PAN-EUROPEAN SOIL EROSION RISK ASSESSMENT:

THE PESERA MAP

VERSION 1 OCTOBER 2003

Explanation of:
Special Publication Ispra 2004 No.73
S.P.I.04.73

Michael J. Kirkby, Robert J. A. Jones, Brian Irvine,
Anne Gobin, Gerard Govers, Olivier Cerdan,
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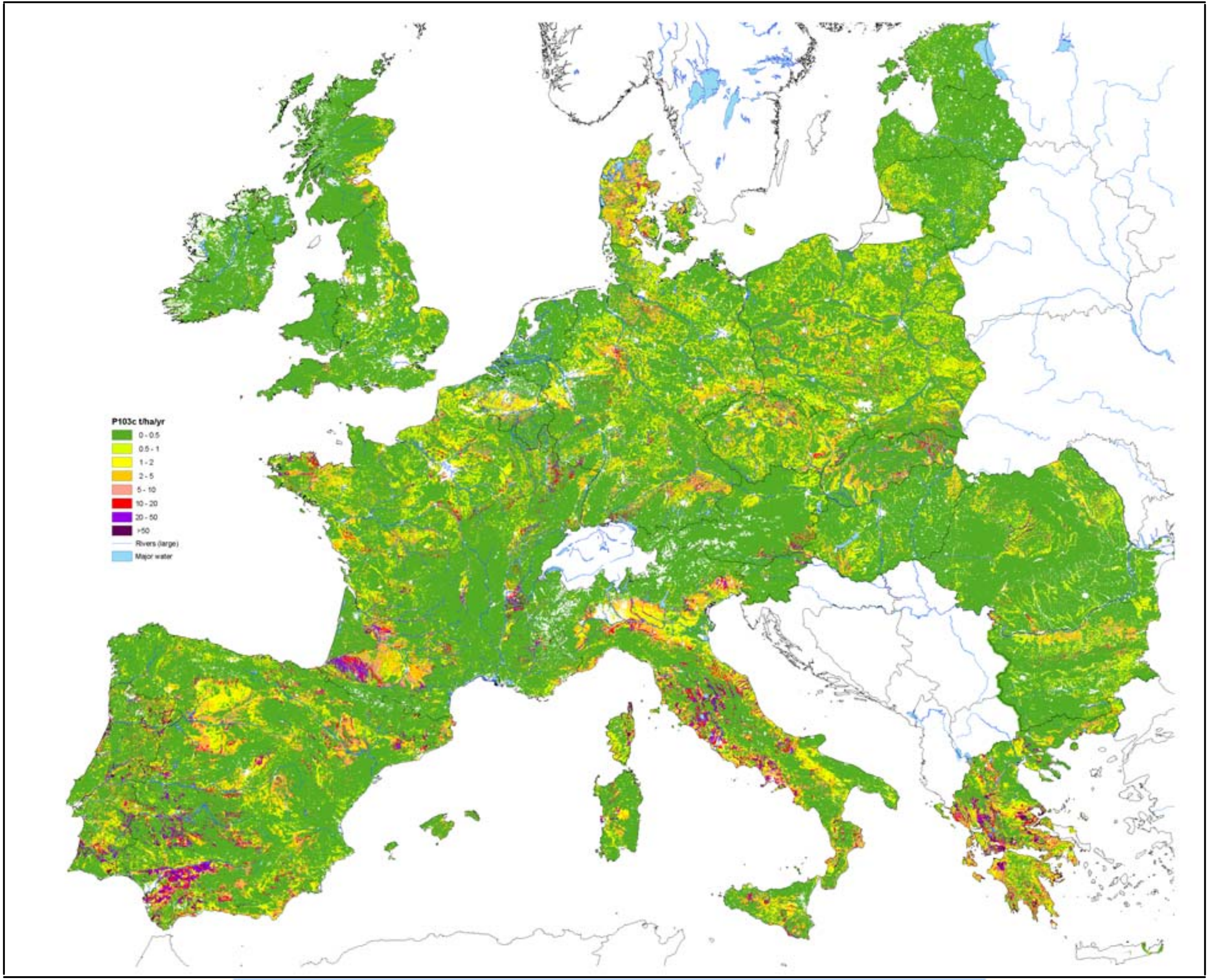

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COVER MAP

THE PESERA MAP OF SOIL EROSION BY WATER
(VERSION 1, OCTOBER 2003)

PAN-EUROPEAN SOIL EROSION RISK ASSESSMENT:

THE PESERA MAP

VERSION 1 OCTOBER 2003

Explanation of:
Special Publication Ispra 2004 No.73
S.P.I.04.73

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The mission of the Institute of Environment and Sustainability is to provide scientific and technical support to EU strategies for the protection of the environment and sustainable development. Employing an integrated approach to the investigation of air, water and soil contaminants, its goals are sustainable management of water resources, protection and maintenance of drinking waters, good functioning of aquatic ecosystems and good ecological quality of surface waters.

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Summary

1. Soil erosion is a natural process, occurring over geologic time, and indeed it is a process that is essential for soil formation.
2. In the context of environmental protection, most concerns about erosion are related to accelerated erosion, where the natural rate has been significantly increased mostly by human activity. Accelerated erosion by running water has been identified as the most severe threat to soil in Europe.
3. Severe erosion is commonly associated with the development of temporary or permanently eroded channels or gullies that can fragment farmland. Such features are often the only visible signs.
4. In a period of rapid change in both climate and land use, and/or in response to revised agricultural policies and international markets, it is very important to be able to assess the state of soil erosion at a European level, using an objective methodology.
5. This report is to accompany Special Publication Ispra 2004 No.73 – S.P.I.04.73, The PESERA Map version 1 October 2003, in ISO B1 format.
6. The PESERA map shows estimated loss of soil by water erosion and it is one of the key outputs from the PESERA research project.
7. The map is based on the application, at 1 km resolution, of the PESERA/RDI model that estimates the rate of loss of soil material from hillsides.
8. Other forms of soil erosion caused by wind, snowmelt, undercutting of river-banks, tillage, trampling by animals, land-levelling and landslides are not included.
9. There are several possible methodologies for creating an erosion map of Europe; some of these are based on the collection of distributed field observations, others on an assessment of factors and combinations of factors that influence erosion rates, and others primarily on a modelling approach.
10. All of these methods require calibration and validation, although the type of validation needed is different for each category.
11. The PESERA (Pan–European Soil Erosion Risk Assessment) model is a physically based and spatial distributed model combining the effect of topography, climate and soil into a single integrated forecast of runoff and soil erosion.
12. PESERA uses the simplest possible storage, or ‘bucket’ model to convert daily rainfall to daily overland flow runoff. Runoff is estimated as Rainfall minus Threshold storage. The threshold depends on a number of factors related to the soil, vegetation cover, tillage and soil moisture status.
13. The calculations described above are performed independently for each cell within a 1 km grid across Europe.
14. A pan-European calibration of erosion rates is not practicable because there are only a limited number (between 50 and 100) of sites, throughout Europe, where acceptable measurements of erosion rates have been made and these differ significantly in methodology and scale.
15. Four main datasets are required to run the PESERA model, to provide essential climate, soils, land cover and topographic data.
16. The MARS database (JRC) provides daily time series of rainfall, temperature and potential evapotranspiration, interpolated to a 50 km grid for Europe. These data have been further interpolated at 1 km resolution, using a inverse-spline mathematical procedure, to provide the monthly data layers for the model.
17. The European Soil Database has been used to provide soil erodibility (converts runoff to erosion rates), soil water storage capacity (maximum storage capacity of the soil before runoff) and crustability (sets the lower limit of storage capacity for a crusted soil in unvegetated areas), on a consistent basis at 1 km resolution across Europe.

18. Land use is based on CORINE land cover at 250 m resolution for 1989, and these data are combined with cereal planting dates to provide the parameters for a crop or natural vegetation growth model.
19. A 30 second (1 km) digital elevation model available from EROS has provided the topographic basis for the PESERA erosion map.
20. The PESERA model has been applied at a 1 km resolution for the whole of Europe except for some areas where some data are missing.
21. For Denmark, the PESERA map shows erosion rates that seem to be high compared with southern Europe, and appear not to be related to planting dates or to crop cover.
22. The map shows erosion rates east of Bayonne that seem quite high compared to other landscape units in France and Spain, whereas for other areas in France the erosion estimates seem to fit better with local observation and/or expert judgement.
23. Estimated erosion rates are shown to be high in the northern part of the Po valley in Italy, despite the fact that the land is relatively flat. In the arable areas of Umbria, Le Marche, Campagne and Molise, the predicted erosion rates accord much better with observation.
24. In Spain, except for the valley of the Guadalquivir and to a lesser extent on the northern Meseta, areas of high erosion are mostly small and localised with predicted soil loss rates in the rest of the country probably being underestimates.
25. The PESERA map probably underestimates erosion rates on the silty soils in the Welsh Borderlands (UK), and on some parts of the South Downs in southern England, but revision of the land use/cover and the climate (rainfall) data might correct this.
26. Although in general it seems as if the current version of the PESERA grid model may over-estimate erosion in valleys and basins where the land is arable but relatively flat, many areas on the map show erosion rates coinciding with observation and measurement, for example parts of the Guadalquivir and Ebro valleys in Spain, around Toulouse in south-west France, the loess belt in Belgium, the Siret catchment in north-eastern Romania, the Alto-Adige (I), agricultural areas in Czech Republic and much of Slovakia.
27. In practice, no erosion map at a European scale can be based on detailed knowledge at every point on the continent and it would be impossible to include every factor of local importance in a comprehensive model.
28. The greatest potential for improvement in these erosion estimates from PESERA version 1, lies in the use of better climate data, potentially available from national archives though not normally ‘free of charge’, more detailed soil information and up-to-date land use/cover.
29. Land cover requires frequent updating, because changes in land use have a major impact on erosion rates. There is the potential to do this through the analysis of remotely sensed images. For future scenarios of erosion, improvements in GCMs and economic forecasts offer a potential that is still far from full realisation.
30. However, by applying a common methodology throughout Europe, based on physical understanding, the PESERA model is able to identify major differences between regions and to highlight areas particularly at risk.
31. To date, PESERA provides the only Europe-wide estimates of soil erosion by water, that are based on a harmonised approach and standard data sets. This first version of the PESERA map is therefore timely in its appearance and should provide the initial basis for planning policies to protect soil at the European level.
32. The possibilities for improvement in the near future look optimistic in view of the vastly improved data on land use and cover together with enhanced data processing capabilities that are now becoming available.
33. The next step will be to compare the PESERA estimates with national measurements and risk assessments. Combining the results of such comparisons with improved data on climate, soil, land use/cover and topography (DEM) should lead to improved estimates of soil erosion by water for input to the forthcoming soil protection strategy for Europe.

Introduction

Soil erosion is a natural process, occurring over geological time, and indeed it is a process that is essential for soil formation. However, in the context of environmental protection, most concerns about erosion are related to accelerated erosion, where the natural rate has been significantly increased mostly by human activity. Accelerated erosion by running water has been identified as the most severe threat to soil in Europe. By removing the most fertile topsoil, erosion reduces soil productivity and can lead to an irreversible loss of natural farmland, that is not always obvious to an increasingly urbanised general public.

Severe erosion is commonly associated with the development of temporary (Figure 1) or permanently eroded channels or gullies (Figure 2) that can fragment farmland. The soil removed by runoff from the land, during a large storm, accumulates below the eroded areas, in severe cases blocking roadways or drainage channels and inundating buildings.

Figure 1 Rill erosion in Hungary (Photograph by Erika Micheli)

The erosion rate is very sensitive to both climate and land use, as well as to detailed conservation practices at farm level.

In a period of rapid changes in both climate and land use, due to global change and/or in response to revised agricultural policies and international markets, it is very important to be able to assess the state of soil erosion at a European level, using an objective methodology.

The value of such a methodology is enhanced by the possibility of repeating assessments as conditions change, or exploring the broad-scale implications of prospective global or Europe-wide changes.

This approach provides a basis for estimating the overall costs attributable to erosion under present and changed conditions, and objectively identifies areas for more detailed study and possible remedial action.

Figure 2 Severe gully erosion of former olive groves in Pedrera, Alicante Spain

Purpose of the map

The PESERA map, published as S.P.I.04.73 in ISO B1 format, shows estimated loss of soil by water erosion and is a key output from the PESERA research project (Contract No QLK5-CT-1999-01323) funded by the European Commission Directorate-General Research (DG RES), under the Quality of Life and Management of Living Resources sector of the 5th Framework Programme. The map is intended to provide an objective assessment of current rates of soil erosion by water, averaged over a series of years under current land use and climate.

The map is based on the application, at 1 km resolution, of the PESERA/RDI model that estimates the rate of loss of soil material from hillsides. Sediment delivery through the river system is explicitly not taken into account, and the model assumes that most of the eroded material generally remains close to its source, with significant off-site effects generally confined to a local area. Other forms of soil erosion caused by wind, snowmelt, undercutting of river-banks, tillage, trampling by animals, land-levelling and landslides are not included.

There are several possible methodologies for creating an erosion map of Europe, some of which are reviewed by Gobin *et al.* (2002) and Grimm *et al.* (2001). Some of these are based on the collection of distributed field observations, others on an assessment of factors, and combinations of factors, which influence erosion rates, and others primarily on a modelling approach. All of these methods require calibration and validation, although the type of validation needed is different for each category.

Figure 3 Rill erosion in winter-sown cereals, Campobasso,, Molise, Italy, April 2004.

There are also differences in the extent to which the assessment methods identify past erosion and an already degraded soil resource, as opposed to risks of future erosion, under either present climate or land use, or under scenarios of global change

Distributed point measurements and observations

One important form of erosion assessment is from direct field observations of erosion features and soil profile truncation. Many erosion features consist of rills (Figures 1 & 3) and gullies (Figure 2 & 4), some of these ephemeral, with associated deposition in creeks and small valleys. Soil profiles may show local loss from the upper horizons, or burial by deposition of material from up-slope. Deposited material may be dateable which can indicate when the erosion occurred, but much of this evidence is cumulative over the period since cultivation began, or in some cases over the whole of the Holocene geological period.

Figure 4 Deep rill/gully erosion in Severn Valley, UK (Photograph by P.N. Owens)

Data may be collected from regional soil scientists or experts on soil erosion (Evans, 2002). They may also be collated from field or remote (air photo) surveys of erosion features. High-resolution satellite imagery (e.g. from IKONOS) may, in the near future, also allow this method to be applied more widely from platforms in space. Some quantitative data are also available from erosion plot sites. Finally, measuring the sediment accumulating in reservoirs can quantify erosion at a catchment level (van Rompaey *et al.*, 2003).

However, these methods all require validation to standardise differences in the intensity of study of different areas and in the clarity of suitable features on different soil types. There are also differences in methods and traditions between scientists in different areas of Europe. More importantly, these methods can provide a complete picture only for small sample areas, and other methods are needed to interpolate between sampling points.

The main advantage of distributed observations of erosion is that, where they exist, the data are unambiguous and give a good indication of the current state of degradation of soil resources. The main disadvantage of distributed observations is that they provide little or no information about when erosion occurred, unless supporting data are available from other sources. Many areas of the Mediterranean are thought to have suffered accelerated anthropogenic erosion since early classical times, with the result that many hills are now denuded of their former natural soil cover (Figure 5). Although of great historical interest, this stage of degradation has little bearing on current or prospective erosion hazards.

Factor or Indicator Mapping

Since many of the processes and factors which influence the rate of erosion are well known, as outlined above, it is possible to rank individual factors for susceptibility to erosion, providing a series of erosion indicators. For example, climatic indices may be based on the frequency of high intensity precipitation, and on the extent of aridity or rainfall seasonality. Soil indicators may reflect the tendency of the surface to form crusts and the experimental erodibility of soil particles or aggregates. Similar rank indicators may be developed for parent materials, topographic gradient and other factors. Clearly a high susceptibility for all factors indicates a high erosion risk, and a low susceptibility for all factors indicates a low erosion risk.

Individual indicators may be mapped separately, but it is more problematic to combine the factors into a single scale, by adding or multiplying suitably weighted indicators for each individual factor. There are difficulties both about the individual weightings and about the assumed linearity and statistical independence of the separate factors. The method should therefore be most effective for identifying the extremes of high and low erosion, but less satisfactory in identifying the gradation between the extremes.

Despite these theoretical limitations, factor or indicator mapping has the considerable advantage that it can be widely applied using data that is available Europe-wide in GIS format for topography and soils at 1 km resolution, and for climate at 50 km resolution. Kosmas *et al.* (1999) provides one example of this approach, applied at a regional scale to areas in Greece, Italy and Portugal.

Process modelling

There is a continuous spectrum between mapping based on ranked indicators and process models with a more explicit physical or empirical basis. Nevertheless it is fruitful to consider, as a third approach towards Europe-wide soil erosion assessment, the application of a process model. Although at first sight, this approach appears to be the most generally applicable, there are major problems of validation, and in particular in relating coarse-scale forecasts to available erosion rate data, much of which is for small erosion plots.

Figure 5 Intensive olive cultivation (trees 5-80 years old) and denuded hill-tops near Sevilla, Spain

Many of the most successful process models require more detailed distributed parameter and rainfall intensity data than are currently available at pan-European scales, so that they cannot be applied without radical simplification. One important aspect of this problem is the need to develop a model that can be used for validation at fine scales, and for Europe-wide forecasting at a coarse scale, so that cross-scale reconciliation must be as explicit as possible. Nevertheless this approach has the potential to provide a rational physical basis to combine factors which can be derived from coarse scale GIS, and overcome the difficulties about weighting and inter-correlation encountered in purely factor based assessments.

Process models have the potential to respond explicitly and rationally to changes in climate or land use, and so have great promise for developing scenarios of change, and 'what-if' analyses of policy or economic options. Set against this advantage, process models generally make no assessment of degradation up to the present time, and can only incorporate the impact of past erosion where this is recorded elsewhere, such as soil databases.

Models also generally simplify the set of processes operating, so that they may not be appropriate under particular local circumstances. Although the Universal Soil Loss Equation (USLE) has been the most widely applied model in Europe (e.g. Van der Knijff *et al.*, 2000, 2002), it is now widely considered to be conceptually flawed, and other models are now emerging, based on runoff thresholds (e.g. Kirkby *et al.*, 2000) or the MIR (Minimum Information Requirement) approach (Brazier *et al.*, 2001) applied to the more complex USDA WEPP model (Nearing *et al.*, 1989).

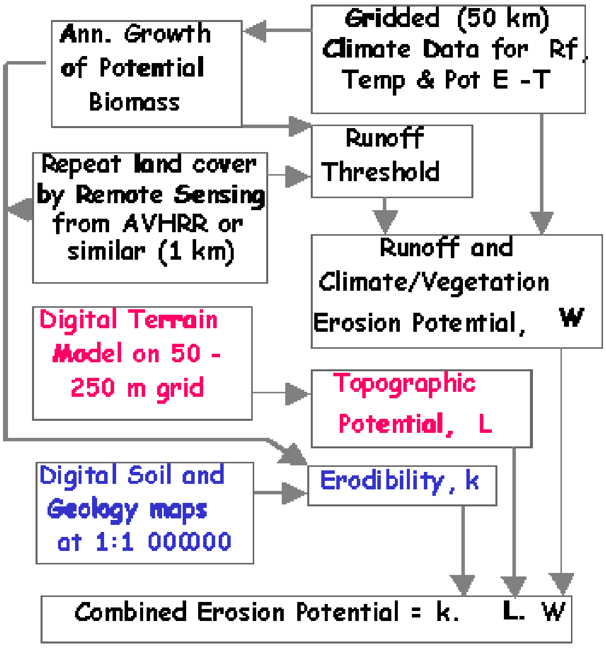


Figure 6 Factors used to estimate erosion rates in the PESERA/RDI model

The application of a process model has been preferred here for three main reasons:

1. It applies the same objective criteria to all areas, and so can be applied throughout Europe, subject to the availability of suitable generic data.
2. It provides a quantitative estimate of erosion rate that can be compared with long term averages for tolerable erosion.
3. The methodology can be re-applied with equal consistency with improved current data, and for scenarios of changed climate and land use.

Scientific Rationale of the PESERA/RDI model

The PESERA (Pan–European Soil Erosion Risk Assessment) model is a physically based and spatial distributed model developed for quantifying soil erosion in environmentally sensitive areas relevant to a regional or European scale and defining soil conservation strategies. The current version of the model was developed during the execution of the PESERA project and was also based on previous funded and un-funded research (Kirkby and Neale, 1987; de Ploey *et al.*, 1991; Kirkby and Cox, 1995; Kirkby *et al.*, 2000).

The PESERA model combines the effect of topography, climate and soil into a single integrated forecast of runoff and soil erosion (Figure 6). Data for each of these three factors have been extracted from existing sources and combined in a physically based model to make rational forecasts of soil erosion.

The model is built in three conceptual stages, explained more fully below.

1. A storage threshold model to convert daily rainfall to daily total overland flow runoff;
2. A power law to estimate sediment transport from runoff discharge and gradient, and interpret sediment transport at the base of the hillside as average erosion loss;
3. Integration of daily rates over the frequency distribution of daily rainfalls to estimate long-term average erosion rates.

Storage Model

PESERA uses the simplest possible storage, or ‘bucket’ model to convert daily rainfall to daily overland flow runoff. Runoff is estimated as Rainfall minus threshold Storage. The threshold depends on a number of factors related to the soil, vegetation cover, tillage and soil moisture status. The most important soil factors, that determine the threshold storage beneath the vegetation-covered fraction of the surface, are texture, depth (if shallow) and organic matter. Where the surface is not protected by vegetation, the susceptibility of the soil to crusting and the duration of crusting conditions generally determine a lower threshold. The final threshold is a weighted average from vegetated and bare fractions of the surface. Corrections are made for the soil water deficit, which may reduce the threshold where the soil is close to saturation.

The PESERA model is normally linked to a simple biomass model to allow crops or natural vegetation to respond to seasonal variations in available moisture, and allows some subsurface drainage of soil moisture. Alternatively the model can make use of vegetation cover derived from remote sensing. This has the advantage of taking into account factors not included in the model, such as grazing intensity and fire, but does not provide scenario capability. All the factors are assessed on a monthly basis so that the threshold may vary markedly through the year. Calculations are modified appropriately where there is frozen ground or snow cover.

Power law sediment model

Daily total runoff is linearly scaled up to discharge for each point in an area, and daily sediment transport is estimated as:

$$\textit{Sediment Transport} = \textit{Erodibility} \times (\textit{Runoff} \times \textit{Distance from divide})^2 \times \textit{Gradient}$$

Erodibility is primarily associated with the soil texture, but is reduced to allow for a full or partial vegetation cover. Gradient is derived from topographic sources, but will not be required for estimating the whole-slope erosion loss.

If sediment transport is estimated at the slope base, then this expression can be re-written for sediment yield

(*Total sediment transport* ÷ *Total slope length*) as:

$$\textit{Sediment Yield} = \textit{Modified Erodibility} \times \textit{Runoff}^2 \times \textit{Relief}$$

Where the modified erodibility includes a small correction factor for the ratio of slope-base local gradient to mean slope gradient (which is implicit in the term Relief = Total slope Length × Mean gradient). This allows the use of coarse resolution DEMs which can estimate Relief as the variability of local elevation, without the need to estimate local gradients directly, which is advantageous where DEM point spacing may be of the same order as total slope length.

Estimating long-term average erosion rates

Daily rainfall data are used because of their wide availability. The forecasting model can be used with a time series of daily rainfalls, but maps derived on this basis show a strong signal associated with the historic locations of the largest storms. Instead the map provides a weighted average of annual erosion, summed over the frequency distribution of daily rainfalls for each month.

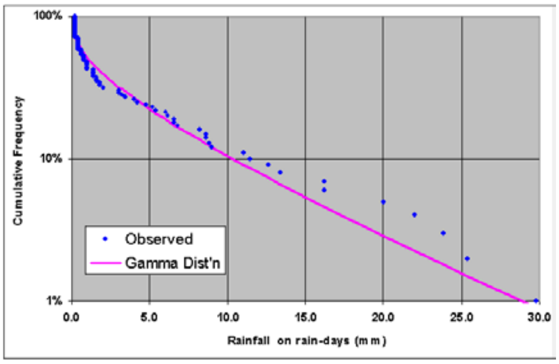


Figure 7 Fitting Gamma distribution to 6 years rainfall data (1997-2002) for Nov/Dec, North 1, Nogalte, Murcia, south east Spain,

This frequency distribution is derived from an analysis of historic time series for each month separately, using the number of rain days, mean rain per rain day and its standard deviation to fit a Gamma distribution which provides an excellent fit (Figure 7) to long data series. The daily runoff and daily erosion for each possible rainfall event is weighted by its frequency in this distribution to estimate the long term averages for each month, and summed to give annual totals.

Integrated model

The calculations described above are performed independently for each cell within a 1 km grid across Europe. The 'one-cell model' is available as an Excel spreadsheet with Visual Basic macros through the PESERA web site (http://pesera.jrc.it) and can be used to estimate runoff and erosion rates for a single point, and to show the effect of changes in land use or climate on expected rates. The main or 'grid' model repeats these estimates for each 1km×1km cell within an area, combining data in ARC-Grid format with FORTRAN code, and creating output maps which can be examined or interrogated in an ArcGIS or similar GIS software environment. Advice on preparation of the databases and running the grid model can also be obtained through the web site, and a prototype system allows the model to be run remotely for small areas (up to 100 km × 100 km) over the Internet.

Calibration and Validation

A pan-European calibration of erosion rates is not practicable because there are only a limited number (between 50 and 100) of acceptable measurements of erosion rates throughout Europe, and these differ significantly in methodology and scale. The overall reliability of the model is based on an internal, intermediate and external calibration.

Internal validation is based on a qualitative and quantitative assessment of the physical representation of processes in the model. This includes our accumulated understanding of process mechanics and their incorporation in the model, in a sufficiently simplified form, with judgements on which processes should be included.

Intermediate validation is based on comparison with spatial distributions that are forecast within the model as intermediate products. The most important of these distributions is of vegetation cover and abundance, which are derived within the model by combining land use data with a growth model, and can be independently corroborated from remote sensing interpretations. Comparison can also be made with seasonal runoff patterns.

External calibration is based on comparison with erosion plot (40 m^2), small catchment (0.01-1 km^2) and reservoir (1-100 km^2) data (Cerdan, 2003; Tsara *et al*, in press; Van Rompaey *et al.*, 2003). These data have been used primarily to modify the pedo-transfer functions, particularly for soil erodibility. Comparative data are considered too sparse to permit a formal independent validation test.

Data: current sources and limitations

Four main data sets are required to run the model, providing essential input data for climate, soils, land cover and topographic. These have been compiled within the PESERA project from a mixture of public and restricted sources.

Climate data

The MARS database, assembled for Monitoring Agriculture with Remote Sensing (MARS Project), at JRC-Ispra, provides daily time series of rainfall, temperature and potential evapotranspiration, interpolated to a 30 second (approximately 50 km) grid for Europe. These data have been analysed to provide the following monthly data layers for the model:

1. Rainfall: number of rain days, mean rain per rain day and its standard deviation to provide the distribution of daily rainfalls.
2. Temperature: mean, mean maximum and mean minimum required only in areas where there is soil freezing or snowfall.
3. Potential evapotranspiration: estimates of actual evapotranspiration, plant production and water balance.

These data are available under licence from the MARS Project, JRC-Ispra. The PESERA project has computed an interpolated version of the 50km data at 1km resolution, using an inverse-spline mathematical procedure (see inset map on S.P.I.04.73). However, such an interpolation procedure does not produce an accurate representation of rainfall commensurate with the resolution of 1km.

This is clearly apparent from close examination of the interpolated data for two parts of Europe. Firstly, throughout Italy there are significant differences between the distribution of annual average rainfall, computed at 5km intervals from national archives (Figure 8a), and the same parameter interpolated to 1km from the 50km MARS climatic database (Figure 8b). Secondly in UK, it is clear from Figure 9 that the interpolated 1km rainfall data set seriously underestimates annual average rainfall in the uplands of Wales and south-west England, with consequent effects on soil erosion estimation.

Using more refined interpolation techniques would result in an improved climate database, particularly for rainfall. For example, if the interpolation procedure (to 1km) incorporated altitude, distance from the sea and aspect of prevailing weather systems, significant improvements in some of the erosion estimates on the main PESERA map would undoubtedly ensue. However at the present time, the 1km interpolated MARS data provide the best resolution climate data available at European level.

Soils data

The European Soil Database, compiled by the European Soil Bureau Network (King *et al.*, 1995; Heineke *et al.*, 1998), under the coordination of the JRC-Ispra, has been used to provide a consistent level of soils data at 1 km resolution across Europe (see inset map on S.P.I.04.73). Under the PESERA Project, in conjunction with a series of pedo-transfer functions based on work by INRA-Orleans and the JRC-Ispra, the database has been used to provide three data layers for the model:

1. *Soil erodibility*, which converts runoff to erosion rates using the power law for sediment transport.
2. *Readily available Soil Water Capacity*, which provides the maximum storage capacity of the soil before runoff, occurs under vegetation.
3. *Crustability*, which sets the lower limit of storage capacity for a crusted soil in unvegetated areas.

Soil water storage capacity is also used to define the drainage characteristics of the soil and Figure 10 shows the distribution across Europe of the data currently used in PESERA. There is scope to produce maps individually for these soil properties and it is well known that pedo-transfer functions over-simplify the complexities of soil dynamic properties. However, it is unrealistic to expect major improvements in these variables in the near future though some improvement can be made where more detailed soil maps are available for areas of particular interest.

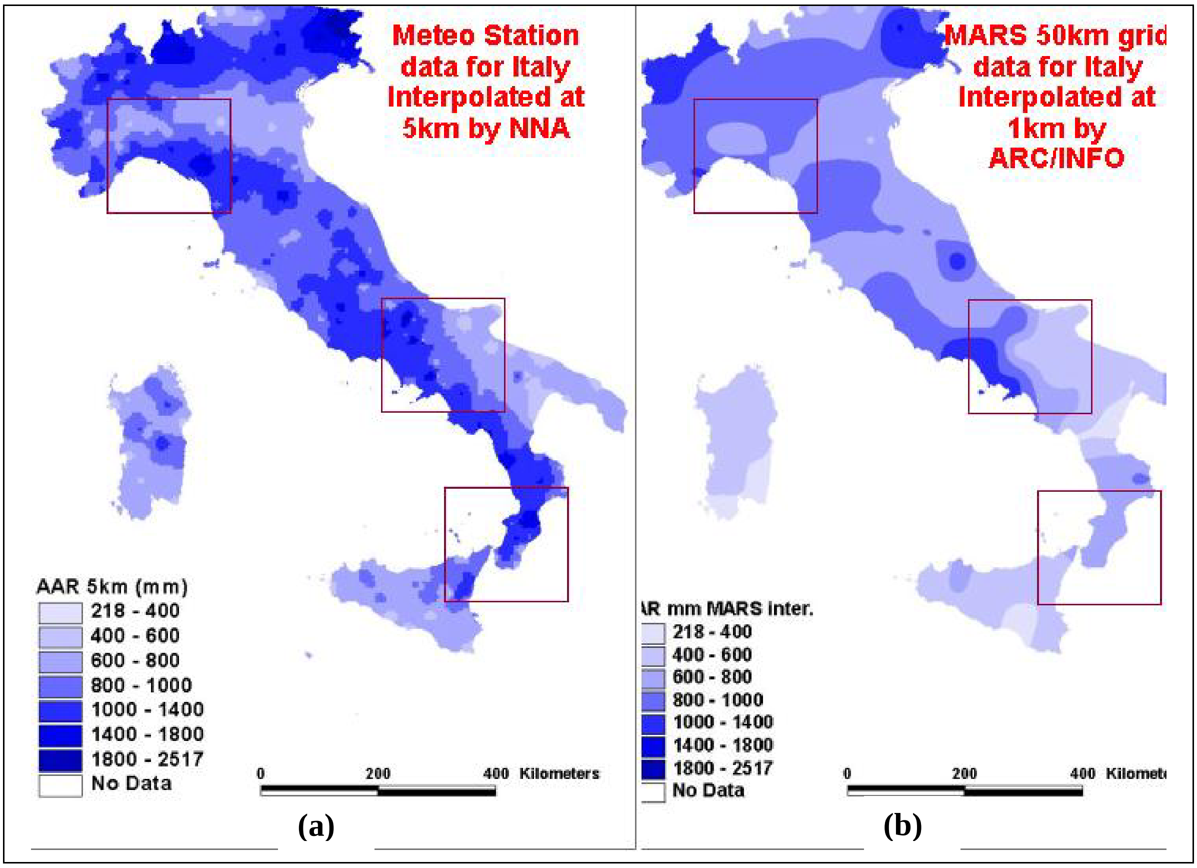
Land cover

Land cover may be derived from remote sensing, or from land use maps in combination with a vegetation growth model. Remote sensing methods use data from AVHRR or LANDSAT imagery. AVHRR provides a 20-year monthly time series at 8 km resolution, and 15 years at 1 km resolution, but is limited by cloud cover in northern Europe.

LANDSAT has the potential to provide 30m resolution, but has not been used. All remote sensing methods have the advantage of providing a measure of cover that includes the effects of all factors, but has no direct potential for scenario analysis, and, therefore, land use surveys have been the primary data source for the erosion map.

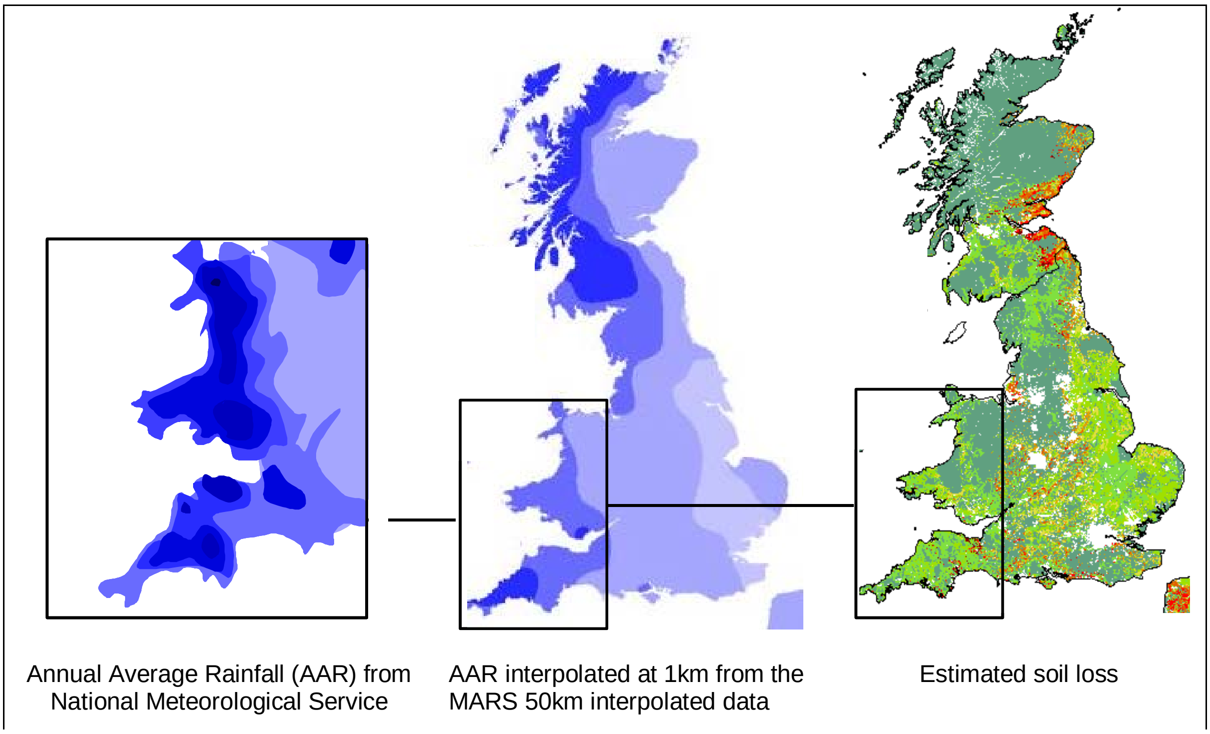
Land use for PESERA is based on CORINE land cover at 250 m resolution for 1989 (see inset map on S.P.I.04.73). This provides a suitable baseline for calculating soil erosion estimates for 1990. Land use will have changed since then and this is a potential source of error in estimating soil loss on the current map. For example, Figure 11 shows some anomalies known to exist in the CORINE land cover data, for example in the Po valley where the flooded rice growing areas have been classified as water and a square of land classified as arable in Sardinia has an unnatural rectangular shape. CORINE 2000 will eventually become available to update the land use/cover estimates.

Land use data are combined with cereal planting dates, generalised from EUROSTAT, to provide the parameters for a crop or natural vegetation growth model.



(a) (b)

Figure 8. Average annual rainfall from (a) national meteorological network (366 stations) compared to (b) MARS 50km data interpolated to 1km, for Italy.



Annual Average Rainfall (AAR) from National Meteorological Service

AAR interpolated at 1km from the MARS 50km interpolated data

Estimated soil loss

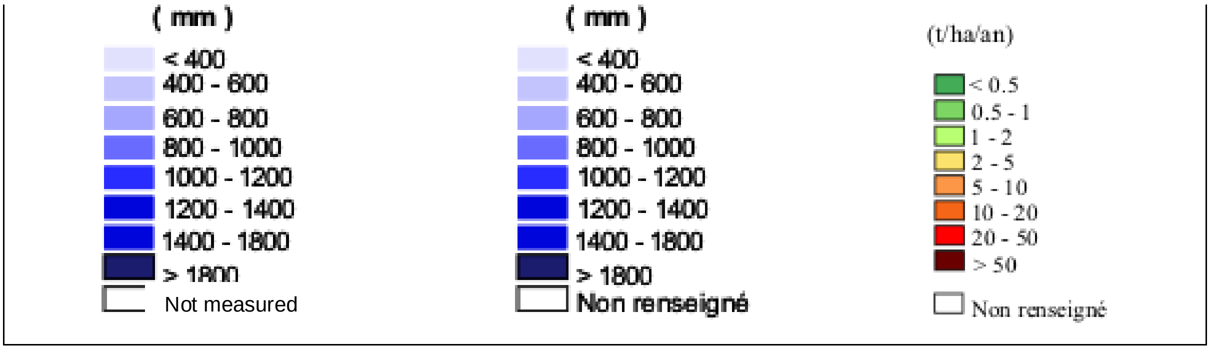


Figure 9. Average annual rainfall from national meteorological network (5000 stations) compared to MARS 50km data interpolated to 1km, in relation to estimated soil loss for UK.

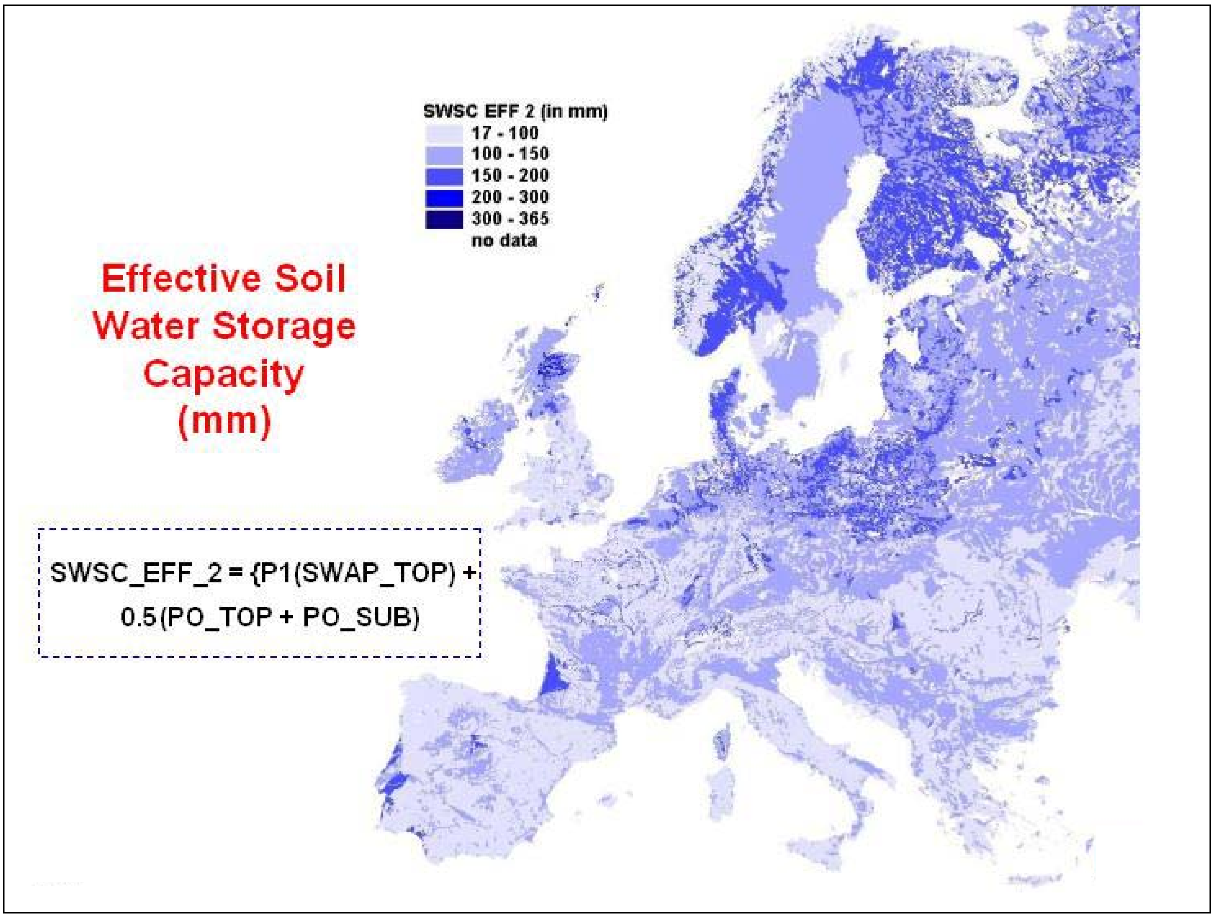


Figure 10. Effective Soil Water Storage Capacity (SWSC_eff) for Europe.

SWSC_EFF_2 is computed (in mm) at 1km from the soil water available to plants in the topsoil(SWAP_TOP) – 0-30cm and the drainable pore space in both the topsoil (P0_TOP) and subsoil(P0_SUB). Full details of these calculations are given in Gobin et al. (2003).

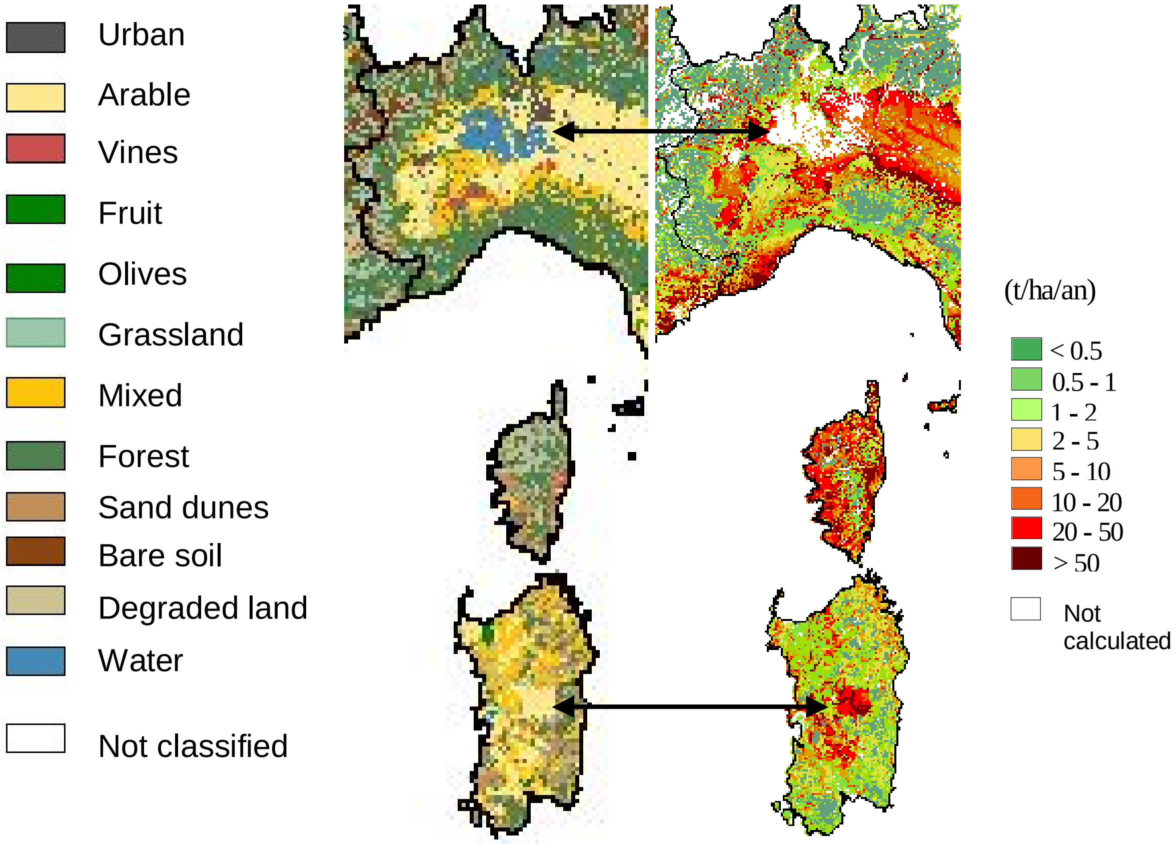


Figure 11 Examples of problems of land use classification in Italy

Topography

A 30 second (1 km) DEM has been available from EROS for some years, and has provided the topographic basis (see inset map on S.P.I.04.73) for work on PESERA, and for the erosion map. The critical parameter for the model is local relief, which has been estimated from DEMs as the standard deviation of elevation within a circle of 3 km diameter around each cell. Comparisons with DEMs at improved resolution (down to 30 m) have shown that this measure is insensitive to DEM resolution, and can therefore be used reliably with the best DEMs available for each area. Recently the SRTM 3 second (90m) DEM has been released for Europe, and this is being used to refine the data layer for local relief.

Erosion estimates: observed anomalies and limitations

The authors of this report have made a number of observations on the estimates of soil loss in areas they know well. These are listed below by country and can be considered as 'expert judgement' on the results summarised by the PESERA map.

Czech Republic

The PESERA soil loss estimates have been compared with those on a map of soil erosion risks, drawn at 1:200,000 scale, for the Czech Republic (Dostal *et al.*, 2003). The soil categories examined comprise agricultural soils and so-called mixed areas, including mostly agriculturally cultivated soil. The estimates of soil loss by PESERA compare favourably with the losses predicted for agricultural soils by Dostal et al.

Denmark

Erosion rates are relatively high compared to southern Europe and appear not to be related to planting dates or to crop cover. This could be a characteristic of the soil erodibility values, which correspond somewhat to the country's borders. The soil properties determining erodibility need to be re-examined and slope recalculated from the DEM for this area.

Greece

About one third of the country such as Crete and islands of the Aegean such as Lesbos have no estimates of soil erosion. This is because of missing land cover data. For the rest of the country, the erosion estimates look realistic except for some areas showing high erosion rates, where the parent material is limestone. In reality, the erosion rates in such areas are low because bedrock is now exposed at the surface.

France

The map shows high erosion rates east of Bayonne that seem quite high compared to other landscape units in France and Spain. Some small areas of high erosion throughout western and central France are correlated with land use. Erosion rates are shown to be high in Brittany but these seem to be related to pattern of interpolated rainfall: see inset map of average annual rainfall in S.P.I.04.73.

Figure 12. Non-agricultural vegetation in Albatera, Alicante Spain

Italy

For the northern part of the Po valley, the map shows high erosion rates yet the land is relatively flat. It seems as if the arable land use is the cause of this. By contrast, the area between the Po valley and Tuscany has low predicted erosion rates. In the arable areas of Umbria, Le Marche, Campagne and the Molise, the predicted erosion rates accord with observation.

Slovakia

The PESERA map shows estimated soil losses that agree closely with those portrayed on a map of actual soil erosion, at 1:500,000 scale, for Slovakia that has been produced by Suri *et al.*, and published in the Landscape Atlas of the Slovak Republic (2002, p.286-8). The actual erosion was estimated by a national methodology.

Spain

Areas of high erosion rates are mostly small and localised (except the valley of the Guadalquivir and to a lesser extent on the northern Meseta) while predicted soil loss rates in the rest of Spain are generally very low. These may be underestimates.

The high erosion rates in the Guadalquivir valley coincide with what we know about the area and with the assessment by Moreira Madueño (1991). The relatively high rates for the northern Meseta are in accordance with a remote sensing-based assessment of land condition made recently for mainland Spain, using 1996-2001 NOAA-NDVI data.

We would have expected to see higher rates in the Pyrenees and in general in the mountain ranges of the interior, as indicated for example by the assessment of erosion rates in Spain by ICONA (1987/88). The ICONA maps were, however, based on the USLE, so probably over-predict soil loss rates from hillslopes with natural vegetation cover.

Nevertheless, there are several factors that may cause the PESERA model to underpredict rates of soil loss in the mountain areas:

1. *Precipitation:* The MARS data set strongly underpredicts precipitation over mainland Spain, especially in the mountain ranges of the interior where mean annual amounts of >800 mm are rather common.
2. *Relief:* though the relief index used in the model is relatively independent of DEM resolution, by using a 1 km DEM grid cell we still lose part of the relief at sub-pixel scale that may be responsible for a significant part of the 'known' hotspots of erosion.
3. *Vegetation*: the vegetation in non-agricultural areas is 'grown' to a hydrological equilibrium by the model. This may lead, of course, to strong under-

prediction of sediment loss rates for areas where the vegetation cover is much sparser than the potential cover, for example in the Albatera area south west of Alicante, (Figure 12). In the LADAMER project, we are analysing NOAA-AVHRR data and found that the vegetation density of substantial areas in mainland Spain deviates significantly from the hydrologically 'possible' density.

United Kingdom

The map probably underestimates erosion of the silty soils in the Welsh Borderlands and on the South Downs in southern England. Revision of the land use/cover and the climate (rainfall) data might result in more realistic estimates.

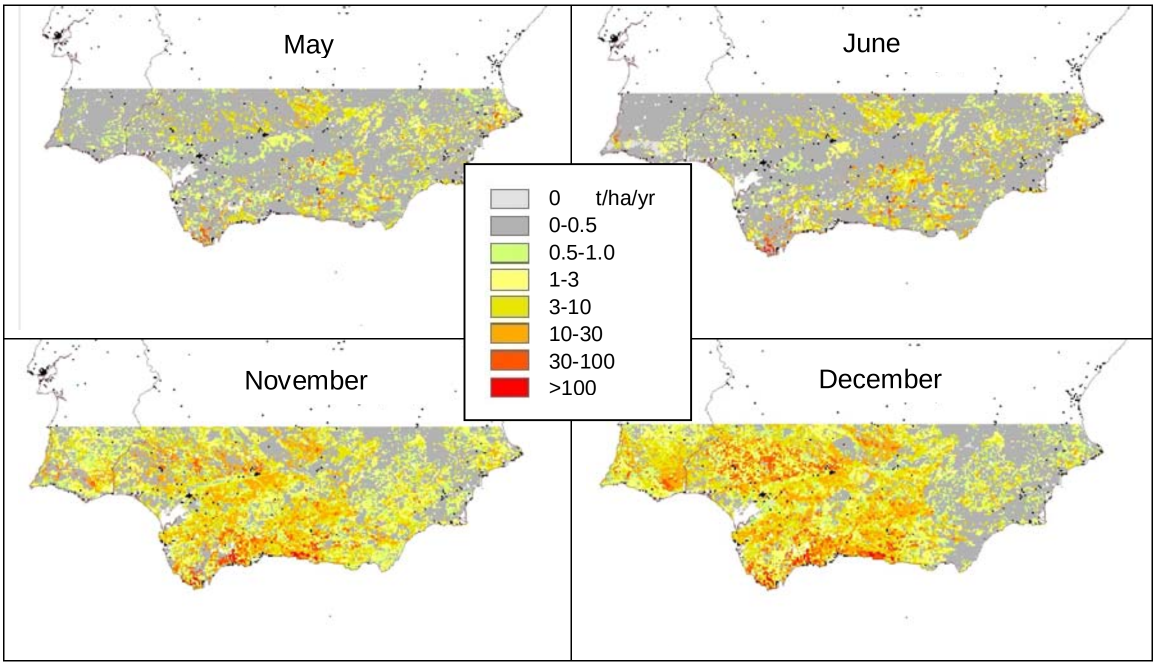


Figure 12. Mean of predicted erosion for the HADRM3 (A2B) scenario 2071-2080, assuming all arable land under maize.

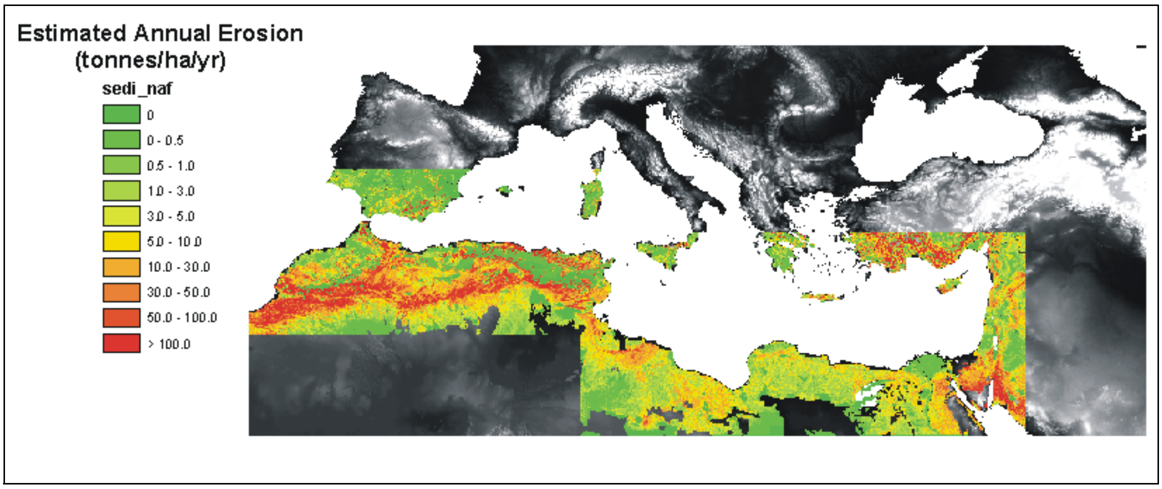


Figure 13. Estimated Annual Erosion for Southern and Eastern Mediterranean.

The Future: Land use and climate scenarios; improvements in data quality

The greatest potential for improvement in the erosion estimates on this first version of the PESERA map lies in using better climate data. Potentially, national meteorological archives are sources of better climate data, although these data are not normally ‘free of charge’. Soils data could also be improved in principle, although this is unlikely to occur in the near future.

Land cover requires frequent updating, because changes in land use have a major impact on erosion rates. There is the potential to do this through the analysis of remotely sensed images. For scenarios of alternative erosion in future, improvements in GCMs and economic forecasts offer a potential that is still far from full realisation.

However, two major components in future erosion studies, a) fluctuating climate patterns and b) changes in land use systems and/or intensity, are explicitly considered in the PESERA model. These components do not operate in an isolated manner but interact with each other; both can have important impacts on the occurrence and severity of erosion.

The PESERA Grid Model was run on climatic scenarios for the period 2071-2080 and a land use scenario, which were compared with model runs on base-line conditions. The climatic scenarios were applied to selected ‘window areas’: southern Spain and Portugal and for an area covering Belgium and northern France (Mantel *et al.*, 2003).

Figure 13 shows the results of applying the HADRM3 climate-change scenario (SRES-A2b), developed by the Hadley Centre for Climate Prediction, assuming a complete coverage with maize. The original 50km resolution of the monthly climatic parameters were interpolated to 1km using Inverse Distance Weighted (IDW) method.

On a ‘business-as-usual’ basis, the European Environment Agency expects an increase in erosion risk of 80% in EU agricultural areas by 2050, especially where erosion is already severe (EEA, 2000).

The PESERA model is currently being applied at 1 km resolution for the whole of Europe, except for some areas where some data are missing. With data at finer resolution for Europe, the model could be applied at 250m or better resolution to areas of particular concern. There is also scope, using globally available data sources, to apply the model world-wide at a resolution of 10km, although with some inevitable degradation of quality.

In a recent development, the PESERA model has been applied to Europe’s neighbouring areas, for example the southern and eastern Mediterranean (Figure 14).

Conclusions

It seems as if the current version of the PESERA grid model may over-estimate erosion in valleys and basins where the land is under arable but relatively flat, for example the Pontine swamps (I), the Po valley (I), the area east of Bayonne (F) and the dominant part of Denmark.

Many hilly to mountainous areas, such as the Apennines and the Pyrenees, are shown with very low or no erosion. It can be argued that the situation there is stable because of the forest cover, except for land-slides which are not catered for by PESERA. In this respect, land use may have too dominant an influence in the model but opinions on this differ.

Conversely, many areas on the map show erosion rates coinciding with observation and measurement, for example parts of the Guadalquivir and Ebro valleys, around Toulouse in south-west France, the loess belt in Belgium, the Siret catchment in north-eastern Romania, Alto-Adige in Italy, agricultural areas in Czech Republic, many parts of Slovakia, and other areas.

No erosion map at a European scale can be based on detailed knowledge at every point on the continent – an impossible task in practice. Furthermore, it would be impossible to include every factor of local importance in a comprehensive model, and there will always be some anomalies and limitations inherent in the data.

However, by applying a common methodology throughout Europe, based on physical understanding, the PESERA Map (S.P.I.04.73) is able to highlight major differences between regions and to highlight areas particularly at risk. It also provides a uniform basis for comparison of erosion estimates across national boundaries and climate zones.

It should emphasised that the PESERA model does not have the same accuracy for all conditions in Europe, ranging from flat to steeply sloping land, cold to hot and wet to dry conditions, intensive to extensive land management and bare to completely vegetated surfaces.

To date, PESERA provides the only Europe wide estimates of soil erosion by water, that are based on a harmonised approach and standard data sets.

This first version of the PESERA map is therefore timely in its appearance and should provide the initial basis for planning policies to protect soil at the European level. The possibilities for improvement in the near future look optimistic, in view of the vastly improved data on land use and cover together with enhanced data processing capabilities that are now becoming available.

The next step will be to compare the PESERA estimates with national measurements and risk assessments. This will be done systematically using GIS. Combining the results of such comparisons with improved data on climate, soil, land use/cover and topography (DEM) will lead to improved estimation of soil erosion by water for input to an overall soil protection strategy. These improvements will be made available in Version 2 of the PESERA Map.

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