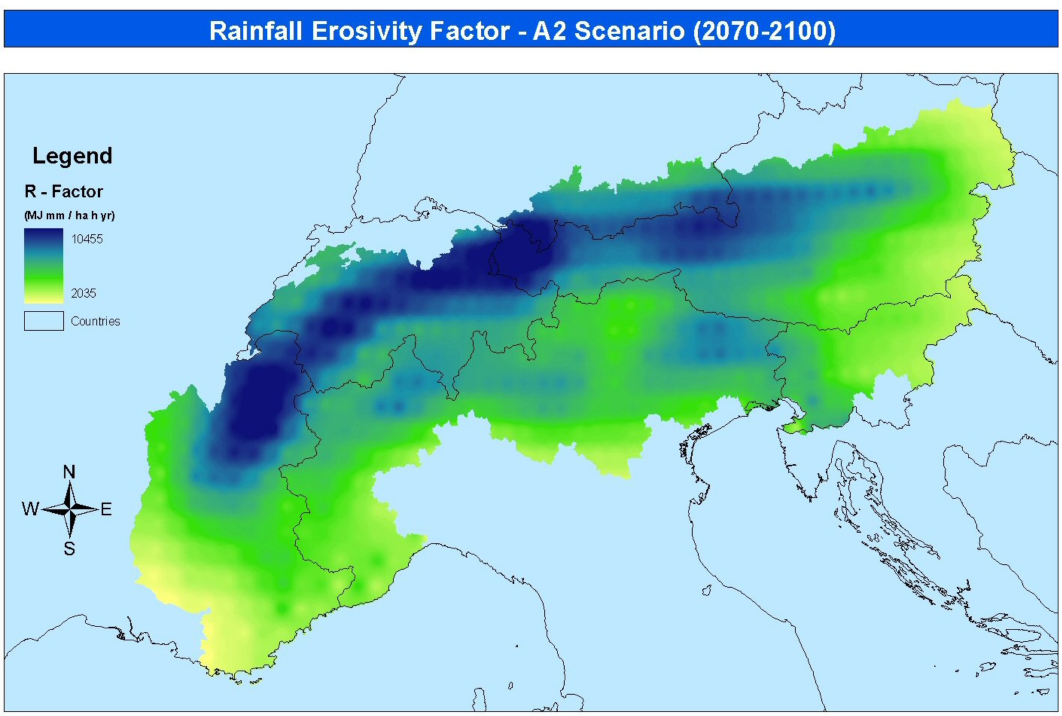

Figure 13: Rainfall Erosivity Factor map (Lo, 1985) based on A2 scenario data (2070 – 2100) (MJ mm ha^{-1} h^{-1} yr^{-1})

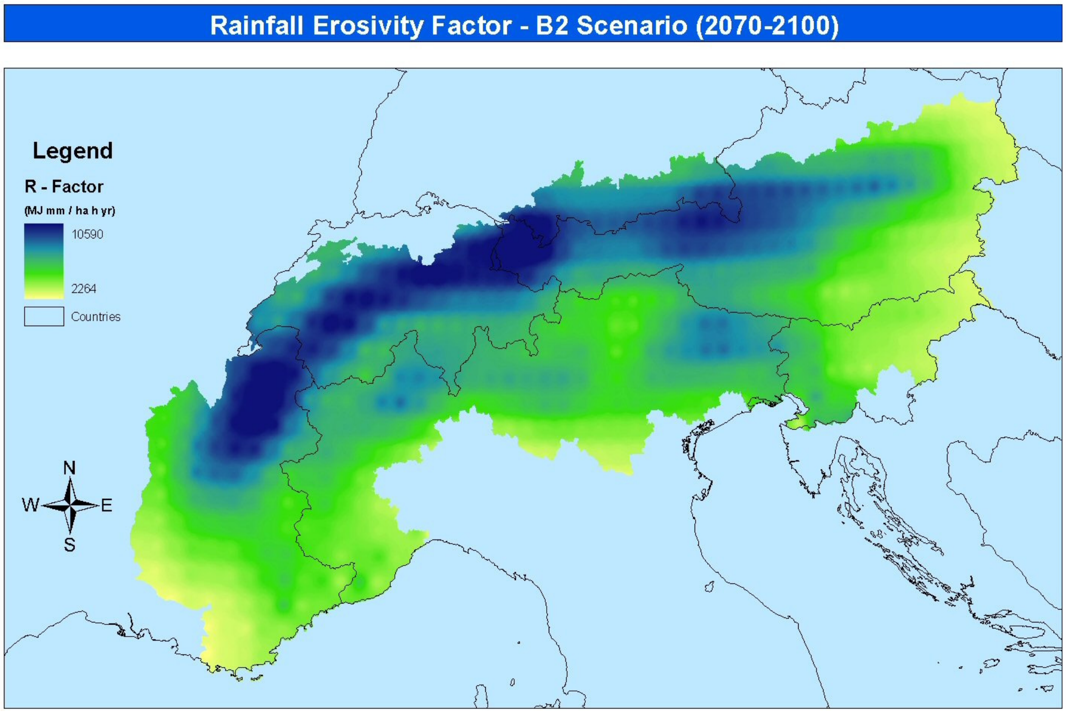

Figure 14: Rainfall Erosivity Factor map (Lo, 1985) based on B2 scenario data (2070 – 2100) (MJ mm ha^{-1} h^{-1} yr^{-1})

4.3 Results and discussion

The integration of the different factors of universal soil loss equation allowed to achieve two erosion maps based on climatic data referred to A2 and B2 (2070 – 2100) climatic data (Figure 15 and Figure 16). These maps have been compared with the map of actual erosion. The analysis allowed the definition of soil erosion trends in relation to different scenarios of climate change (Figure 17 and Figure 18).

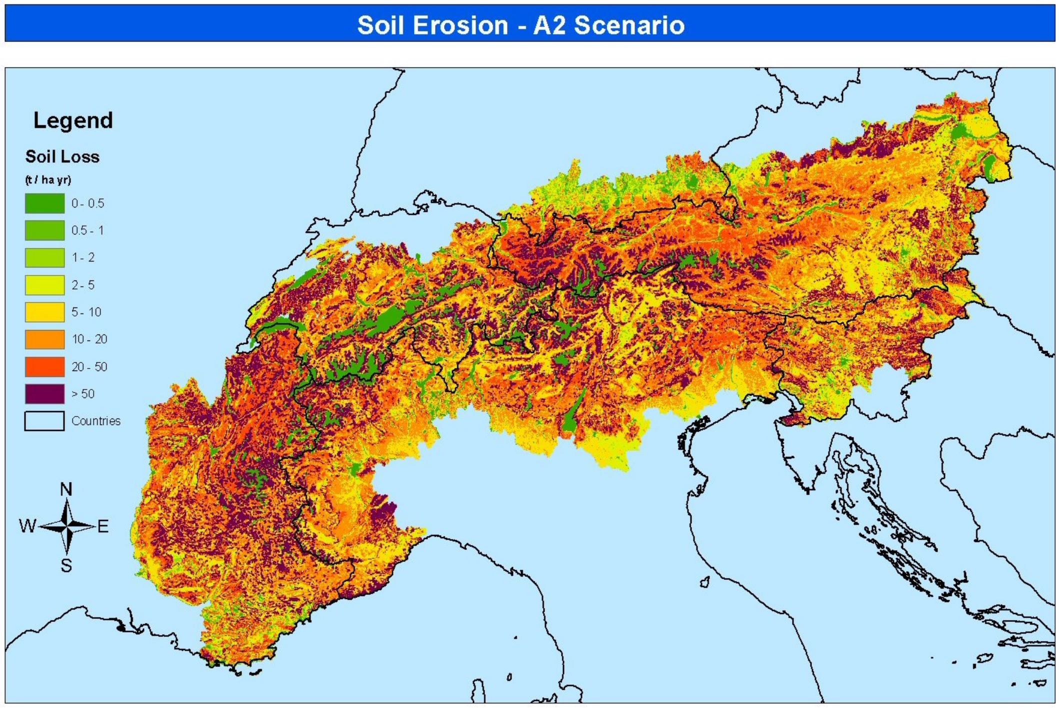

Figure 15: A2 scenario Soil Erosion (t ha^{-1} yr^{-1})

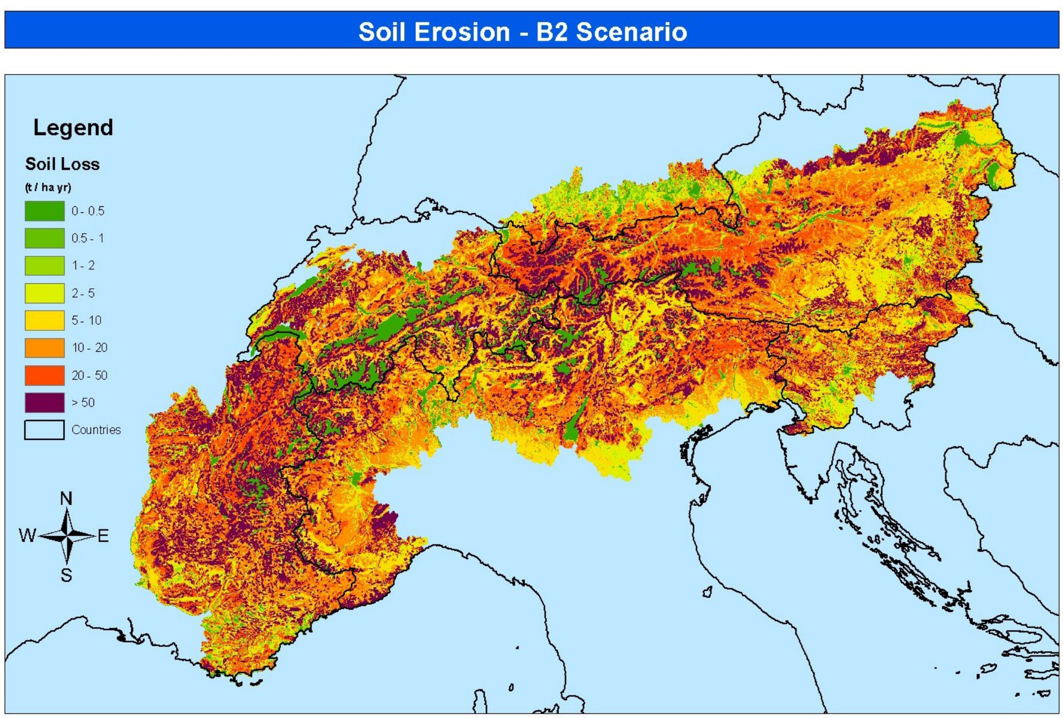

Figure 16: B2 scenario Soil Erosion (t ha^{-1} yr^{-1})

Soil Erosion - Actual VS A2

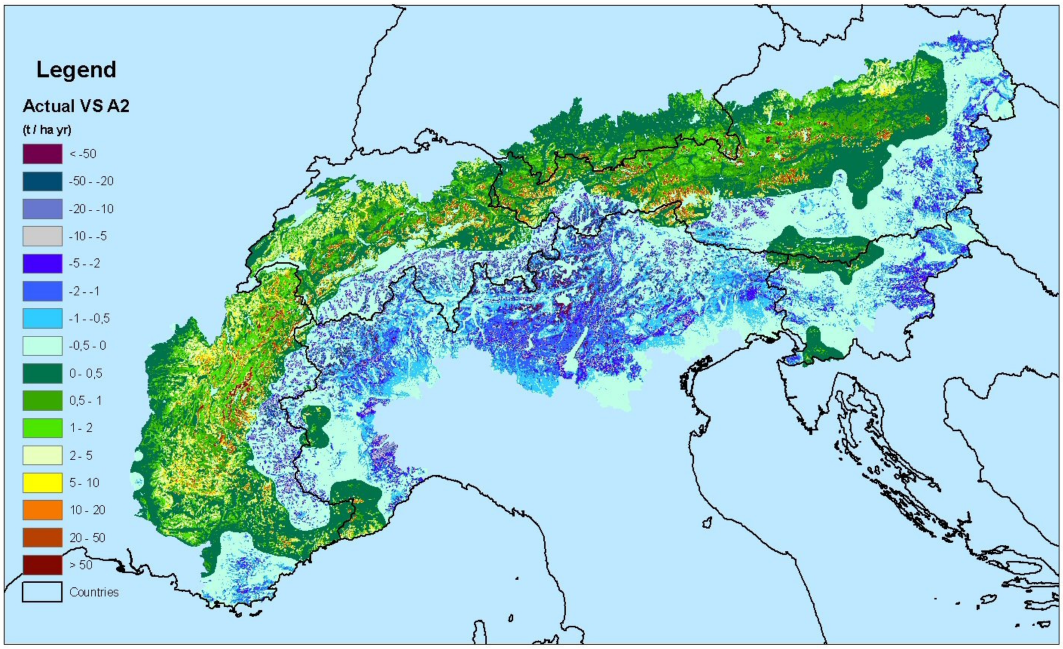

Figure 17: Soil Erosion trend. Actual vs. A2 scenario (t ha^{-1} yr^{-1})

Soil Erosion - Actual VS B2

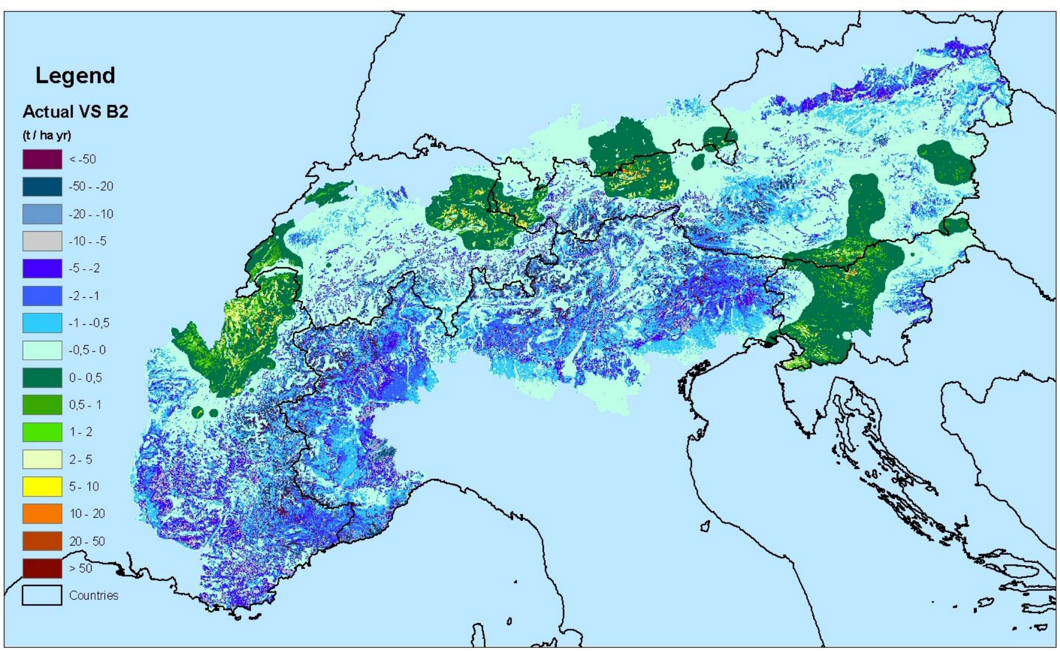

Figure 18: Soil Erosion trend. Actual vs. B2 scenario (t ha^{-1} yr^{-1})

From the analysis some evaluations come out:

- from a general comparison between actual soil erosion (1960 – 1990) and future soil losses (A2 and B2 scenarios. 2070 – 2100), it is evident that erosion rates remain nearly constant (Figure 19). The spatial extension of each class, in fact, is almost unvaried.

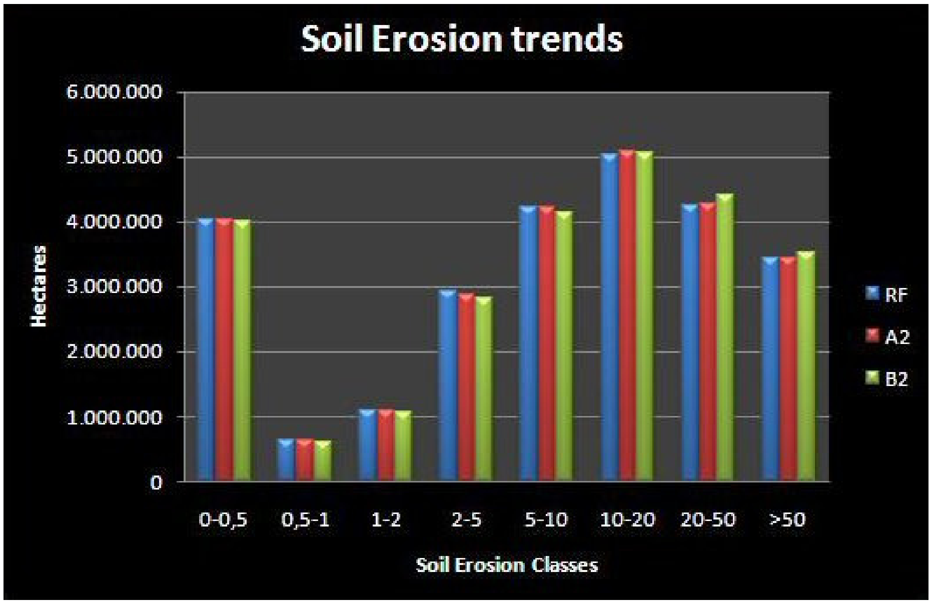

Figure 19: spatial extension of soil erosion classes in the analysed scenarios.

- By comparing the relative variations of soil losses in future scenarios with the actual situation, a low increase in areas with rate of erosion > 10 t ha^{-1} yr^{-1} comes out. As a consequence, areas with an erosion rate lower than that decrease (Figure 20). This phenomenon is more pronounced in B2 scenario. This scenario shows, in particular, a low increase in the extension of areas with an erosion rate higher than 20 t ha^{-1} yr^{-1} rising from 31.7 % to 32.7 %. Also the analysis on altimetrical zone gives, compared to the actual situation, a similar distribution of soil erosion rates.

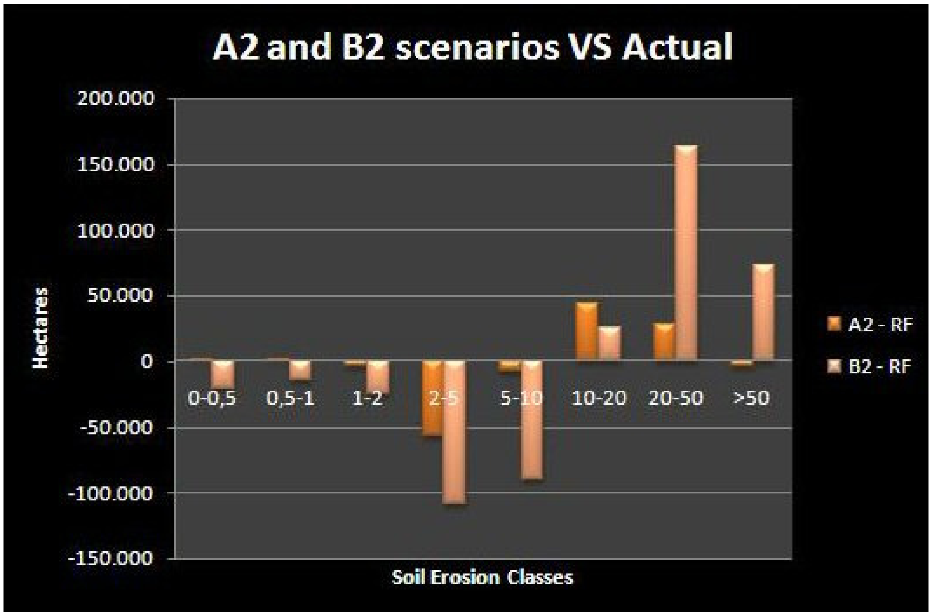

Figure 20: relative variation of soil erosion in A2 and B2 scenarios compared with actual erosion

- Some evidences arise from a spatial analysis of maps defining, for each grid cell, differences between actual erosion data and A2 - B2 scenarios (Figure 17 and Figure 18). B2 scenario shows a general growth of soil losses over a significant part of the alpine space. The increase is, however, of low entity. From A2 scenario comes out, instead, a strong distinction between northern and southern Alps. Northern part should experience a low reduction of soil erosion, whilst in southern areas a rise of soil losses should take place.

Ongoing climate change contributes to arise the spatial variability of rainfalls. They should decrease in subtropical areas and increase at high latitudes and in part of the tropical zones. The precise location of boundaries between regions of robust increase and decrease remains uncertain and this is commonly where atmosphere-ocean general circulation model (AOGCM) projections disagree. The Alps are just located in this transition zone. This is the reason because, as a consequence of the expected climate change, a very little variation in soil erosion rates over the alpine space was predictable. RegCM model, which produced rainfall data used in this study, places the transition zone more southward in B2 than in A2 scenario. Due to this difference in the placement of the transition zone, even though A2 scenario foresees heavier climate change than other scenarios, the B2 scenario shows, over the Alps, higher rainfall rates. This is the reason because in B2 scenario a higher number of areas with erosion rates > 10 t ha^{-1} yr^{-1} are present. In A2 scenario, moreover, prevailing winds come from the south. This explains the sharp demarcation line between northern and southern Alps and the increase of rainfalls on the southern side. B2 scenario is characterized by a low increment in soil erosion rates, even if some isolated areas present an opposite trend, which is difficult to explain. The investigation of these phenomena requires further analysis, going beyond the aims of this study. They are possibly explainable from a modelling point of view and could be due to non linearity problems, easily coming out at these scales. To justify their origin different models should be used, with the aim of a deeper calibration of results. This is the reason because IPCC derived results of its four report on climate change making use of 20 climate models.

As mentioned before, soil erosion trends in the alpine region are mainly attributable to changes in rainfall regimes. A better estimation of soil losses in climate change scenarios could be assured by evaluating future variations of cover management factor.

5. A FOCUS ON THE ITALIAN ALPINE TERRITORY: SOIL EROSION TRENDS IN CLIMATE AND LAND USE CHANGES SCENARIOS

As outlined in a previous paragraph (par. 3), soil cover is one of the factors that mostly influence soil erosion processes. With the aim of determining the spatial distribution of erosion rates in future scenarios, on the Italian side of the alpine territory it has been analysed, beside the climatic component, the evolution of land use and land cover. To this aim, the CLUE-s (the Conversion of Land Use and its Effects at Small regional extent) model (Verburg et al., 2002) was applied. It is a land use change model able to simulate a reliable future distribution of land use/land cover.

5.1 The CLUE-s model

The CLUE-s model uses two modules, a module of non-spatial demand and a module of allocation spatially explicit. In the non-spatial demand module the changes in land use are estimated for a series of years at the aggregate level. Then, the spatial module has to translate the changes in demand into changes in land use pattern within the study region using a raster-based system.

The model, its theoretical bases, the type of parameterization and the input data derivation are deeply described in the Chapter 3 ("*Climate impact scenarios on forest biodiversity and land use changes in Alpine zone*") of the ClimChAlp Climate Change Report.

5.2 The application of the CLUE-s model

Here, we briefly want to focus on:

- the land use classes considered in the simulation.
- The driving factors used to explain the land use preference.
- The types of simulations made.

Regarding the land use classes, we used the following re-classification (Table 9) of the CORINE LAND COVER legend at the third level for the year 2000, according to the parameterization of C-factor.

The aggregation of classes into macro-classes was made both taking into account codification of the C-factor reported in literature and the similarity among land uses in order to reasonably associate them in the land use change dynamics.

As regards the driving factors, after several attempts aimed at an adequate run of the model, and after studying previous works about land use change modelling with CLUE-s, the most adequate predictors were selected, derivable from datasets already existing. All data were thoroughly checked and updated. In particular, it was decided to work with 12 driving factors falling into different categories: socio-economic, accessibility, geography, biophysics, climate etc. (Table 10).

CORINE LAND COVER classes	CLUE-s classes	C-factor value
111	0	0
112		
121		
122		
123		
124		
131		
132		
133		
141	1	0.001
142		
211	2	0.335
212		
213		
242		
221	3	0.55
222		
223		
231	4	0.01
241	5	0.4
243	6	0.1
244	7	0.4
311	8	0.05
312		
313		
321	9	0.01
322		
324		
323	10	0.1

331	11	0
332		
333	12	0.55
334		
335	13	0
411	14	0.001
412		
421		
422		
423		

Table 9: reclassification of the CORINE Land Cover classes (first column) at an aggregate level (second column) according to the parameterization of C factor (third column)

DRIVING FACTORS OF LAND USE CHANGES
1. density of workers in industry and other services (employed per sq. Km)
2. density of enterprises in industry and other services (enterprises per sq. Km)
3. population density (inhabitants per sq. km)
4. distance from channel network (m)
5. distance from transport network (m)
6. distance from urban centre (m)
7. elevation (m a.s.l.)
8. aspect (clockwise from north)
9. slope (% rise)
10. depth to rock (categorical variable)
11. organic carbon in the topsoil (categorical variable)
12. soil erodibility (categorical variable)
13. mean annual precipitation (mm)
14. mean annual temperature (°K)

Table 10: list of the driving factors considered for the application of CLUE-s

All the input data, spatialized or not, had to be imported into GIS format (GRID structure) and homogenized (the Projected Reference System was WGS84 UTM zone 32 N, their final resolution was 250 meters), in order to allow an easy implementation of the procedure, to make all the necessary analyses and overlays among different layers and to supply the results with the same structure.

Among the input parameters, we have to specify the possibility or not, for each land use class, to be converted into another land use class. This was made by means of a conversion matrix class by class, reporting 1 if the conversion is allowed and 0 if it is not allowed. In this case, only the conversion of urban land uses toward other classes was not allowed.

Then it was necessary to evaluate the stability of different land uses, that is their capability to resist to some stresses. This stability was indicated with an index varying from 0 (dynamic land use) to 1 (stable land use) (Table 11).

CLASSES	Elasticity
0	0.41
1	0.28
2	0.37
3	0.56
4	0.25
5	0.55
6	0.54
7	0.49
8	0.47
9	0.56
10	0.56
11	0.56
12	0.56

Table 11: list of the elasticity values given to each land use class

A further basilar input datum for the application was the map of "restricted" areas representing those areas protected or managed in a manner that does not permit existing land use to change. It was decided to consider, as a region of un-permitted changes, the one consisting in lakes (class 511 of the CORINE LAND COVER legend) and in Special Protection Zones (ZPS) according to Italian regulations.

Finally, we made two types of simulations: the former considering as climatic input (precipitation and temperature) the ones predicted by IPCC scenario A2 and the latter considering the IPCC scenario B2. The A2 and B2 scenarios are both relative to 2070 - 2100 period.

5.3 Soil erosion trends in future climate and land cover scenarios

The maps of land use classes resulting from the previous simulations were used as input layers (after their re-sampling to 100 m of resolution) of land use for the RUSLE model. In particular, they were used to associate to each pixel of the study area a value of C factor according to Table 9.

Land cover maps in A2 and B2 scenarios show very little differences. By comparing these maps with actual land use data some trends, relative to specific classes, come out:

- the “artificial surfaces” class raises from 6.5 % to 8 %.
- Permanent crops raise from 2.4 to 4.7 %.
- Further rises, although of lower importance, concern the classes “forests” (from 30 to 30.8 %) and “scrubs and/or herbaceous vegetation associations” (from 10.5 to 11.2 %).
- Arable land, on the contrary, strongly decrease and lower from 32 to 28.5 %.
- The other classes are nearly unvaried.

The application of RUSLE model with CLUE-s A2 and B2 scenarios as input for C factor computation showed, over the alpine space, a geographical distribution of soil loss levels similar to the previous assessments. By comparing actual vs. A2 and B2 erosion maps (Figure 21 and Figure 22), it comes out a general low raise in erosion rates both in A2 and in B2 scenarios. However, in A2 scenario, at specific areas where a low reduction of rainfalls is expected, an attenuation of soil loss rates could take place (Figure 21).

Locally, both in A2 and B2 scenarios, erosion maps show a large number or areas, often small, which are expected to experience a reduction in soil erosion rates. They are prevalently located at areas where, according to CLUE-s model simulations, an increase in urban conglomerations and in the extension of forests and permanent crops is expected, to the detriment of arable lands.

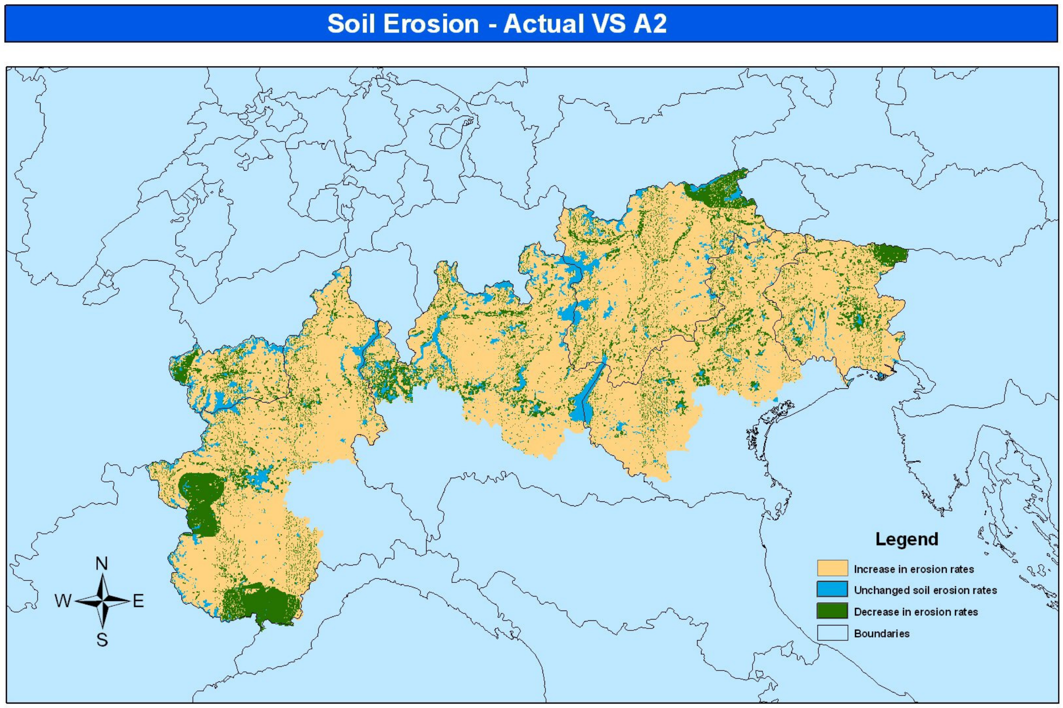

Figure 21: Soil Erosion trend in the Italian alpine territory. Actual vs. A2 (climate and land cover) scenario

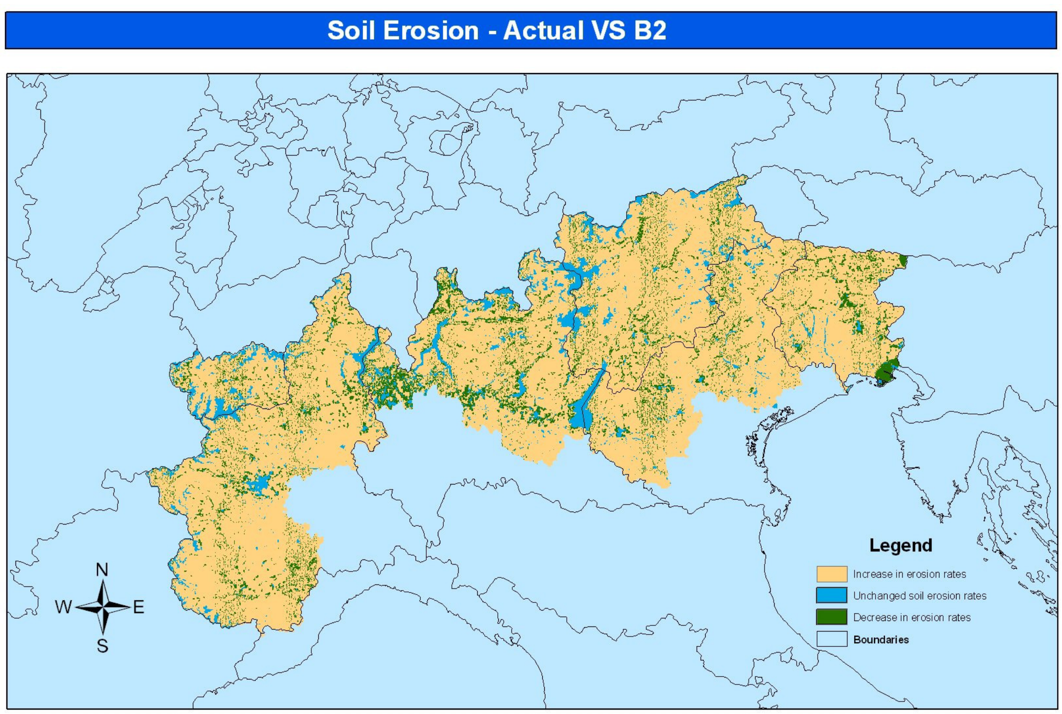

Figure 22: Soil Erosion trend in the Italian alpine territory. Actual vs. B2 (climate and land cover) scenario

6. CONCLUSIONS

With this study, soil erosion processes over the whole alpine space were estimated, with the specific aim of comparing actual erosion rates (1960 – 1990) with the A2 and B2 (2070 – 2100) IPCC scenarios data.

The alpine region is a highly complex area. The study shows that the territory of the Alps is subject to a high vulnerability with regard to soil erosion. About 32% of the alpine space, in fact, shows a rather high risk of erosion (> 20 t ha^{-1} yr^{-1}). In the high mountain zones, in particular, more than 25% of the territory is interested by very high erosion rates (> 50 t ha^{-1} yr^{-1}). Vegetation cover plays a key role in mitigating the soil loss processes. The vulnerability of the Alps is mainly imputable to the geomorphologic complexity of their territory and to the type of rainfall they are subject to. As regards erosion trends in future climate scenarios (IPCC A2 and B2 data), our methodology points out that over the alpine space raises in soil losses are not expected to be significant. In spite of that, some evidences come out: B2 scenario shows a growth of low entity of soil losses over a significant part of the alpine space. In A2 scenario a clear distinction between northern and southern Alps comes out. Northern part should experience a low reduction of soil erosion, whilst in southern areas a rise of soil losses should take place.

The analysis performed on the Italian side of the alpine region, taking into account, besides climatic data, land use and land cover scenarios, showed a geographical distribution of soil loss levels similar to the previous assessments. A general low raise in erosion rates, both in A2 and in B2 scenarios, is expected. Some areas could, on the contrary, experience a reduction of soil losses as a consequence of local reduction of rainfall rates and of an increase in urban conglomerations and in the extension of forests and permanent crops, to the detriment of arable lands.

Erosion processes are extremely complex and a huge number of factors influence them. Different datasets are hence necessary with the aim of modelling soil losses. Suitable spatial and thematic resolution are often difficult to obtain over large areas. Our results could be improved making use of a digital elevation model with better spatial resolution, of more accurate information relative to soil structure and of a larger number of rainfall data with adequate temporal resolution. As regard to the latter data, during ClimChAlp project the lack of time made not possible the collection of a significant set of adequate rainfall information. With the aim of complying with the time scheduling of the project, we preferred to use a dataset of modelled data. They were promptly available and assured a better comparison of actual and future soil losses in different climate scenarios.

One of the most critical points in soil erosion studies is the estimation of rainfall erosivity. The climate model we used makes available rainfall data with daily resolution. It is not adequate for the strict computation of R factor in the universal soil loss equation, which requires a temporal resolution of 30 minutes.

To get round this problem, simplified algorithms can be applied. By the use of monthly or yearly average rainfall data they allow the computation of R but they do not take into consideration the specific intensity of single rainfall events. As climate change could produce a tendency to tropicalization, with highly intense rainfall events, a complete understanding of climate change impact on erosion trends is difficult to obtain.

As regards future investigations, a downscaling approach will be useful for a better comprehension of water erosion processes in the Alps. It would allow to carry out more and more accurate predictions and estimations at regional or local scales. To this aim, evaluations on possible future variations of timberline, pastures or woods distribution and vegetation cover are critical. It is moreover crucial to take into better consideration the erosivity power of snow melting processes, which can strongly influence soil erosion phenomena, both sheet and rill. Above all, further researches should be carried out with the aim of a better determination of rainfall erosivity factor. It still persists, moreover, the need for a deep calibration and validation of models, by means of field measures and with monitoring activity on soil and their degradation.

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